Concrete durability standards: International trends and the South African context

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Durability problems in reinforced concrete (RC) structures are an issue of global concern, since they threaten economic growth, natural resources and human safety. As a result, attempts have been made in design standards developed in most countries to include requirements to provide durable RC structures. This paper examines and compares such durability requirements in standards from the United States, Australia, Canada, Europe, India and South Africa. It focuses on aspects such as exposure conditions, limiting values of material compositions and proportions, and cover depth to the reinforcing steel. The paper describes issues behind prescriptive standards and deals with challenges confronting performance approaches for concrete durability. Following international trends, it is evident that the South African Standards, particularly SANS 10100-2, must undergo substantial updating and improvements to durability requirements. The paper suggests the means of re-drafting and implementing durability specifications in any revised version of SANS 10100-2, taking into account both prescriptive and performance alternatives. Further, a methodology of developing durability specifications suitable for the South African concrete industry is proposed, and recommendations are made for future developments.

INTRODUCTION

Concrete performance is vital for underpinning a country's essential services and economic activities. Despite the ability of concrete to provide useful and long-lasting infrastructure, concrete structures may face durability challenges mainly due to premature deterioration. This is an issue of global concern since it threatens economic growth, natural resources and human safety (Gjørv 2011). Durability problems related to premature deterioration have been described in numerous publications (Al-Bahar *et al* 2003; Gjørv 2009). In the USA, annual costs of repair and replacement of bridges approaching US$8.3 billion were estimated by Yunovich *et al* (2001), and are expected to increase to about US$9.4 billion over the next 20 years (Darwin 2007). In Western Europe, annual costs of US$5 billion for repair of reinforced concrete (RC) structures were estimated as long ago as 1998 (Knudsen *et al* 1998). In the Arabian Gulf, repair and replacement costs of about US$798 million due to extensive deterioration resulting from corrosion of reinforcing steel have been reported (Al-Bahar *et al* 2003). The extensive costs of repair and maintenance of RC structures resulting from premature deterioration illustrates the seriousness of the durability problems, and threatens the concrete construction industry worldwide.

Although concrete durability problems are complex and varied, mitigation measures for ensuring durability are generally available and accessible. Rostam (2003) describes two means of ensuring durable concrete, i.e. avoidance of the deterioration mechanisms, and optimisation of material compositions and proportions. The former relies on protective measures, such as use of non-reactive materials or surface treatments which are beyond the scope of this paper. The latter is of particular importance as it allows different approaches which can be covered in standards and specifications for durability – the focus of this paper.

The current approach to deal with concrete durability in standards and specifications is commonly the so-called *prescriptive approach* that outlines requirements for material compositions and proportions, procedures and test methods. Although such approaches may encompass requirements for, *inter alia*, minimum compressive strength, maximum water/binder (w/b) ratio, minimum supplementary cementitious materials (SCMs) content and cover depth, the desired concrete performance is not described (Lobo *et al* 2005; Bickley *et al* 2006). Material and construction variability are not taken into account, and even if intensive site supervision is carried out, it is difficult to ensure that all specified requirements are achieved (Day 2005). Moreover, requirements

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Table 1 Recommended Durability Requirements in ACI 318 (2008)

Exposure class	Sub-classes	Max w/b*	Min f_c, MPa#	Additional requirements**
F Freezing and thawing	F0 : Negligible; concrete not exposed to freezing and thawing	–	–	–
	F1 : Moderate; occasional exposure to moisture	0.45	31	Low entrained air
	F2 : Severe; in continuous contact with moisture	0.45	31	Higher entrained air
	F3 : Very severe; in continuous exposure with moisture and de-icing chemicals	0.45	31	Higher entrained air and limits on SCMs
S Sulfate	S0 : Negligible; $SO_4 < 0.10\%$ (soil) $SO_4 < 150$ mg/*l* (water)	–	–	—
	S1 : Moderate; $0.10\% \leq SO_4 \leq 0.20\%$ (soil) $150 \leq SO_4 \leq 1\,500$ mg/*l* (water)	0.50	28	Cement types: ASTM II, IP(MS), IS(<70)(MS) Maximum expansion (ASTM C 1012) : 0.10% at 6 months
	S2 : Severe; $0.20\% \leq SO_4 \leq 2.00\%$ (soil) $1500 \leq SO_4 \leq 10\,000$ ppm (water)	0.45	31	Cement types: ASTM V, IP(HS), IS(<70)(HS) No calcium chloride admixture Maximum expansion (ASTM C 1012) : 0.05% at 6 months or 0.10% at 12 months
	S3 : Very severe; $SO_4 > 2.00\%$ (soil) $SO_4 > 10\,000$ mg/*l* (water)	0.45	31	Cement types: ASTM V + Pozzolan or slag, IP(HS) + Pozzolan or slag or IS(< 70)(HS) + Pozzolan or slag No calcium chloride admixtures Maximum expansion (ASTM C 1012): 0.10% at 18 months
C Corrosion	C0 : Negligible; concrete dry and protected from moisture			Maximum water-soluble chloride ion (Cl^-) content in concrete, percentage by weight of cement for reinforced concrete
		–	–	1.00
	C1 : Moderate; concrete exposed to moisture but not to external source of chlorides	–	–	0.30
	C2 : Severe; concrete exposed to moisture and an external source of chlorides	0.40	35	0.15 Adequate cover concrete
P Requiring low permeability	P0 : Concrete where low permeability to water is not required	–	–	–
	P1 : Concrete required to have low permeability to water	0.50	28	–

