Department for Environment Food & Rural Affairs

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delivering benefits through evidence

Impact of climate change on asset deterioration

Appendix A – Material degradation

Report - SC120005/R2

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Contents

1 Introduction

1.1 Scope

This appendix reports the results of a literature review into material degradation processes and rates for various materials that are typically used for flood and coastal defence assets.

This appendix is split into two parts:

- Degradation processes
- Degradation rates

1.2 Material degradation processes

The tables in Section 2 have been developed from the various literature listed at the end of this document. These include the following material types:

- Concrete
- Metals
- Rock
- Timber
- Blockwork/Masonry
- Asphalt
- Sealants

These tables help to improve understanding of the different types of degradation and how each can occur.

1.3 Material degradation rates

Section 3 of this appendix summarises from available literature any details on rates of degradation, describing also the key influences upon their degradation.

Information on degradation rates have been reported for each of the following materials:

- Concrete
- Metals (Structural Steel)
- Rock
- Timber

It has not been possible to establish degradation rates for Blockwork/Masonry, Asphalt or Sealants. However, this is not considered to be as important, for the following reasons:

Blockwork/Masonry:	The degradation of such materials will be similar to those of their constituent parts (e.g. where the properties are similar to those of concrete).
Asphalt:	The design life of asphalt is relatively low (c. 25 years) and degradation of its component parts is unlikely to be significantly affected by climate change over that period.
Sealants:	Again sealants have a relatively short design life and degradation is unlikely to be significantly affected by climate change over that period. Sealants can easily be changed as a maintenance operation.

2 Material degradation processes

2.1 Concrete

Mechanisms of degradation	Cause	Effect
Physical degradation		
Erosion/abrasion	Wear caused by action of fluids containing solid particles in suspension fluids (wet attrition)/wear caused by rubbing and friction (dry attrition)	Wear on surfaces, loss of cover leading to exposure of steel
Cavitation	Formation of vapour bubbles and their subsequent collapse	High instantaneous pressures that impact on the concrete surfaces, causing pitting, noise and vibration
Crystallisation of salts	Happen when the concentration of the solute (c) exceeds the saturation concentration (Cs)	Production stresses that may damage the concrete structure
Freeze–thaw cycles	Transformation of ice from liquid water generates a volumetric dilation of 9%	Cracking if the tensile stresses that develop exceed the tensile strength of the concrete
Heat	Exposed to fire or unusually high temperatures	Concrete can lose strength and stiffness
Overload and impact	Unintentional overloading, and other unusual circumstances	Loss of structural integrity
Weathering	Climatic factors, especially temperature	Variations in the visual appearance of the structure
Chemical degradation		
Chloride-induced corrosion	Intrusion of chloride ions, present in de-icing salts and seawater	De-passivation and consequent corrosion of steel reinforcement in concrete

Mechanisms of degradation	**Cause**	**Effect**
Carbonation	Penetration of atmospheric CO_2, especially at a relative humidity of between 50 and 70%	Corrosion and cracking followed by spalling
Sulphate attack	Soluble sulphates of sodium, potassium, magnesium and calcium, which often exist in groundwater, may react with hydrates such as calcium hydroxide from cement hydration	Producing expansive products inside cement paste matrix and near aggregate interface, resulting in the exposure of aggregates and cracking
Alkali–aggregate reaction, alkali–silica reaction and alkali–carbonate reaction	Some aggregates react with the alkali hydroxides in concrete	Expansion and cracking over a period of years
Biological degradation		
Biological attack	Lichen, moss, algae and roots of plants	Cracks and weak spots

2.2 Metals

Mechanisms of degradation	**Cause**	**Effect**
Uniform (most common)	Corrosive attack of water (or moisture in the air), acids, bases, salts, oils and certain chemicals	In most cases uniform degradation is objectionable only from an aesthetic standpoint
Pitting	Low dissolved oxygen concentrations, high concentrations of chlorides, poor application of the protective coating system	Localised damage to the surface, formation of a cavity or hole in the material can also cause stress risers
Crevice (general, filiform and pack rust)	Stagnant solution on the surface of a metal	Lowering of oxygen content, depletion of natural corrosion inhibitors, creation of an acidic condition, build-up of chlorides
Galvanic	Two (or more) dissimilar metals are brought into contact in the presence of moisture	One of the metals becomes the anode and corrodes faster than it would in isolation
Lamellar	Degradation that proceeds laterally from the site of the initial corrosion along parallel planes	Layered appearance, lamellar corrosion
Erosion/abrasion	Wear caused by action of fluids containing solid particles in suspension fluids (wet attrition)/wear caused by rubbing and friction (dry attrition)	Rapidly increasing erosion rates
Cavitation	Fluid's pressure drops below its vapour pressure causing gas pockets and bubbles to form and collapse	Can easily reduce the material thickness, erosion at pipe elbows and tees
Intergranular (general and exfoliation)	Associated with impurities within the metal that are concentrated at the grain boundaries	Reduction of adequate corrosion resistance which in turn makes the grain boundary zone anodic relative to the remainder of the adjacent grain surface
Environmental cracking (stress corrosion cracking)	Combination of tensile stresses and a corrosive environment	Potential to result in catastrophic material failure

Mechanisms of degradation	Cause	Effect
Environmental cracking (corrosion fatigue)	Combined action of alternating or cyclical material stresses in the presence of a corrosive environment	Reduction of its resistance
Environmental cracking (hydrogen embrittlement)	Dissolved hydrogen assists in a fracture of the metal	Development of local plastic material deformations

2.3 Rock

Mechanisms of degradation	Cause	Effect
Erosion/abrasion	Action of wind, rain and thermal change, windblown particles and water	Reduction in size and interlock between rocks
Crumbling	It may be caused by an inherent weakness in the rock (or gradual breakdown of any binder), or it may be the result of external factors affecting the strength and durability of the limestone	Certain brittleness or tendency of the stone to break up or dissolve
Chipping	Generally caused by degradation, or by accident or vandalism	The separation of small pieces or larger fragments
Cracking	Variety of causes, such as structural overloading due to settlement, or a flaw in the rock	Reduction in size and interlock between rocks
Flaking	Capillary moisture or freeze–thaw cycles	Detachment of small flat thin pieces of the outer layers of stone from a larger piece of stone
Peeling	Inherent defect in the surface of the rock or the result of weathering	Flaking away of the rock surface from the underlying rock in layers
Spalling	Pressure of salts and freeze–thaw cycles of moisture trapped under the surface (sub-florescence)	Layers begin to break off (unevenly), or peel away in parallel layers from the larger block of rock
Sub-florescence	Potentially harmful internal accumulation of soluble salts coming from host rock or water flowing or groundwater typically expand (with high temperatures) and contract (with low temperatures) weakening the rock, to the point where erosion occurs	It can create substantial pressures within the rock, causing pieces to break off along the planes of deposition. Pressure build-up within the rock, which, if sufficient, may cause parts of the outer surface of the rock to spall off or delaminate

2.4 Timber

Mechanisms of degradation	Cause	Effect
Biological factors		
Fungi (dry rot, wet rot, moulds and others)	Production of microscopic spores that can spray in various ways (active temperature ranges 20–35°C)	Softening and weakening the wood
Bacteria	Wood with a high moisture content	Significant loss of strength over long period of time (decades)
Insects	Wood-destroying insects (e.g. some species of beetles and ants)	Wood destroyed
Marine borers	Borers such as gribble and teredo attack in seawater or brackish water (most active temperature 10°C)	Wood damaged and ultimately destroyed
Non-biological factors		
Weathering	Drying, wetting effects, exposure to light, freezing and thawing, and exposure to chemical	Surface effects, does not particularly effect the mechanical properties of wood
Exposure to chemicals and other environmental factors	Chemicals or fire attack	Damages depending on kind and importance of the attack
Abrasion	Wear caused by action of fluids containing solid particles in suspension fluids (wet attrition)/wear caused by rubbing and friction (dry attrition)	Loss of section and structural integrity

2.5 Blockwork/Masonry

Mechanisms of degradation	Cause	Effect
Blistering	De-icing salts and ground moisture	Swelling accompanied by rupturing of a thin uniform skin
Chipping	May be caused by later alterations or repairs, such as use of too hard a mortar	Small pieces or larger fragments of masonry separating from the masonry unit
Cracking	Variety of conditions, such as structural settlement of a building, too hard a repointing mortar etc.	Small cracks or longer cracks (may be serious or not depending on circumstances)
Crazing	Generally due to expansion and contraction of the material	Random cracking
Crumbling	May be caused by an inherent weakness of the masonry and gradual dissolution of the binder or as a result of external factors affecting the strength or durability of the masonry	Tendency of the masonry to craze and break up or dissolve
Delamination	May be a natural condition of sedimentary stones such as sandstone or limestone; the presence of clay-rich layers can accelerate the process	Surface of the stone splits apart into laminae or thin layers and peels off the face of the stone
Detachment	May be caused and/or accelerated by the penetration of water into the structure behind the stone, causing rust and corrosion of the anchoring system	This is not a failure of the material per se but a failure of the construction system, i.e. the connectors and/or joints
Efflorescence	Excessive 'pulling' of soluble salts into the masonry and out through the surface, leaving behind white deposits	Its presence on older or historic masonry often serves as a warning, indicating that water has found a point of entry into the structure
Erosion/abrasion	Natural action of wind or windblown particles and water	Wearing away of the surface, edges, corners or carved details of masonry