Notes:
1. * 'b' is taken throughout to refer to the total cementitious materials content, i.e. the binder content.
2. \# Unless otherwise specified, requirements for minimum strength f_c shall be based on 28-day tests of cylinders.
3. ** Cement types: IS – Portland blast-furnace slag; IP – Portland – pozzolan; MS – Moderate Sulfate Resistance; HS – High Sulfate Resistance.

such as maximum w/b and minimum cement content are impractical or costly to verify in practice (Alexander *et al* 2010). These requirements have limited effectiveness and often stifle innovation (Bickley *et al* 2006).

Recent research has focused on performance approaches, which measure relevant properties of the concrete, in particular transport-related properties for durability (Alexander *et al* 2010). Ideally these approaches should be fully performance-based, but in practice an intermediate mixed approach is often more useful – termed as a 'hybrid' approach. To be fully performance-based, the approach should be an integrated one, linking durability requirements (including durability indicators from relevant test methods) and durability design through service life models in order to estimate the service life of the RC structure (Beushausen & Alexander 2006; Alexander & Santhanam 2012). Importantly, in a full performance approach, specified concrete properties should be measurable in-situ to ensure that *as-built* quality is actually achieved.

A 'hybrid' approach is a mix of prescriptive and performance requirements, but with greater emphasis on the performance criteria. The client and/or specifier decide on the desired level of performance in a certain exposure condition, and propose relevant 'durability indicators' which are used to prepare specifications (Taylor 2004). The durability indicators are chosen based on technical recommendations without necessarily or explicitly defining a design service life period. Generally both approaches – full performance-based and hybrid – are aimed at achieving relevant durability indicators that demonstrate the suitability of the concrete and its composition with respect to the exposure conditions. Performance approaches are now gaining acceptance in the concrete industry since they promote innovation, while the desired concrete performance during its service life and the *as-built* structural concrete properties can be specified prior to construction. However, it should be noted that there are only a few instances in practice where actual in-situ or *as-built* properties are measured. It is the authors' opinion that approaches that do not measure *as-built* properties cannot be regarded as fully performance-based.

While prescriptive specifications are still the norm in most countries, including South Africa, a few countries have successfully implemented performance specifications to a certain point. The following section describes concrete durability provisions in selected international standards, with the focus on performance aspects.

REVIEW AND CRITIQUE OF DURABILITY PROVISIONS IN CURRENT STANDARDS AND SPECIFICATIONS

United States of America

ACI 318 (2008)

The US concrete building code, ACI 318 *Building Code Requirements for Structural Concrete* (ACI 2008), provides minimum requirements for materials, design and construction practices. It is mainly a prescriptive standard regarding durability aspects, with some partial performance elements such as, for example, sulphate resistance. Chapter 4 defines exposure classes (including those relating to reinforcement corrosion, but excluding carbonation) based on the degree of severity, and imposes limits to maximum w/b and minimum compressive strength. It also limits air content, SCM content and chloride content, and specifies cement types as additional requirements. Although ACI 318 provides cover depth requirements based on the concrete quality, it does not link these directly with the exposure classes.

Durability requirements in ACI 318 are summarised in Table 1, which indicates that concrete exposed to sulphate conditions can be evaluated on a performance basis (subject to the reservations expressed earlier). While the commentary to ACI 318 recommends that concrete exposed to conditions requiring low permeability should be evaluated using ASTM C1202 (2007) (i.e. the Rapid Chloride Permeability Test (RCPT)), no limits or performance criteria are given. ACI 318 seeks to promote improvement of concrete properties related to penetrability by limiting the w/b ratio and by use of hydraulic cements conforming to ASTM C1157 (2011). However, the code is essentially prescriptive and not performance-based.

Australia

AS 3600 (2001)

The Australian Standard, AS 3600 *Concrete Structures* (AS 2001), provides minimum requirements for the design and construction of plain and RC structures. It is prescriptive regarding durability provisions. AS 3600 defines exposure classes from A to C, where A represents the most benign condition and C indicates the most severe conditions. A class ‘U’ is included representing an exposure condition for which the degree of severity is not fully known and needs proper assessment prior to specifying concrete.

Durability requirements in AS 3600 for different exposure classes are given in terms of minimum compressive strength and types of curing, as summarised in Table 2.

Table 2 Recommended Durability Requirements in AS 3600 (2001)

Surface and exposure environments	Exposure classification for reinforced concrete			
	Curing requirement			
	Class	Minimum strength (MPa)$^{\#}$	Initial continuous curing (days)*	Average strength at completion of curing (MPa)
In contact with ground				
(a) Members protected with damp-proof membrane	A-1	> 20	3	> 15
(b) Residential footings in non-aggressive soils	A-1	> 20	3	> 15
(c) Other members in non-aggressive soils	A-2	> 25	3	> 15
(d) Members in aggressive soils	U	–	–	–
In interior environments				
(a) Fully enclosed within a building, except during construction	A-1	> 20	3	> 15
(b) In industrial buildings, the member being subject to repeated wetting and drying	B-1	> 32	7	> 20
In above-ground exterior environments in areas that are:				
(a) Inland (> 50 km from coastline) environment being:				
i) non-industrial and arid climate zone	A-1	> 20	3	> 15
ii) non-industrial and temperate climate zone	A-2	> 25	3	> 15
iii) non-industrial and tropical climate zone	B-1	> 32	7	> 20
iv) industrial and any climatic zone	B-1	> 32	7	> 20
(b) Near-coastal (1–50 km from coastline) any climatic zone	B-1	> 32	7	> 20
(c) Coastal (up to 1 km from coastline but excluding tidal and splash zone), any climatic zone	B-2	> 40	7	> 25
In water				
(a) Fresh water	B-1	> 32	7	> 20
(b) Sea water				
i) permanently submerged	B-2	> 40	7	> 25
ii) in tidal and splash zones	C	> 50	7	> 32
(c) Soft or running water	U	–	–	–
In other environments				
Any exposure environment not otherwise described in the items above	U	–	–	–
Additional requirements for freezing and thawing exposure	Strength > 32 MPa and 40 MPa for occasional and frequent exposure respectively Air content between 8% to 4% for 10 to 20 mm nominal size aggregate, or 6% to 3% for 40 mm nominal size of aggregate			

Notes:

1. $^{\#}$ Requirements for minimum compressive strength shall be based on tests of cylinders.
2. * Provisions will not apply for concrete cured by accelerated methods. However, average compressive strength requirement at the completion of accelerated curing will govern.
3. Where the compressive strength requirement of class C cannot be satisfied due to inadequate aggregate strength, concrete with compressive strength not less than 40 MPa may be used provided that cement content of the mix is not less than 470 kg/m^3 and cover required by clause 4.10.3 of AS 3600 is increased by 10 mm.
4. Permeable soils with a pH < 4.0, or with groundwater containing more than 1 g/*l* of sulphate ions, would be considered aggressive. Salt-rich soils in arid areas should be considered as exposure classification C.

The concept of “average strength at completion of curing” is introduced as an attempt to achieve quality of construction; while this is novel, it suffers from a lack of guidance on acceptable curing methods and the fact that strength is measured on samples made under laboratory conditions rather than the *as-built* structure. This approach is further

Table 3 Hybrid Specifications for Concrete Durability in CSA A23.1/23.2 (2009)

Exposure category	Class of exposure	Prescriptive requirements				Performance requirements
		Maximum w/b*	Minimum compressive strength, MPa and age (d) at test*	Air content for 14–20 mm nominal aggregate size	Curing type for normal concrete***	
Extreme chloride	C-XL	0.37	50 within 56 d	4–7% or 5–8% if exposed to freezing	Extended	ASTM C1202** < 1 000 Coulombs at 56 d, with no single value > 1250 Coulombs
Chloride and/or chemical	C-1 or A-1	0.40	35 at 28 d	4–7% or 5–8% if exposed to freezing	Additional	ASTM C1202** < 1 500 Coulombs at 56 d, with no single value > 1 750 Coulombs
	C-2 or A-2	0.45	32 at 28 d	5–8%	Additional	–
	C-3 or A-3	0.50	30 at 28 d	4–7%	Basic	–
	C-4 or A-4	0.55	25 at 28 d	4–7%	Basic	–
Freezing and thawing	F-1	0.50	30 at 28 d	5–8%	Additional	ASTM C457 Average spacing factor < 0.23 mm, with no single test > 0.26 mm
	F-2	0.55	25 at 28 d	4–7%	Basic	–
Negligible	N#	As per mix design	For structural design	None	Basic	–
Sulfate	S-1	0.40	35 at 56 d	4–5%	Additional	CSA A3004-C8 Maximum expansion < 0.05% at 6 months, or 0.10% at 12 months
	S-2	0.45	32 at 56 d	4–7%	Basic	
	S-3	0.50	30 at 56 d	4–7%	Basic	CSA A3004-C8 Maximum expansion < 0.10% at 6 months