Mechanisms of degradation	**Cause**	**Effect**
Exfoliation	Expansion and contraction of trapped moisture, by chemical action such as rusting of metal, or by weathering	Peeling, scaling or flaking off of the surface of stone in thin layers
Flaking	Capillary moisture or freeze–thaw cycles	Flaking of the masonry
Friability	An inherent characteristic of some types of stone	Tendency to break up, crumble or powder easily
Peeling	Improper application of masonry coatings which result in failure of the coating and/or stone surface. It may also result from a defect in the stone, or from weathering	Flaking away of the stone surface from the substrate in strips or layers
Pitting	May be the result of natural weathering or erosion of an inherently porous type of masonry	Development or existence of small cavities in a masonry surface
Salt fretting	Salt erosion	Spalling and exfoliation of the stone surface
Spalling	Sub-florescence, freeze–thaw, improper repointing with too hard a mortar mix containing too much Portland cement, or structural overloading of the stone. Pressure of salts and freeze–thaw cycles of moisture trapped under the surface (sub-florescence)	Separation and breaking away of pieces of stone
Sub-florescence	Salt crystallisation inside masonry units, which can cause damage to the internal structure	It can create substantial pressures within the masonry, causing pieces to break off along the planes of deposition. Pressure build-up within the masonry, which, if sufficient, may cause parts of the outer surface of the masonry to spall off or delaminate
Sugaring	Salts dissolved in and transported through the stone by moisture and consequent dissolution of the binder	Gradual surface disintegration

Mechanisms of degradation	**Cause**	**Effect**
Surface crust/surface induration	Movement of moisture towards the surface of stone and the outer edges, chemical reaction	Formation of a hard crust on the surface parallel to the worked surface of the stone, pollutants leading to the dissolution
Weathering	Natural disintegration and erosion of stone caused by wind and rain	Granular and rounded surfaces

2.6 Asphalt

Mechanisms of degradation	Cause	Effect
Cracking	The most common type of asphalt degradation. Drainage problems, frost heaving or joint failures, or may be load induced, poor bonding between the asphalt surface layer and the layer below, lack of support of the shoulder due to weak material or excess moisture	Fatigue cracking, longitudinal cracking, transverse cracking, block cracking, slippage cracking, reflective cracking, edge cracking – all potentially leading to failure of surface layer
Surface deformation (rutting, corrugations, shoving, depressions, swell)	Too much asphalt cement, too much fine aggregate, or rounded or smooth-textured coarse aggregate, localised bulging of the pavement, localised consolidation or movement of the supporting layers beneath the surface course due to instability, frost heaving or by moisture	Displacement of material, localised bowl-shaped areas that may include cracking, roughness, allow water to collect, localised upward bulge on the pavement surface
Disintegration (potholes, patches)	Inadequate strength in one or more layers, usually accompanied by the presence of water	Progressive breaking up of the asphalt into small, loose pieces
Surface defects (ravelling, bleeding, polishing, delamination)	Insufficient adhesion between the asphalt cement and the aggregate, presence of excess asphalt, wearing of aggregate on the surface	Loss of material from the surface, patches of asphalt cement, dangerous low friction surface

2.7 Sealants

Mechanisms of degradation	Cause	Effect
Weathering	Can be caused by prolonged exposure to water, ultraviolet light and freeze–thaw cycles	Chalking, discoloration, cracking or softening of the surface area
Cohesive failure	Degradation of the internal integrity of the sealant	Cracking parallel to the interface of the joint is an indication of this type of failure
Loss of adhesion	May be caused by the presence of coatings or contaminants that prevent proper adhesion, exposure to prolonged periods of wetting, poor surface preparation, incompatibility of substrate with selected sealant, or incompatibility of old sealant with new sealant	Sealant separates from the substrate
Uncured sealant	Incomplete or improper mixing of the sealant components, or from using materials that have outlived their shelf life	Most common in multi-component urethane sealants. Sealant uncured
Bubbling and blistering of the surface	In single-component types, this can be caused by curing at high temperatures or high humidity; in multi-component types, this can be caused by curing at high temperatures	Affects both the cure and durability of the sealant

3 Material degradation rates

3.1 Concrete

This section focuses primarily on reinforced concrete; however, the comments in this section related to exposure classification, sulphate attack, freeze–thaw damage and erosion/abrasion apply equally to mass concrete.

Concrete degradation is caused by physical, mechanical and chemical factors and can be induced by factors external and internal to the concrete structure. Physical and chemical degradation are most influenced by climate. However, based on the literature search there are no published degradation rates for concrete, as the primary causes are affected by several factors and no general conclusions appear to have been reached.

In coastal environments the degradation process is mostly affected by chloride-induced corrosion of reinforcement, particularly in the splash zone, which leads to cracking and spalling and, more severely, to the loss of cross-sections of the reinforcement and structural failure. Other forms of attack include sulphate attack, the freeze–thaw cycle and physical damage such as erosion, abrasion and weathering. Incorrectly specified concrete mixes can also be weakened by the action of sulphates and by salt weathering of the surface.

In situations where chloride-induced corrosion has been avoided by appropriate design and specification, or by designing with unreinforced concrete or non-ferrous reinforcement, the effects of sulphates could prove to be the critical factor in the longer term. However, in the medium term, sulphate attack is reduced in the presence of chlorides and is less of a risk in warm water conditions than cold water conditions.

In colder climatic regions, freeze–thaw damage is an important consideration, the risk of damage being greater in concrete saturated by salt water.

For a reinforced concrete structure there is unlikely to be a ‘safe’ amount of degradation that can be accepted, as any loss of reinforcement section could significantly reduce its structural integrity. Instead British Standard (BS) 6349 Maritime works (in its various parts) sets out various exposure classes for which the differing parts of the structure should be designed to achieve the required design life.

3.1.1 Exposure classifications

BS 6349 Maritime works is considered to be the most appropriate starting point for the planning, design, construction and maintenance of structures and facilities set in the maritime environment in the UK.

BS 6349-1–4:2013 Maritime works – Part 1–4: General – Code of practice for materials cross-refers to BS 8500-1:2015 (Concrete – Complementary British Standard to BS EN 206 Part 1: Method of specifying and guidance for the specifier) for the descriptions of exposure classes, and adds a further exposure class (XS2/3) to include a specific maritime condition.

Exposure classes for various environmental and ground conditions are shown in Table A3.1, abstracted from BS 8500-1:2015 (Table A.1).

Table A3.1 Exposure classes – reinforced concrete (abstracted from BS 8500-1:2015 (Table A.1))

CLASS DESIGNATION	CLASS DESCRIPTION
No risk of corrosion or attack (X0 class)	
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze–thaw, abrasion or chemical attack. For concrete with reinforcement or embedded metal: very dry
Corrosion induced by carbonation (XC classes) *(where concrete containing reinforcement or other embedded metal is exposed to air and moisture)*	
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3 and XC4 (XC3/4)	Moderate humidity or cyclic wet and dry
Corrosion induced by chlorides other than from sea water (XD classes) *(where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water)*	
XD1	Moderate humidity
XD2	Wet, rarely dry
XD3	Cyclic wet and dry
Corrosion induced by chlorides from sea water (XS classes) *(where concrete containing reinforcement or other embedded metal is subject to contact with sea water or airborne salt originating from sea water)*	
XS1	Exposed to airborne salt but not in direct contact with sea water
XS2	Permanently submerged
XS3	Tidal, splash and spray zones
XS2/3	Frequently wetted (e.g. mid and lower tidal zone and backfilled)
Freeze–thaw attack (XF classes) *(where concrete is exposed to significant attack from freeze–thaw cycles while wet)*	
XF1	Moderate water saturation without de-icing agent
XF2	Moderate water saturation with de-icing agent
XF3	High water saturation without de-icing agent
XF4	High water saturation with de-icing agent or sea water
Chemical attack (XA classes) *(where concrete is exposed to chemical attack)* *Chemical attack by aggressive ground (ACEC classes)*	
XA1	Slightly aggressive chemical environment
XA2	Moderately aggressive chemical environment
XA3	Highly aggressive chemical environment
Chemical attack from sea water (XAS class) *(where concrete is exposed to chemical attack from sea water)*	
XAS	Exposed to sea water

3.1.2 Chloride-induced corrosion

Chloride-induced corrosion of reinforcement is usually the critical factor for reinforced concrete degradation in a coastal environment, and rates of chloride penetration are related to the moisture state of the concrete.

The moisture state is critical to the processes of chloride penetration and subsequent electrochemical corrosion. The most important climatic factors are temperature and rainfall, which control the rate of chemical reactions and the drying out characteristics of the cover concrete.

Rainfall, humidity and the location of a structural element in relation to seawater level fluctuation control the wetness of the concrete and thus the mechanisms for the penetration of chlorides and of oxygen. The wetting and drying depth in a temperate climate might not exceed 20mm.

There are four main subdivisions of **macro**climate that affect chloride-induced corrosion, and thus the durability category:

- cold with freezing
- temperate
- hot wet
- hot dry

A similar approach is adopted in Australian Standard AS 3600-2001 Concrete structures. However, AS 3600-2001 characterises the macroclimate as tropical, temperate or arid, but does not specify a ‘cold’ macroclimatic condition.

There are also four levels of **micro**environmental classification for chloride-induced corrosion to consider with respect to concrete durability (see Table A3.1, XS classes therein).