Notes:
1. * The w/b shall not be exceeded for a given class of exposure, regardless of exceeding the strength requirement.
2. ** Where calcium nitrite corrosion inhibitor is to be used, the same concrete mixture, but without calcium nitrite, shall be pre-qualified to meet the requirements for the permeability index in this table.
3. *** *Basic curing* – 3 days at ≥ 10°C or the time necessary to attain 40% of the specified strength; *Additional curing* – 7 days at ≥ 10°C and the time necessary to attain 70% of the specified strength; *Extended wet curing* – A wet-curing period of 7 days at ≥ 10°C. The curing types allowed are ponding, continuous sprinkling, absorptive mat, or fabric kept continuously wet.
4. # To allow proper finishing and wear resistance, Type N concrete intended for use in an industrial concrete floor with a trowelled surface exposed to wear shall have a minimum cementing materials content of 265 kg/ m^3.

problematic as it may discourage the use of SCMs that are known to enhance durability properties, but have a slower strength development, such as slag or fly ash. Types of formwork and compaction, i.e. standard formwork for normal compaction and rigid formwork for intensive compaction, are given in AS 3600 for cover depth requirements based on grades of concrete.

Table 4 Example of payment adjustments for normal concrete by OPSS 1350 (2010)

Measured parameters	Action
Air void system in accordance with ASTM C457	
Air content > 3.0 %, and Spacing factor of 0.23 mm or less	Full payment or bonus payment based on a combination of two measured parameters
Air content < 3.0 % or Spacing factor > 0.23 mm	Owner may require removal of the concrete or keep the concrete in place at a reduced payment
Rapid chloride permeability (RCP) in accordance with ASTM C1202	
Average Coulombs ≤ 1 000	Fully payment, no bonus available
Average Coulombs > 1 000 and < 2 000	Accepted with a price reduction
Average Coulombs > 2 000	Unacceptable and shall be removed and replaced at the contractor's expense

Note:
Spacing factor describes, for the majority of the concrete paste, the distance to the nearest air void.

AS 1379 (2007)

AS 3600 does not cover requirements for material constituents and proportions. These are covered in AS 1379 *Specification and Supply of Concrete* (AS 2007), which sets out requirements for materials, production, testing and compliance with specified properties of fresh concrete such as slump, maximum nominal size of aggregate, air entrainment, etc, and hardened concrete which include strength grade and exposure classifications as specified in AS 3600. In AS 1379, concrete is specified either as *Normal Class* or *Special Class* concrete. *Normal Class* refers to concretes that can be produced by plants throughout Australia, while *Special Class* concretes require additional or different characteristics from *Normal Class* that are not available from all plants or locations in Australia. Requirements for *Normal Class* concrete in AS 1379 should conform to other requirements, for example strength, presented in AS 3600. In terms of *Special Class* concrete, this can be specified either on a prescriptive or a performance basis when ordering concrete conforming to AS 1379. Appendix B of AS 1379 claims to provide guidance for the specification of *Special Class* concrete. In reality it does not, but rather indicates parameters such as cement type, chloride and sulfate content, air content, strength, exposure classification, etc, to be considered when specifying *Special Class* concrete. Further, Appendix B describes the consequences when *Special Class* concrete is selected. Such consequences include: increase in the cost of production by importing materials that are not locally available, reduced competition for suppliers able to supply concrete, and impact on the cost, availability and perhaps the continuity of supply due to the logistics of providing special resources.

Canada

CSA A23.1/23.2 (2009)

The Canadian Standard CSA A23.1/23.2 (2009) *Concrete materials and methods of concrete construction / Test methods and standard practices for concrete* provides requirements for materials and methods of construction. It gives both prescriptive and performance options for specifying concrete for durability, and is thus a 'hybrid' specification. Prescriptive clauses are given in terms of maximum w/b ratio, minimum compressive strength, age at test, air content, and minimum period and type of curing. For performance aspects, defined acceptance criteria are given for chloride permeability, air-void system, and maximum expansion for chlorides, freeze/thaw and sulphates respectively, as indicated in Table 3.