Slater and Sharp (1998), in the publication The design of coastal structures, identified severity rating for chloride-induced corrosion on a scale of 1–12 for different locations relative to seawater on the basis of macroclimate and microclimate. These are shown in Figure A3.1, indicating the impact of temperature/humidity on chloride-induced corrosion of reinforcement.

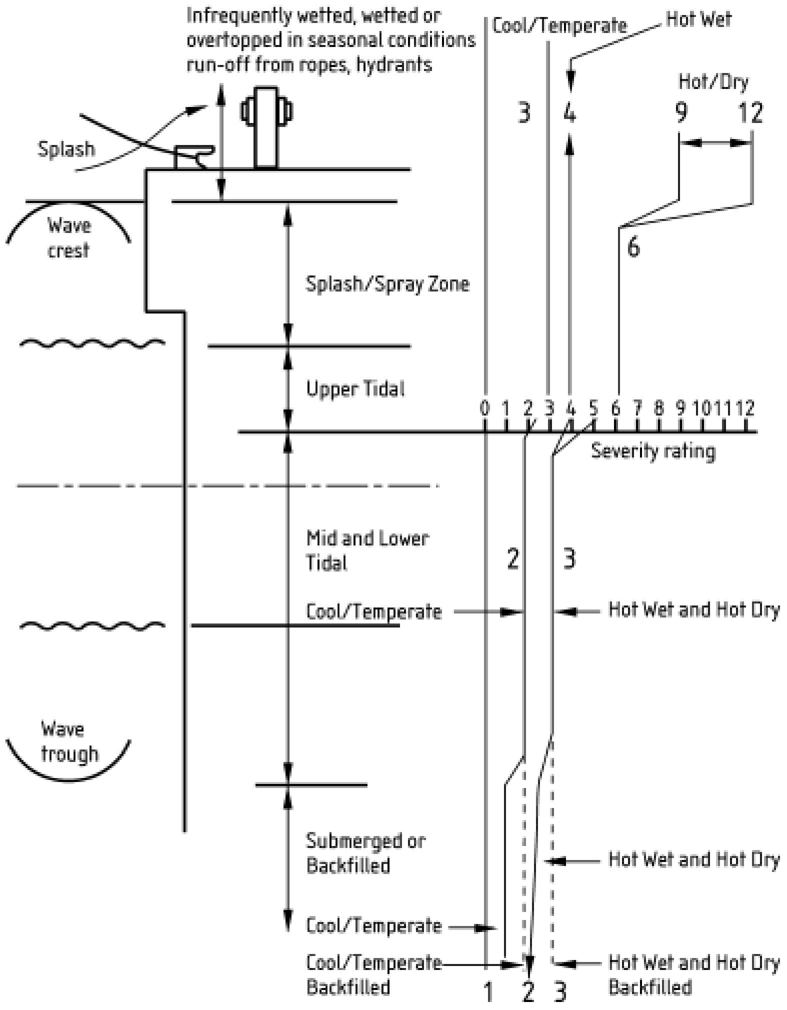


Figure A3.1 Suggested severity ratings for chloride-induced corrosion of reinforcement on a scale of 1–12 (reproduced from Slater and Sharp 1998)

3.1.3 Sulphate attack

Exposure classes for sulphates in the ground and groundwater are normally related to the type of sulphate and concentration of sulphate ions. However, the disruptive effect of sulphates is mitigated in seawater by the presence of chlorides. Blends of cements or combinations containing blast furnace slag or fly ash and Portland cement provide good sulphate resistance as well as having enhanced resistance to chloride ion penetration.

Where sulphates are present, the vulnerability of the concrete to attack and associated degradation depends upon the cement type used and the use of any additional protective measures to enhance chemical resistance. So, any potential for this to occur is not readily determined without structure-specific design information.

3.1.4 Carbonation

Carbon dioxide combines with the free lime (and other cement hydrates) in the presence of moisture, leading to a decrease in alkalinity. This ultimately results in de-passivation of the steel as the pH of the adjacent cement paste drops below a certain level. This leads to general corrosion of the reinforcement, ultimately causing cracking and spalling of the adjacent concrete.

The optimum effective relative humidity (RH) in the concrete for carbonation is 50–60%. At a relative humidity above 95% the diffusion of carbon dioxide is very slow because of the reduced space for gaseous diffusion in water-filled pores. At a relative humidity below 50% the supply of water to dissolve the carbon dioxide is limited and the rate of attack slows.

The effects of carbonation in maritime structures exposed to the marine environment and wetting are generally less critical than the effects due to chloride-induced corrosion.

3.1.5 Freeze–thaw damage

The four exposure classes specific to freeze–thaw damage are indicated in Table A3.1 (XF classes).

Although serious freeze–thaw exposure conditions are not generally experienced in UK waters, freeze–thaw damage is associated with either colder temperatures than are found in the sea around the UK, or the application of de-icing salts.

3.1.6 Erosion/abrasion

For abrasion and impact, the interactions of the various mechanisms including saltation (i.e. bouncing, or jumping of abrasive particles from one place to another), sliding, rolling and impact, in isolation or combination, are extremely complex. From the literature the principal factors that affect the degree of damage are:

- the characteristics of the particles in suspension (i.e. size, shape, quantity and hardness)
- the angle of impact
- the velocity of the water

- time of exposure
- the size and hardness of the coarse aggregates used in the concrete mix
- the compressive strength of the concrete and construction methods (e.g. curing time)

Very little guidance or information on how to undertake a quantitative assessment of water-borne abrasion of concrete exists. As the above list demonstrates, there are several variables relating to the nature of the concrete and its exposure conditions, including the nature of the abrasive material, which will affect the rate of erosion.

3.1.7 Conclusions

Concrete degradation can be affected directly and indirectly by climate change such as increasing concentrations of atmospheric CO_2, rising air temperatures and sea level rise. However, based on the literature search there are no published degradation rates for concrete and no general conclusions can be reached at present.

One of the main differences that may result from climate change will be the change in exposure zones, particularly for maritime structures, which could affect (accelerate or decelerate) material degradation due to changes in levels of wetting/drying.

However, it is clear that the base rate of any degradation, and thus change in that due to climate change, is going to be highly dependent upon the nature of the concrete mix design and its construction, which is going to be entirely asset specific. The same conclusion is reached for potential abrasion of concrete, which is further dictated by the nature of the abrasive material and the level of exposure of the asset.

In summary, the rate of material degradation without climate change is unpredictable unless specific concrete design information is known, and thus predicting a generic change in this due to climate change influences is also not possible.

3.1.8 References: concrete section

- Maritime works (BS 6349)
- Maritime works – Part 1–4: General – Code of practice for materials (BS 6349-1–4:2013)
- Concrete – Complementary British Standard to BS EN 206 Part 1: Method of specifying and guidance for the specifier (BS 8500-1:2015)
- Concrete structures, Australian Standard AS 3600-2001
- The design of coastal structures by D. Slater and B. Sharp, 1998

3.2 Structural steel

The main issue for steel used in construction of assets in wet environments is corrosion, and this is one of the few material types where reasonable information on rates of degradation exists.

Corrosion rates also vary considerably dependent upon the setting/environment the steel is in, and can be variable within a single structure dependent upon the different levels of exposure being experienced. For example, steel structures exposed to seawater can experience corrosion rates in the splash zone of more than double that in the tidal zone; likewise rates of corrosion of steel embedded in marshy soils can be considerably higher than steel embedded in undisturbed sands or clay. Out of water, rates can also differ considerably due to a number of factors, including the type of soil, variation of the level of the groundwater table, the presence of oxygen and the presence of contaminants.

3.2.1 Corrosion in the atmosphere

Corrosion in the atmosphere can be very variable and depend upon whether the steel is protected or unprotected. Protective coatings are often used and maintenance painting carried out as necessary or at planned maintenance intervals to mitigate atmospheric corrosion. The use of slow rusting ‘weathering’ steels containing copper and other alloying additions will also have an influence.

The loss of thickness due to atmospheric corrosion may be taken as 0.01mm per year in normal atmospheres and as 0.02mm per year in locations where marine conditions may affect the performance of the structure (source: BS EN 1993-5:2007 Eurocode 3 – Design of steel structures – Part 5: Piling).