Cover depth requirements are based on the life expectancy of the structure, exposure conditions, protective systems and consequences of corrosion.

The Ontario Provincial Standard Specification 1350 (OPSS 2010)

The OPSS 1350 (2010) is an Ontario Provincial Specification covering only performance requirements with respect to materials and methods for proportioning, test methods, acceptance criteria, and payment adjustments for normal and high-performance concretes. A penalty-bonus system is in place in order to ensure compliance and consistency of measured parameters. Table 4 illustrates a typical example of a penalty-bonus provision in the standard for normal concrete with regard to air void system and rapid chloride permeability. The details in the table are based on freezing/thawing and chloride and/or chemical exposure conditions, and are independent of the cover depth or service life duration requirements.

Europe

EN 206-1 (2013)

The European Standard EN 206-1 (2013) *Concrete – Part 1: Specification, Performance, Production and Conformity* describes the

Table 5 Exposure Classes in EN 206-1, modified for South African conditions

Class designation	Description of the environment	Informative examples where exposure classes may occur
X0	No risk of attack	Applies to all exposure categories where there is no risk of attack, *e.g.* reinforced concrete in a very dry condition
Corrosion induced by carbonation (reinforced concrete exposed to air and moisture)		
XC1	Permanently dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact, *e.g.* many foundations
XC3	Moderate humidity (60%–80%)	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure Class XC2
Corrosion induced by chlorides from sea water (reinforced concrete in contact with chlorides from sea water or air carrying salt originating from sea water)		
XS1	Exposed to airborne salt but not in direct contact with sea water	Reinforced concrete surfaces near to or on the coast
XS2a	Permanently submerged	Reinforced concrete surfaces completely submerged and remaining saturated, *e.g.* concrete below mid-tide level A)
XS2b*	XS2a + exposed to abrasion	As above, but with heavy wave action with abrasion
XS3a	Tidal, splash and spray zones	Reinforced concrete surfaces in intertidal, splash, or spray zones B)
XS3b*	XS3a + exposed to abrasion	As above, but with heavy wave action with abrasion
Corrosion induced by chlorides other than from sea water (reinforced concrete in contact with water containing chlorides, including de-icing salts, from other sources)		
XD1	Moderate humidity	Concrete structures exposed to airborne chlorides Parts of structures exposed to slightly chloride conditions
XD2	Wet, rarely dry	Reinforced concrete surfaces totally immersed in water containing chlorides A)
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides, e.g. pavements and car park slabs
Freeze/thaw attack with or without de-icing agents (for concrete exposed to significant attack by freeze/thaw cycles whilst wet)		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing splash zones of marine structures exposed to freezing
Chemical attack (for concrete exposed to sulphate attack from natural soils and ground water)		
XA1$^+$	Slightly aggressive chemical environment acc to Table 2$^\#$	Natural soils and ground water
XA2$^+$	Moderately aggressive chemical environment acc to Table 2$^\#$	
XA3$^+$	Highly aggressive chemical environment acc to Table 2$^\#$	

Notes:

1. * Additional sub-clauses for South African coastal conditions.
2. A) Concrete members where one surface is immersed in water containing chlorides and another is exposed to air are potentially more vulnerable, especially where the dry side is at a high ambient temperature. Specialist advice should be sought where appropriate, to develop a specification that is appropriate to the actual conditions likely to be encountered.
3. B) Exposure XS3a covers a range of conditions. The most extreme conditions are in the splash and spray zone. It is recommended to take into account the most extreme conditions within this class.
4. \+ Sulphate attack from natural soil and ground water.
5. \# Table 2 refers to the relevant table in EN 206-1 (2013).

Table 6 Recommended Durability Requirements in IS 456 (2000)

Environmental exposure conditions	Min cement content$^+$ kg/m^3	Max free w/c	Min concrete grade$^\#$	Min cover depth (mm)*
Mild: Concrete surfaces protected against weather or aggressive conditions, except those situated in coastal area	300	0.55	M 20	20**
Moderate: Concrete surfaces sheltered from severe rain or freezing whilst wet; concrete exposed to condensation and rain; concrete continuously under water; concrete in contact or buried under non-aggressive soil/ ground water; concrete surfaces sheltered from saturated salt air in coastal area	300	0.50	M 25	30
Severe: Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation; concrete completely immersed in sea water; concrete exposed to coastal environment	320	0.45	M 30	45***
Very severe: Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing conditions whilst wet; concrete in contact with or buried under aggressive sub-soil/ground water	340	0.45	M 35	50***
Extreme: Surface of members in tidal zone; members in direct contact with liquid/ solid aggressive chemicals	360	0.40	M 35	75

Notes:

1. $^+$ Cement content prescribed in the table is irrespective of the grades of cement and it is inclusive of SCMs.
2. $^\#$ In the designation of concrete mix M refers to the mix and the number to the specified compressive strength of 150 mm size cube at 28 days, expressed in N/mm^2.
3. * For a longitudinal reinforcing bar in a column, nominal cover shall not be less than 40 mm, nor less than the diameter of such bar.
4. ** For reinforcement up to 12 mm diameter bar for mild exposure, the nominal cover may be reduced by 5 mm.
5. *** For severe and very severe exposure conditions, reduction of 5 mm may be made where concrete grade is M35 and above. The actual cover depth should not deviate from the required nominal cover by more than +10 mm.

requirements for classification, properties, verification, design types, delivery, conformity control and criteria, and production control of concrete. The standard makes reference to possible use of performance requirements for durability, but has adopted prescriptive requirements arguing that test methods are not yet sufficiently developed to be included in the standard. The earlier 2000 version of EN 206-1 contained an informative Annex J on 'performance-related design methods with respect to durability', although it gave no actual guidance on how to choose performance requirements and criteria. This Annex is not in the 2013 version, where emphasis is now placed on the 'equivalent performance concept', which can be applied to both strength and durability. Regarding durability, this amounts to the need to prove that the concrete has an 'equivalent performance' with respect to its resistance to environmental actions when compared with a reference concrete in conformity with the deemed-to-satisfy requirements for the relevant exposure classes. Performance-related parameters are also permitted, provided they can be shown to provide durability equivalent to the 'rules'. The document states that 'performance-based concepts as alternatives to the concept of limiting values are under development'.

The exposure classifications in EN 206-1 are well defined, but require investigation and verification for specific local exposures. Since EN 206-1 is being considered for use in SANS 10100-2 (2013) revisions, such exposure classes are presented here in Table 5. These exposure classes are, however, in a modified format to suit South African conditions – an approach suggested by the authors and co-workers over several years. EN 206-1 (2013) considers common cements conforming to EN 197-1 (2011), for which 'suitability for use in a considered exposure class has been established in provisions valid in the place of use', i.e. the specific geographical location.

BS 8500-1 (2006)

The British Standard, BS 8500-1 (2006) *Concrete – Complementary British Standard to EN 206-1 – Part 1: Method of specifying and guidance for the specifier* covers materials, methods, testing and procedures that extend the scope of EN 206-1 for relevance to the UK. It has adopted similar exposure classes to EN 206-1, with slight changes especially in the informative examples. For concrete exposed to chemical attack, exposure classes vary significantly when compared to EN 206-1.

In BS 8500-1 the specifier is offered five alternatives for the specification of concrete mixes: designated, designed, prescribed, standardised prescribed and proprietary concrete mixes. Curiously, the first two and the last category are termed 'performance approaches', but on closer examination these are in effect prescriptive (with requirements for maximum w/c, minimum cement content, and strength class). Importantly, BS 8500-1 makes provision for different binder types in relation to the various exposure classes. The maximum w/c and minimum cement content are modified to suit the intended service life of 50 and 100 years, while in EN 206-1 such requirements are based on a 50-year service life assumption. Cover depth requirements for different degradation mechanisms are presented in Tables A.4 and A.5 of BS 8500-1, which are not requirements in EN 206-1. Nevertheless, the specified parameters (other than cover) cannot be measured and therefore cannot strictly be called performance-based.

India

IS 456 (2000)

The Indian Standard IS 456-00 (2000) *Plain and Reinforced Concrete* provides requirements for general use of concrete, both plain and reinforced. It is a prescriptive standard for parameters related to durability. It defines exposure conditions in qualitative terms, such as mild, moderate, etc, which are limiting. However, suggestions to widen exposure classes with respect to the degradation mechanisms have been proposed by Kulkarni (2009) so as to modernise the standard in keeping with international developments.

Although IS 456 imposes limits on material constituents and proportions as detailed in Table 6, it encourages the use of SCMs to enhance durability.