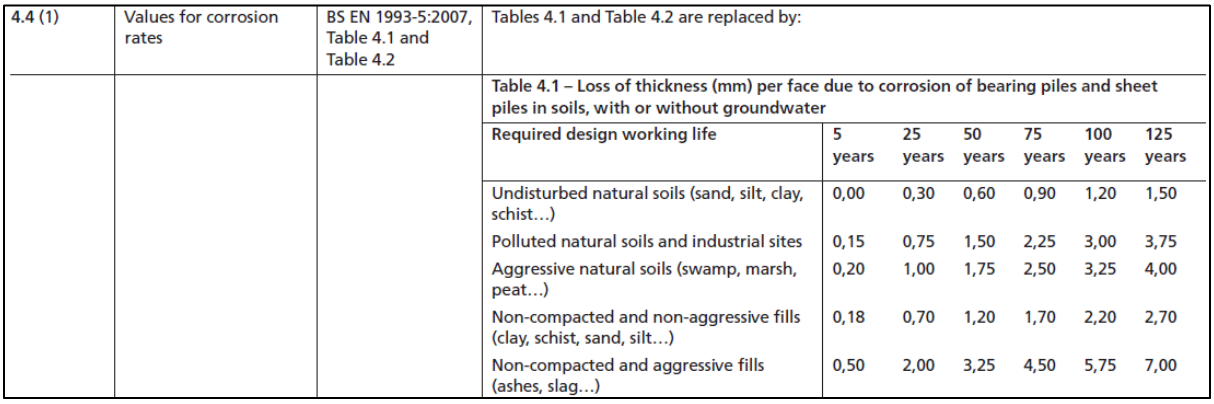
3.2.2 Corrosion of steel buried in soil and water

The following factors have a major influence on the corrosion rates in soils:

- the type of soil
- the variation of the level of the groundwater table
- the presence of oxygen
- the presence of contaminants

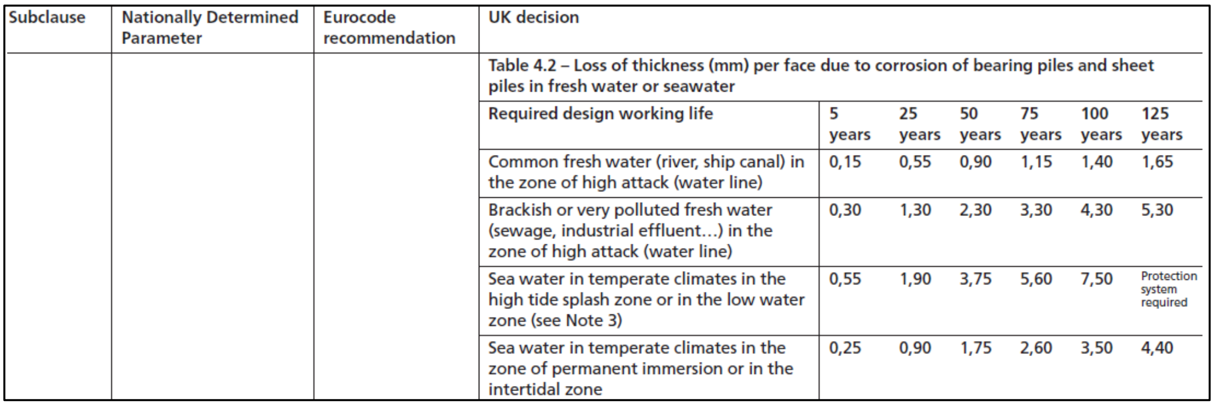
Current recommended values for the loss of thickness of steel members due to corrosion are shown in Tables A3.2a and A3.2b, abstracted from the UK National Annex to Eurocode 3: Design of steel structures – Part 5: Piling (NA to BS EN 1993-5:2007).

Table A3.2a Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in soils, with or without groundwater (abstracted from NA to BS EN 1993-5:2007)



4.4 (1)	Values for corrosion rates	BS EN 1993-5:2007, Table 4.1 and Table 4.2	Tables 4.1 and Table 4.2 are replaced by:						
			Table 4.1 – Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in soils, with or without groundwater						
			Required design working life	**5 years**	**25 years**	**50 years**	**75 years**	**100 years**	**125 years**
			Undisturbed natural soils (sand, silt, clay, schist…)	0,00	0,30	0,60	0,90	1,20	1,50
			Polluted natural soils and industrial sites	0,15	0,75	1,50	2,25	3,00	3,75
			Aggressive natural soils (swamp, marsh, peat…)	0,20	1,00	1,75	2,50	3,25	4,00
			Non-compacted and non-aggressive fills (clay, schist, sand, silt…)	0,18	0,70	1,20	1,70	2,20	2,70
			Non-compacted and aggressive fills (ashes, slag…)	0,50	2,00	3,25	4,50	5,75	7,00

Table A3.2b Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in freshwater or seawater (abstracted from NA to BS EN 1993-5:2007)



Subclause	**Nationally Determined Parameter**	**Eurocode recommendation**	**UK decision**						
			Table 4.2 – Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in fresh water or seawater						
			Required design working life	**5 years**	**25 years**	**50 years**	**75 years**	**100 years**	**125 years**
			Common fresh water (river, ship canal) in the zone of high attack (water line)	0,15	0,55	0,90	1,15	1,40	1,65
			Brackish or very polluted fresh water (sewage, industrial effluent…) in the zone of high attack (water line)	0,30	1,30	2,30	3,30	4,30	5,30
			Sea water in temperate climates in the high tide splash zone or in the low water zone (see Note 3)	0,55	1,90	3,75	5,60	7,50	Protection system required
			Sea water in temperate climates in the zone of permanent immersion or in the intertidal zone	0,25	0,90	1,75	2,60	3,50	4,40

3.2.3 Corrosion in seawater

BS EN 1993-5:2007 Eurocode 3 – Design of steel structures – Part 5: Piling, Section 4: Durability, recommends that measures against corrosion effects be taken into account if substantial losses of steel thickness are to be expected, dependent upon the aggressiveness of the media surrounding the steel member.

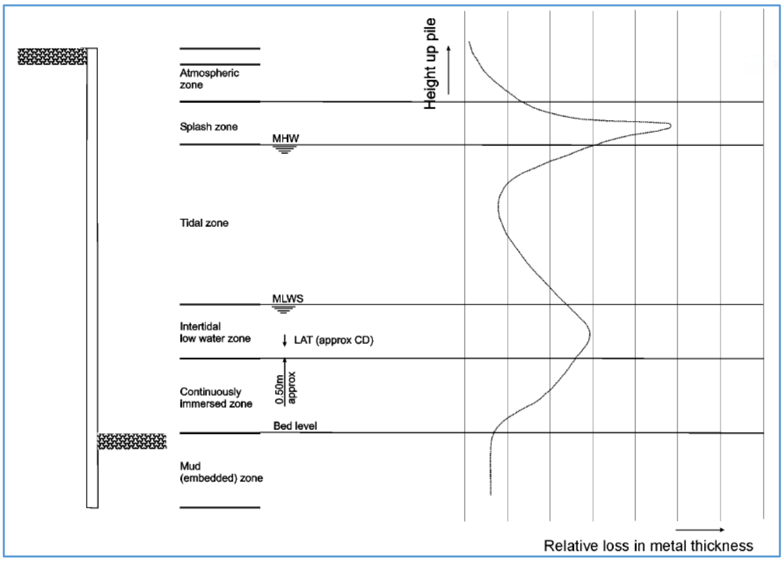
Exposure zones

Marine environments usually include several exposure zones with differing degrees of aggressiveness. The corrosion performance of coastal assets therefore requires separate consideration in each of these zones. When considering steel structures that will be exposed to seawater it is normal to divide the structure into different zones, namely:

- atmospheric zone
- splash zone
- tidal zone
- intertidal low water (ILW) zone

- continuous immersion zone
- mud (embedded) zone

Figure A3.2 indicates the corrosion rate distribution on a typical maritime structure.



Note: Corrosion rate distribution and zones of seawater aggressiveness may vary considerably from the example shown, dependent upon the conditions prevailing at the location of the structure.

Figure A3.2 Schematic showing corrosion zones and typical profile for 'traditional' corrosion behaviour

Historically, the Code of practice for foundations (BS 8004:1986) proposed that below seabed level the corrosion rate will be typically less than 0.01 to 0.02mm/year on total thickness and in the full seawater immersion zone the corrosion rate is unlikely to exceed 0.08mm/year for each side exposed to seawater (i.e. 0.16mm/year on total thickness losses). Between mean low and mean high water levels, the corrosion rate will be similar to that in the fully immersed zone. However, there are two marine exposure zones where the corrosion rate may exceed the values quoted. These are located just above mean high water level (the splash zone) and between low water neap and low water spring tide levels, where the corrosion rate is typically 0.15mm/year per exposed face and somewhat higher in severely exposed marine environments. In the sheltered environments of enclosed harbours, the splash and low water zone corrosion rates are generally much less than 0.15mm/year and even slight oil pollution will inhibit very considerably the corrosion of steel piling. If the aggressiveness of the soil or water is different on opposite sides of a steel pile wall, different corrosion rates may apply. These values are not dissimilar to the current recommendations.

From more recent literature, the notional average and upper limit values quoted elsewhere for the different exposure zones are given in Table A3.3. These provide a good summary of typical corrosion rate values for steel per exposed side in the various zones, but in themselves illustrate the variability that can exist.

Table A3.3 Comparative corrosion rates found in literature

Exposure zone	Mean corrosion rate (mm/side/year)			Upper limit corrosion rate (mm/side/year)		
	CIRIA[1]	BS 6349-1:2000[2]	Corus[3]	CIRIA[1]	BS 6349-1:2000[2]	Corus[3]
Atmospheric zone	0.02 – 0.04	0.04	-	0.10 – 0.41	0.10	-
Splash zone	0.08 – 0.42	0.08	0.09	0.17 – 0.30	0.17	0.18
Tidal zone	0.04 – 0.10	0.04	0.05	0.10 – 0.18	0.10	0.11
Intertidal low water zone	0.08 – 0.20	0.08	0.09	0.17 – 0.34	0.17	0.18
Continuous immersion zone	0.04 – 0.13	0.04	0.05	0.13 – 0.20	0.13	0.14
Below seabed level	0.03 – 0.08	-	0.03	0.02 – 0.10	0.015	0.03

[1] *Table 2.1, CIRIA C634, Management of accelerated low water corrosion in steel maritime structures*

[2] *Table 25, BS 6349-1:2000, Maritime structures – Part 1: Code of practice for general criteria*

[3] *Corus, Durability and protection of steel piling in temperate climates, 2002*

There are further examples which also demonstrate how such numbers need to be considered with a degree of caution. In a case study looking at a welded strengthening plate on steel sheet piled wall at the Port of Southampton (Steele 2002), the results revealed that up to 8.5mm of steel (equivalent to 0.9mm/year) had been lost from the front face and occasionally corners of outpans in a zone 1.0m high just above low water. Elsewhere on piles in the submerged zone virtually no corrosion was detected.

When considering how climate change might affect rates, it may also be appropriate to look to non-UK climates. For example, corrosion rates assumed for marine projects in tropical environments where cathodic protection has not been installed have been of the order of four times those previously quoted in BS 6349-1:2000, based on guidance from CIRIA C634, which collated expected corrosion rates in the various marine exposure zones from sources including Europe, USA and Japan (Halcrow, 2006).

Accelerated low water corrosion

Accelerated low water corrosion (ALWC) is a particularly aggressive form of localised corrosion, defined in the British Standard for Maritime structures (BS 6349-1:2000) as a type of low water ‘concentrated corrosion’. It has become a high profile problem, associated with unusually high rates of metal wastage and holing on unprotected, or inadequately protected, steel maritime structures. Average corrosion rates in the range of 0.3 to 1.0mm/wetted side/year are typically reported, but higher instantaneous rates are probable once ALWC has initiated on a structure. Indeed examples from older literature reporting the incidence of this from elsewhere outside the UK quote corrosion rates of 1.25mm/side/year observed in South Africa (1950s), and in Hong Kong corrosion rates of 2mm/wetted side/year (1910s).

Microbiologically induced corrosion

The detailed mechanism of ALWC continues to be a matter of some debate but the evidence is that ALWC is associated with bacterial activity and it is, therefore, a form of microbiologically induced corrosion (MIC). The most important group of micro-organisms associated with the corrosion of steel in marine environments is sulphate reducing bacteria (SRB). These have been responsible for rapid and severe localised corrosion on steel in marine environments, with reports of localised (pitting) corrosion rates of up to 8mm/year in the case of seawater ballast tanks (Campbell 1990).

3.2.4 Corrosion in freshwater

Historically, the Code of practice for foundations (BS 8004:1986) proposed that in freshwater the corrosion rate for steel fully immersed will be typically 0.05mm/year and negligible below river or canal bed level. In freshwater from carboniferous strata, calcite deposition on steel-piled structures is possible, in which case steel corrosion rates may eventually fall to very low values comparable with below-ground values of 0.01mm/year.

Where steel piling is placed in canals or rivers having essentially constant water levels, a narrow band of localised corrosion, often less than 300mm wide, may occur just below water level. The amount and distribution of this localised corrosion will be variable depending upon such factors as oxygen availability and pollution level. Normally, the rate of corrosion will be in the range 0.05 to 0.10mm/year although, in exceptional cases, corrosion rates as high as 0.25 to 0.30mm/year have been recorded. Where past experience shows that corrosion rates may be high, some form of corrosion protection may be necessary depending upon the life required from the piling, initial section thickness and stress levels.

3.2.5 Conclusions

Corrosion rate distribution and aggressiveness vary considerably, depending upon the location and conditions prevailing at the location of the structure. This is particularly apparent in seawater, where conditions are highly variable across different elevations, but may also depend upon the presence of microbiological organisms, soil conditions and measures taken to protect the structure.

With such variability in the present-day base rates, predicting the effects of climate change upon the material degradation is impossible; quoted mean rates vary by a factor of two to three and the upper limit rates can be several times greater. Consequently, the change in rate occurring for any given structure may still fall within the upper bounds, or even typical ranges quoted, and may only really be estimated at an asset-specific level with base data for that particular asset.

Even though it may not be readily quantified, it is possible to conclude that steel degradation is likely to be affected directly by climate change such as rising air temperatures, changes in humidity and sea level rise, as the chemical reactions tend to increase with increased temperature and exposure to more humid conditions.

One of the main differences that could affect a change in corrosion rate, particularly for coastal assets, may be the change in exposure zones due to sea level rise. This could affect (accelerate or decelerate) steel degradation due to changed zones of wetting/drying. Similar changes may occur in fluvial settings with increases in river flows altering the exposure of the steel to air and water, or affecting groundwater conditions in the soil.

One other factor, not assessed here due to lack of information, is the potential for abrasion of steel. This would occur due to the movement of sediments on a beach or within a river channel. Changes in climate which may lead to more aggressive conditions (e.g. faster flows or larger waves resulting in greater mobility of the sediments) will therefore have an impact upon the rate with which that occurs.

3.2.6 References: structural steel section

- Eurocode 3: Design of steel structures – Part 5: Piling (BS EN 1993-5:2007)

- UK National Annex to Eurocode 3: Design of steel structures – Part 5: Piling (NA to BS EN 1993-5:2007)
- Code of practice for foundations (BS 8004:1986)
- Maritime works – Parts 1–4: General – Code of practice for materials (BS 6349-1-4:2013)
- Maritime structures – Part 1: Code of practice for general criteria (BS 6349-1:2000)
- Durability and protection of steel piling in temperate climates, Corus, 2002
- Management of accelerated low water corrosion in steel maritime structures – CIRIA C634, London, 2005
- Accelerated low water corrosion experiences from the port of Felixstowe and port of Southampton, by Steele G., Associated British Ports, Accelerated Low Water Corrosion Conference, Denmark, 2002
- Halcrow International Partnership, Project Palm Jebel Ali Technical Note, Taisei Bridges, 2006
- Microbially assisted pitting corrosion of ships hull plate, by Campbell S.A., Scannell R.A. and Walsh F.C., Industrial Corrosion, 1990

3.3 Rock

Being a natural material, the characteristics of rock types vary greatly. Because of that, a series of tests and criteria are available as a guide to quality and durability, with rock generally being classed as ‘Excellent’, ‘Good’, ‘Marginal’ or ‘Poor’. Across those classes the degradation potential and rates will also vary considerably.

The differences in possible demands on the performance of rock from aggressive applications to mild ones are also substantial. Without knowledge of site conditions and the design application it is therefore not always possible to be confident from test results alone whether the rock materials will be suitable or unsuitable at design, let alone exact rates of any subsequent degradation. Degradation models can be used to take such differences into account, but although the rock manual (CIRIA C683, Chapter 3, Section 3.6) provides systematic methodologies for degradation prediction, validation, calibration and refinement of such degradation models is recommended (e.g. by back analysis of case histories).

3.3.1 Rock durability

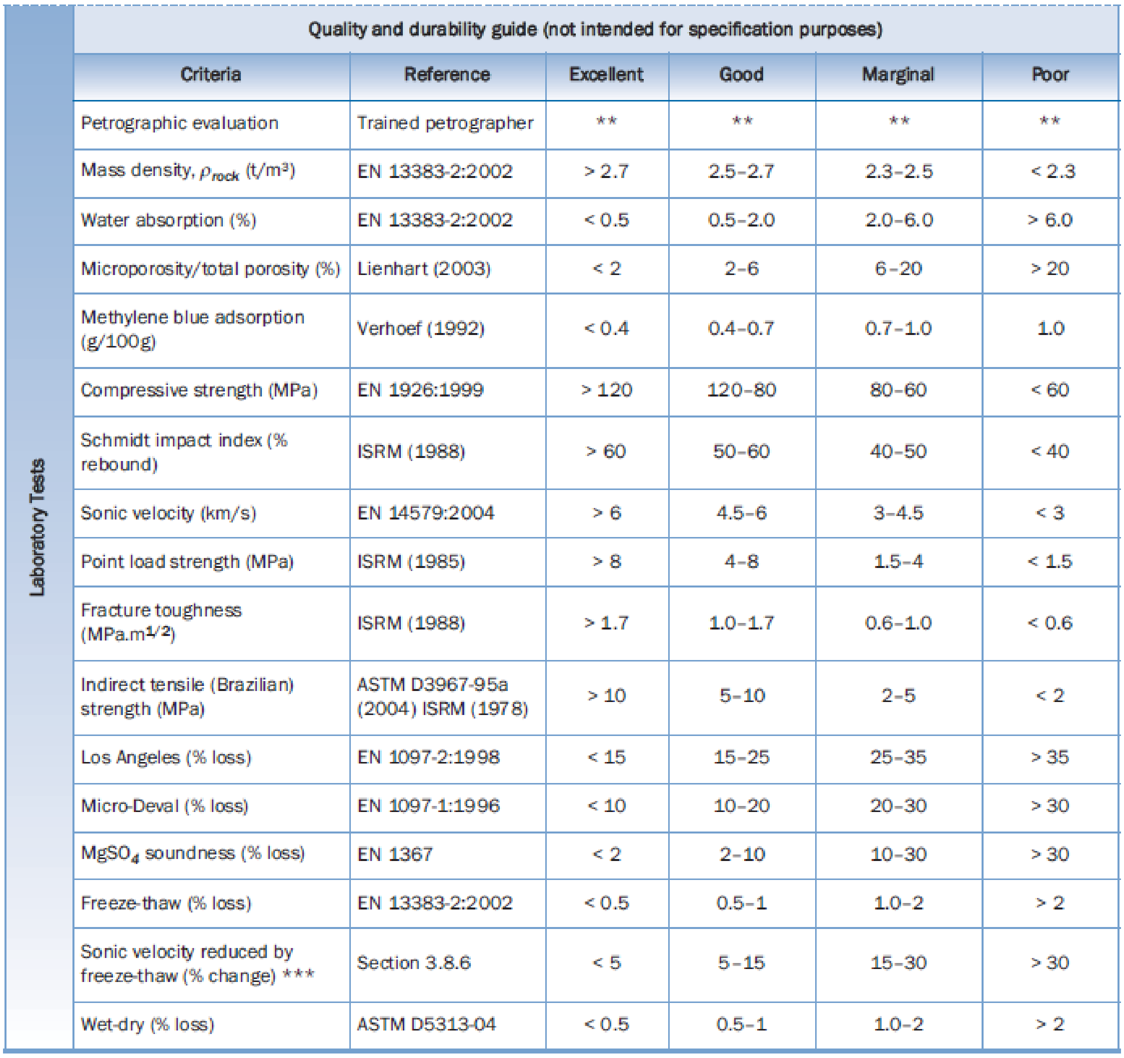
Degradation processes can be broadly classified as wear, fracture and pervasive disintegration. These can also depend on the location of the stone within the structure.