Cover depth requirements are provided for corrosion protection with allowable

Table 7 Recommended Durability Requirements in SANS 10100-2 (Draft 2013)

1	2	3	4	5	6	7
Condition of exposure	**Description of member/surface to which the cover applies**	**Class of concrete**				
		20	**25**	**30**	**40**	**50**
		Characteristic minimum cover depth (mm)				
Moderate [a]	1 Surfaces protected by the superstructure, namely the sides of beams and the undersides of slabs and other surfaces not likely to be moistened by condensation	50	45	40	30	25
	2 Surfaces protected by a waterproof cover or permanent formwork not likely to be subjected to weathering or corrosion					
	3 Enclosed surfaces					
	4 Structures or members permanently submerged in water					
	5 Limited structures of the relevant national body (see foreword): i) Surfaces of precast elements not in contact with soil ii) Surfaces protected by permanent formwork not likely to be subjected to weathering or corrosion iii) Surfaces in contact with ballast iv) All other surfaces					
Severe	1 All exposed surfaces	NA	50	45	40	35
	2 Surfaces on which condensation takes place					
	3 Surfaces in contact with soil					
	4 Surfaces permanently under running water					
	5 Structures of the relevant national body (see foreword) i) Surfaces of precast elements not in contact with soil ii) Surfaces protected by permanent formwork not likely to be subjected to weathering or corrosion iii) Surfaces in contact with ballast iv) All other surfaces					
	1 Cast in-situ piles i) Wet cast against casing ii) Wet cast against soil iii) Dry cast against soil	50 75 75	50 75 75	50 75 75	50 75 75	50 75 75
Very severe	1 All exposed surfaces of structures within 30 km from the sea	NA	NA	NA	60	50
	2 Surfaces in rivers polluted by industries	NA	NA	NA	60	50
	3 Cast in-situ piles, wet cast against casings	NA	NA	NA	80	80
Extreme	1 Surfaces in contact with sea water or industrially polluted water 2 Surfaces in contact with marshy conditions	NA	NA	NA	65	65

Notes:
1. [a] Concrete exposed to mild conditions: The specified strength shall be determined by structural design considerations. If the concrete is to include embedded metal, the characteristic strength shall not be less than 20 MPa. There is no requirement for maximum water/cement ratio or for minimum cement content.
2. The cover values are characteristic minimum cover values and not more than 5% of cover requirements should fall below these values. In addition, no single cover measurement should fall below 5 mm less than the relevant cover value indicated above.
3. In un-cracked concrete the degree of protection that the concrete affords the reinforcing steel depends on the quality and thickness of the cover. Apart from the class of the concrete, the quality of the cover will among other things be affected by the method and duration of curing and the type of binder used, for example well-cured fly ash concrete without extenders (sic).
4. NA = Not applicable

flexibility depending on the type of structural member and exposure conditions.

South Africa

SANS 10100-2 (2013) (Draft SA Standard)

The South African Standard SANS 10100-2 *Structural use of concrete Part-2: Materials and execution of works* (Draft 2013), although currently unpublished, was intended to replace the 1992 version of SANS 10100-2. The standard deals with materials and execution of work related to the structural use of concrete in buildings and structures for reinforced, pre-stressed and precast concrete. Although it reflects some advances in concrete technology, it still lags behind in many aspects related to durability. The standard defines exposure conditions qualitatively and somewhat arbitrarily, using terms such as mild, moderate, severe, etc, and recommends cover depth requirements depending on the grade ('class') of concrete as shown in Table 7.

The descriptive elaborations of exposure classes are of some assistance, but better guidance to assist the specifier to choose the correct exposure class is needed. Further, cover depth requirements reduce with increasing concrete strength, which may conflict with durability requirements, since strength is increasingly not favoured as a proxy for durability. The standard does not restrict the types of cements or SCMs, and it also gives no limits to w/b ratio for many exposure conditions, except for freeze/thaw attack and for concrete requiring low permeability.

As discussed later, the proposal in South Africa is to replace SANS 10100-2 by adopting EN 206-1 and producing a 'guidance document' for engineers that will also incorporate useful material from the current SANS 10100-2. (This proposal is being pursued presently under the SABS Committee, SABS SC 81A).