- In the armour (cover) layer, rock may be exposed to weathering such as freeze and thaw, salt crystallisation, wetting and drying, and temperature cycling when above water. For structures designed to adjust dynamically, the movement of armour stones may lead to breakage, attrition and greater overall wear; similarly, settlement of these structures as a whole may be a cause of such processes.
- In the underlayer, rock is exposed to weathering effects to a lesser degree than in the armour layer.
- Core material is less exposed to weathering agents. Dissolution may take place below water, although the solubility is highly dependent upon the water chemistry as well as the mineral content and rock porosity. For example, most types of limestone will not dissolve in the chemical environment of most seawaters, but will dissolve slowly in acidic freshwater.

Damage prediction is more complex where the armour is mobile during storms. Aggregated distances travelled by stones, possibly producing degradation by corner breakage and rounding, as well as splitting, are considerations. Both integrity and abrasion resistance are therefore important considerations for such circumstances.

The durability of rock in any given structure may be quantified by the rate of loss of material performance (such as reduction of mean mass or interlock) attributable to changes in armour-stone property over the lifetime of the structure. A series of tests and criteria are available to guide quality and durability, and Table A3.4 provides a summary of the most significant quality-related intrinsic attributes of a source of armour-stone, based on field and laboratory data.

Table A3.4 Rock quality and durability guide (ref: CIRIA, The rock manual)



	Quality and durability guide (not intended for specification purposes)					
	Criteria	**Reference**	**Excellent**	**Good**	**Marginal**	**Poor**
Laboratory Tests	Petrographic evaluation	Trained petrographer	**	**	**	**
	Mass density, ρ_{rock} (t/m^3)	EN 13383-2:2002	> 2.7	2.5–2.7	2.3–2.5	< 2.3
	Water absorption (%)	EN 13383-2:2002	< 0.5	0.5–2.0	2.0–6.0	> 6.0
	Microporosity/total porosity (%)	Lienhart (2003)	< 2	2–6	6–20	> 20
	Methylene blue adsorption (g/100g)	Verhoef (1992)	< 0.4	0.4–0.7	0.7–1.0	1.0
	Compressive strength (MPa)	EN 1926:1999	> 120	120–80	80–60	< 60
	Schmidt impact index (% rebound)	ISRM (1988)	> 60	50–60	40–50	< 40
	Sonic velocity (km/s)	EN 14579:2004	> 6	4.5–6	3–4.5	< 3
	Point load strength (MPa)	ISRM (1985)	> 8	4–8	1.5–4	< 1.5
	Fracture toughness (MPa.m$^{1/2}$)	ISRM (1988)	> 1.7	1.0–1.7	0.6–1.0	< 0.6
	Indirect tensile (Brazilian) strength (MPa)	ASTM D3967-95a (2004) ISRM (1978)	> 10	5–10	2–5	< 2
	Los Angeles (% loss)	EN 1097-2:1998	< 15	15–25	25–35	> 35
	Micro-Deval (% loss)	EN 1097-1:1996	< 10	10–20	20–30	> 30
	$MgSO_4$ soundness (% loss)	EN 1367	< 2	2–10	10–30	> 30
	Freeze-thaw (% loss)	EN 13383-2:2002	< 0.5	0.5–1	1.0–2	> 2
	Sonic velocity reduced by freeze-thaw (% change) ***	Section 3.8.6	< 5	5–15	15–30	> 30
	Wet-dry (% loss)	ASTM D5313-04	< 0.5	0.5–1	1.0–2	> 2

3.3.2 Conclusions

Rock degradation is by its nature inexact and difficult to judge. Differences in rock type (e.g. granite or limestone), and even the characteristics of individual rocks within the same rock type, make any attempt to define typical rates of degradation meaningless. It therefore also follows that changes in those rates due to climate change cannot be generically estimated.

On the assumption that a reasonable quality of rock has been used for construction, then there will generally be little effect from weathering, dissolution or freeze–thaw in a UK climate, either now or with climate change. The impact of climate change upon the rate of degradation of rock is most likely to result from more aggressive conditions (waves or flows), resulting in more movement of pieces and thus increasing the potential for wear and breakage. Even then, the potential for this cannot be generically stated but might be assessed using models discussed in The rock manual.

3.3.3 References: rock section

- The rock manual, CIRIA C683, London, 2007

3.4 Timber

The performance and service life of timber structures are affected by a wide range of issues including:

- severity of exposure (e.g. biological and/or mechanical damage as well as structural loading)
- durability and quality of materials (fastenings and fixings as well as timber components)
- quality of design, detailing and construction (particularly joints and connections)
- frequency of maintenance or remedial works

Over the course of time and through the influence of the external environment, timber structures experience degradation. At best, degradation is limited to the surface layers of the timber structure. However, given the right conditions, degradation will eventually affect the whole structure, particularly in terms of mechanical performance, strength and durability. The rate of degradation is usually specific to the particular timber species and the environmental conditions of service. The process of degradation can be subdivided into biological, chemical, photochemical, thermal, fire and mechanical degradation.

3.4.1 Timber durability

Timber is an inherently durable material, which is resistant to most biological attack provided it remains dry. However, prolonged wetting leads to a risk of decay by wood-rotting fungi, although susceptibility varies according to the wood species (i.e. its ‘natural durability’).

BS EN 350:1994, Durability of wood and wood-based products, identifies five natural durability ratings. The equivalent British Standard, BS 5589:1989, Code of practice for preservation of timber, also classifies timber into five durability ratings. The durability ratings are summarised in Table A3.5. For a wider range of species the reader should refer to BS EN 350: Part 2 and BS 5589. The natural durability ratings defined in BS 5589 and BS EN 350 do not, however, consider the resistance of the timber to marine borer attack.

Table A3.5 Timber durability ratings (abstracted from BS EN 350:1994)

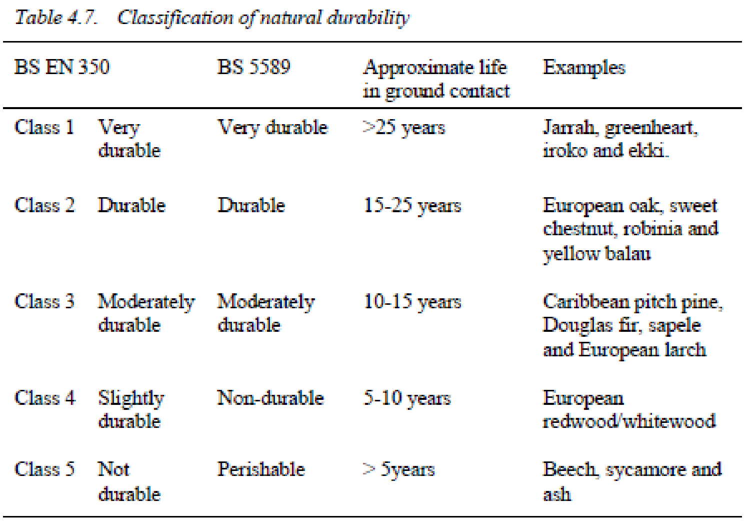


Table 4.7. Classification of natural durability

BS EN 350		BS 5589	Approximate life in ground contact	Examples
Class 1	Very durable	Very durable	>25 years	Jarrah, greenheart, iroko and ekki.
Class 2	Durable	Durable	15-25 years	European oak, sweet chestnut, robinia and yellow balau
Class 3	Moderately durable	Moderately durable	10-15 years	Caribbean pitch pine, Douglas fir, sapele and European larch
Class 4	Slightly durable	Non-durable	5-10 years	European redwood/whitewood
Class 5	Not durable	Perishable	> 5years	Beech, sycamore and ash

Mechanical abrasion of timber may be uneven and this may be a reflection of local conditions or variation in the natural properties of the timber species such as density. At the coast, the greatest abrasion usually occurs in the intertidal zone between the lower limit of shingle and the average high tide level. The rate of wear will vary from beach to beach and from species to species. However, only once they are installed is it really possible to estimate the rate of wear of the timber components by carrying out annual inspections of the structures.

3.4.2 Marine borers

There are two types of marine borer present in UK waters. The crustacean *Limnoria* spp. (gribble) is ubiquitous, whereas the mollusc *Teredo* spp. (shipworm) tends to be limited to the south-west coast. Various laboratory studies and field tests have been carried out to compare the relative durability of different timber species to marine borers both in the UK and elsewhere.

For example, Table A3.6 shows feeding rates on different timber species compared to two benchmark species, Ekki and Greenheart (ref: Assessment of the durability and engineering properties of lesser-known hardwood timber species for use in marine and freshwater construction – TRADA Technology 2010). Tests were carried out on blocks kept in running seawater at temperatures comparable to the temperature at the source of seawater in Langstone Harbour near Portsmouth, UK. This table illustrates considerable variability depending upon timber species.

Table A3.6 Feeding rates on timber species (Ref. Trada, 2010)

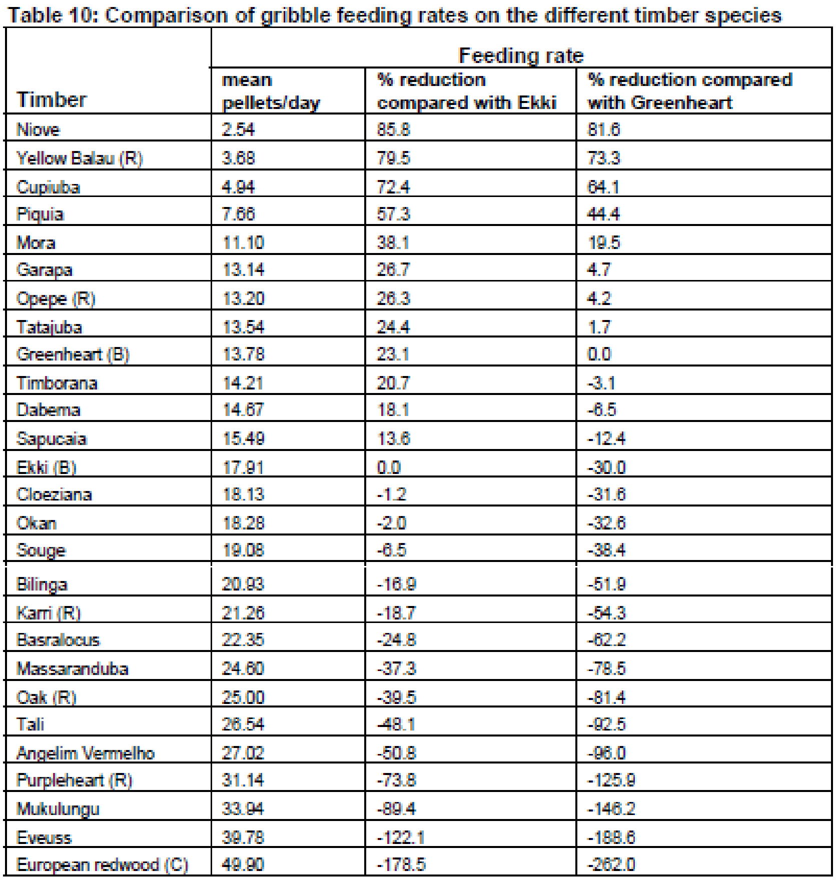


Table 10: Comparison of gribble feeding rates on the different timber species

Timber	Feeding rate		
	mean pellets/day	% reduction compared with Ekki	% reduction compared with Greenheart
Niove	2.54	85.8	81.6
Yellow Balau (R)	3.68	79.5	73.3
Cupiuba	4.94	72.4	64.1
Piquia	7.66	57.3	44.4
Mora	11.10	38.1	19.5
Garapa	13.14	26.7	4.7
Opepe (R)	13.20	26.3	4.2
Tatajuba	13.54	24.4	1.7
Greenheart (B)	13.78	23.1	0.0
Timborana	14.21	20.7	-3.1
Dabema	14.67	18.1	-6.5
Sapucaia	15.49	13.6	-12.4
Ekki (B)	17.91	0.0	-30.0
Cloeziana	18.13	-1.2	-31.6
Okan	18.28	-2.0	-32.6
Souge	19.08	-6.5	-38.4
Bilinga	20.93	-16.9	-51.9
Karri (R)	21.26	-18.7	-54.3
Basralocus	22.35	-24.8	-62.2
Massaranduba	24.60	-37.3	-78.5
Oak (R)	25.00	-39.5	-81.4
Tali	26.54	-48.1	-92.5
Angelim Vermelho	27.02	-50.8	-96.0
Purpleheart (R)	31.14	-73.8	-125.9
Mukulungu	33.94	-89.4	-146.2
Eveuss	39.78	-122.1	-188.6
European redwood (C)	49.90	-178.5	-262.0

Note: Rates are expressed as a percentage reduction in daily faecal pellet production rate compared to the reference timbers, Ekki and Greenheart. A negative figure indicates comparatively worse performance whereas a positive figure indicates comparatively better performance; for example, it can be seen in the table that niove exhibits 85.8% and 81.6% reduction in daily faecal pellet production when compared to ekki and greenheart respectively, indicating comparatively greater resistance than both greenheart and ekki.

3.4.3 Abrasion

Laboratory tests to determine, in a short period of time, the comparative resistance of the long list of candidate timbers to abrasion in the marine environment against the benchmark timbers Greenheart and Ekki are also reported by TRADA, 2010.

These tests simulated a period equivalent to approximately two years, although it should be borne in mind that direct comparisons to exposure in situ are difficult to make and the assumptions made for those tests could be viewed as theoretical. Nonetheless, a direct comparison can be made between the relative performances of different timber species, as shown in Table A3.7, which presents average volume loss.

These tests again illustrate considerable variability depending upon timber species, as Table A3.7 shows.

Table A3.7 Abrasion rates for timber species (ref. Trada, 2010)

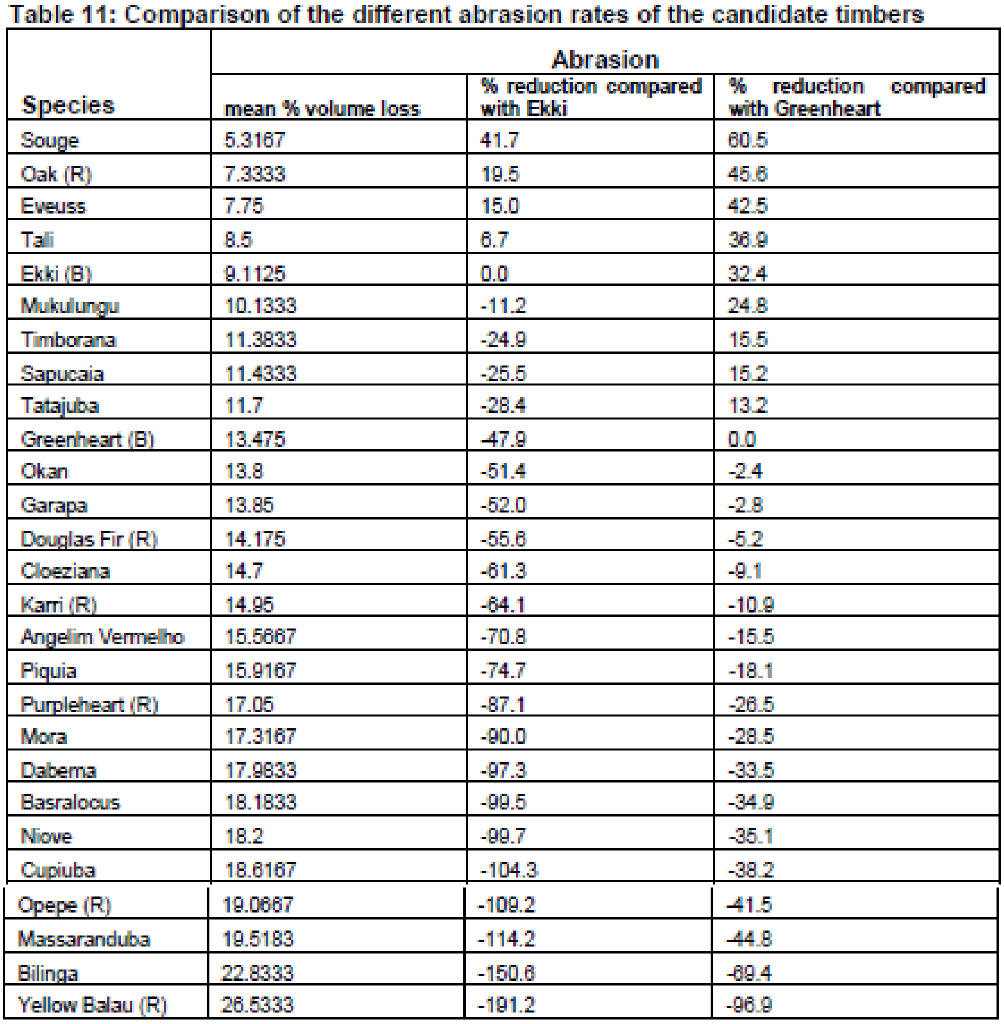


Table 11: Comparison of the different abrasion rates of the candidate timbers

Species	Abrasion		
	mean % volume loss	% reduction compared with Ekki	% reduction compared with Greenheart
Souge	5.3167	41.7	60.5
Oak (R)	7.3333	19.5	45.6
Eveuss	7.75	15.0	42.5
Tali	8.5	6.7	36.9
Ekki (B)	9.1125	0.0	32.4
Mukulungu	10.1333	-11.2	24.8
Timborana	11.3833	-24.9	15.5
Sapucaia	11.4333	-25.5	15.2
Tatajuba	11.7	-28.4	13.2
Greenheart (B)	13.475	-47.9	0.0
Okan	13.8	-51.4	-2.4
Garapa	13.85	-52.0	-2.8
Douglas Fir (R)	14.175	-55.6	-5.2
Cloeziana	14.7	-61.3	-9.1
Karri (R)	14.95	-64.1	-10.9
Angelim Vermelho	15.5667	-70.8	-15.5
Piquia	15.9167	-74.7	-18.1
Purpleheart (R)	17.05	-87.1	-26.5
Mora	17.3167	-90.0	-28.5
Dabema	17.9833	-97.3	-33.5
Basralocus	18.1833	-99.5	-34.9
Niove	18.2	-99.7	-35.1
Cupiuba	18.6167	-104.3	-38.2
Opepe (R)	19.0667	-109.2	-41.5
Massaranduba	19.5183	-114.2	-44.8
Bilinga	22.8333	-150.6	-69.4
Yellow Balau (R)	26.5333	-191.2	-96.9

3.4.4 Timber performance

As indicated in Table A3.8, which is based upon tables 1 and 2 from TRADA Wood information sheet, WIS 2/3-66, February 2011, there are considerable differences in the ways in which different timbers will degrade.

These tables show that while certain timber types might be more resistant to decay fungi or marine borers, they are less resistant to abrasion, and vice versa. Consequently, the rate of degradation is not only dependent upon the timber type, but also upon which degradation process is dominant and which of the climate change factors has occurred.

Table A3.8 Resistance of timber species (ref. Trada, 2011)

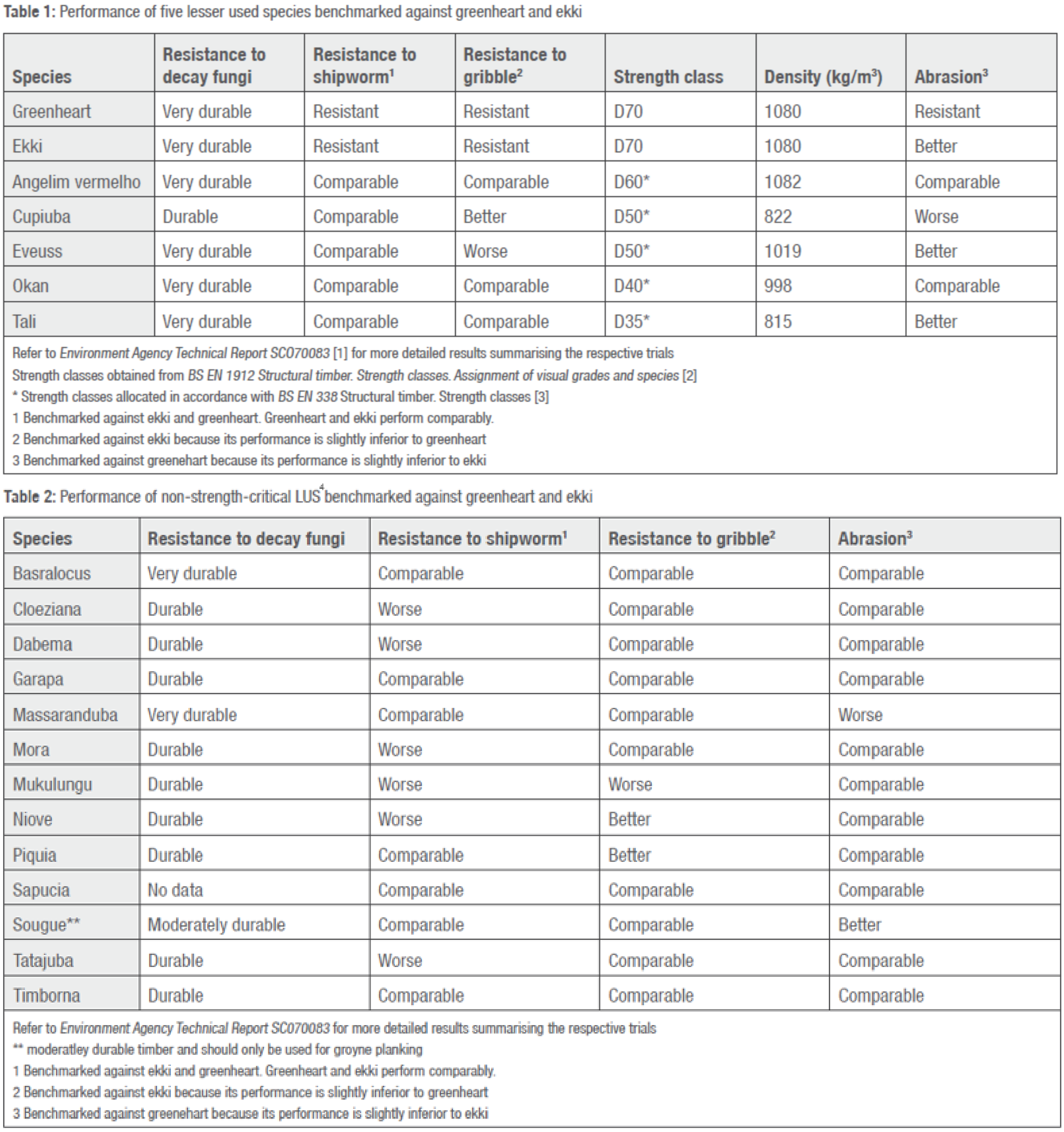


Table 1: Performance of five lesser used species benchmarked against greenheart and ekki

Species	Resistance to decay fungi	Resistance to shipworm[1]	Resistance to gribble[2]	Strength class	Density (kg/m^3)	Abrasion[3]
Greenheart	Very durable	Resistant	Resistant	D70	1080	Resistant
Ekki	Very durable	Resistant	Resistant	D70	1080	Better
Angelim vermelho	Very durable	Comparable	Comparable	D60*	1082	Comparable
Cupiuba	Durable	Comparable	Better	D50*	822	Worse
Eveuss	Very durable	Comparable	Worse	D50*	1019	Better
Okan	Very durable	Comparable	Comparable	D40*	998	Comparable
Tali	Very durable	Comparable	Comparable	D35*	815	Better

Refer to *Environment Agency Technical Report SC070083* [1] for more detailed results summarising the respective trials

Strength classes obtained from *BS EN 1912 Structural timber. Strength classes. Assignment of visual grades and species* [2]

* Strength classes allocated in accordance with *BS EN 338* Structural timber. Strength classes [3]

1 Benchmarked against ekki and greenheart. Greenheart and ekki perform comparably.

2 Benchmarked against ekki because its performance is slightly inferior to greenheart

3 Benchmarked against greenehart because its performance is slightly inferior to ekki

Table 2: Performance of non-strength-critical LUS[4] benchmarked against greenheart and ekki

Species	Resistance to decay fungi	Resistance to shipworm[1]	Resistance to gribble[2]	Abrasion[3]
Basralocus	Very durable	Comparable	Comparable	Comparable
Cloeziana	Durable	Worse	Comparable	Comparable
Dabema	Durable	Worse	Comparable	Comparable
Garapa	Durable	Comparable	Comparable	Comparable
Massaranduba	Very durable	Comparable	Comparable	Worse
Mora	Durable	Worse	Comparable	Comparable
Mukulungu	Durable	Worse	Worse	Comparable
Niove	Durable	Worse	Better	Comparable
Piquia	Durable	Comparable	Better	Comparable
Sapucia	No data	Comparable	Comparable	Comparable
Sougue**	Moderately durable	Comparable	Comparable	Better
Tatajuba	Durable	Worse	Comparable	Comparable
Timborna	Durable	Comparable	Comparable	Comparable

Refer to *Environment Agency Technical Report SC070083* for more detailed results summarising the respective trials

** moderatley durable timber and should only be used for groyne planking

1 Benchmarked against ekki and greenheart. Greenheart and ekki perform comparably.

2 Benchmarked against ekki because its performance is slightly inferior to greenheart

3 Benchmarked against greenehart because its performance is slightly inferior to ekki

[4] Lesser-Used Species (LUS)

3.4.5 Conclusion

Timber degradation can be affected directly and indirectly by climate change through changes in water levels altering the exposure to wetting and drying (which may result in more rotting), changing temperatures (which may alter the levels of marine borers found in the water), or larger waves/greater flows (which may change the dynamic regime and thus produce more aggressive and abrasive conditions). No doubt, climate change will increase these rates, but the rates are also highly dependent upon the local environment (e.g. the presence and nature of abrasive material).

Attributing values to the impact resulting from climate change is difficult to determine, as baseline values for present-day conditions are not generically identifiable. This is further complicated because there is considerable variability in the resistance of timber species to different degradation processes. Some timbers are more resistant to one process (e.g. marine borers) but less to another (e.g. abrasion), while others have the opposite characteristics. Consequently, the rate of degradation is not only critically dependent upon whatever timber has been used for any specific asset, but also upon which degradation process is dominant and the actual nature of the climate change, i.e. whether that results in more aggressive hydrodynamic conditions or a change in water temperature.

3.4.6 References: timber section

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