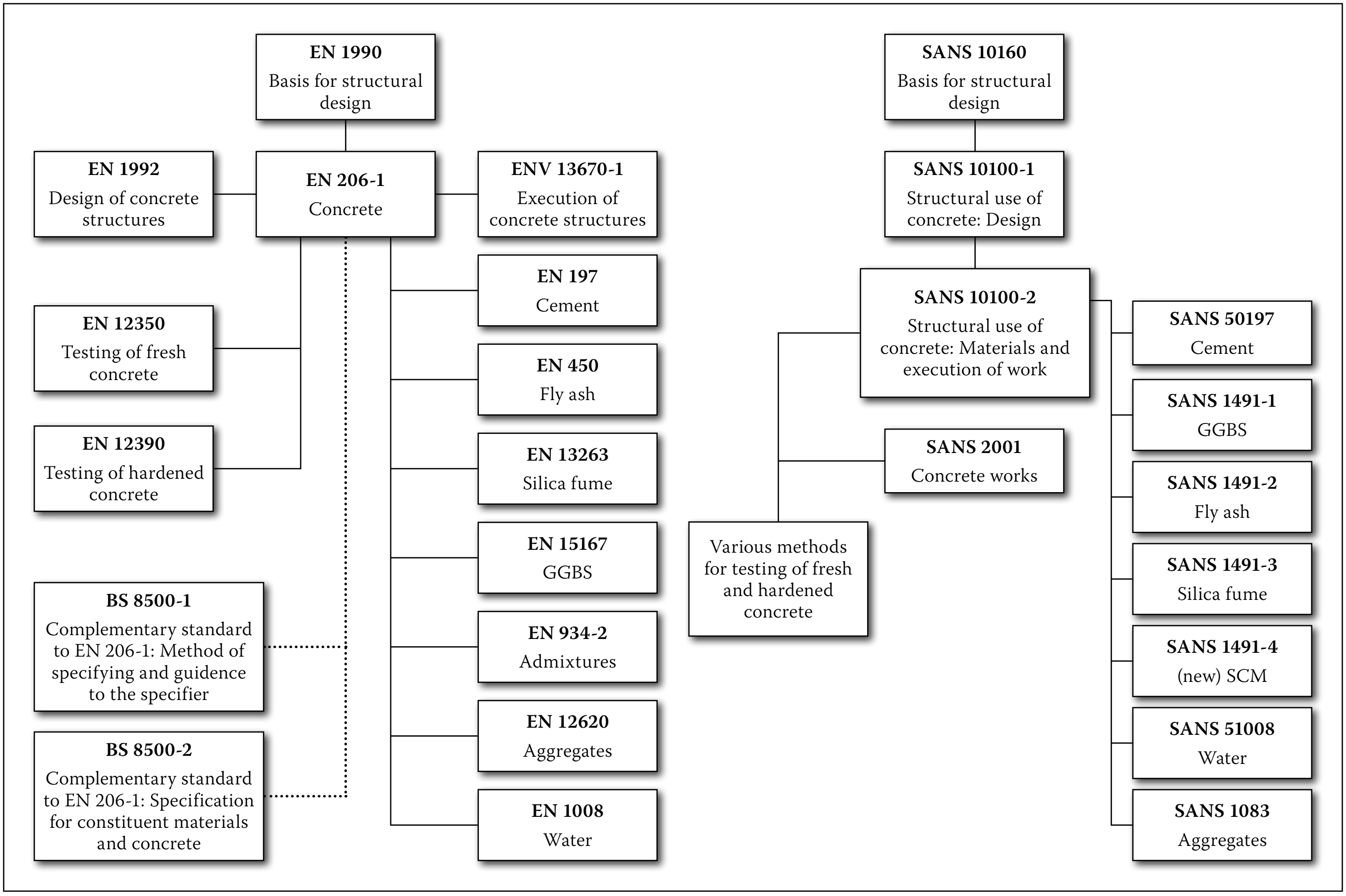

Figure 1: Framework of the EN and SANS code documents (Alexander 2010)

SUMMARY OF MAIN OBSERVATIONS AND TRENDS IN THE STANDARDS REVIEWED

Most of the standards reviewed prescribe limits for concrete composition (including the use of SCMs either as separate additions or incorporated in blended cements), mix proportions, compressive strength and cover depth for different exposure conditions, in respect of durability provisions. Such limits are based on laboratory data and past experience, leading to the typically prescriptive approach which, however, cannot ensure long-term performance under a variety of exposure conditions (Clifton 1993; Folic 2009). Attempts have been made in certain standards to create a more rational approach based on performance to ensure adequate durability. Nevertheless, performance requirements in these standards are actually 'hybrid', since they still present some prescriptive requirements. Such 'hybrid' requirements may be useful in moving practice forward and may be effective in providing simple ways for extending the service life of RC structures.

Development and implementation of performance-based approaches is not an easy task. For example, barriers may exist that include lack of reliable, consistent and standardised test methods which can evaluate concrete performance routinely over time; lack of adequate service life models which can capture the main aspects involved in deterioration, including environment-specific factors; and lack of experience in developing performance requirements with appropriate acceptance criteria (Andrade 2007; Carino *et al* 2010). Such barriers need to be addressed in current research in order to implement this approach properly. Successful implementation would be a critical step for solving many durability problems that threaten the performance of RC structures.

DRAFTING AND IMPLEMENTATION OF DURABILITY REQUIREMENTS IN THE SOUTH AFRICAN CONTEXT

Although there have been many publications in South Africa in recent years that address concrete durability requirements, such published work has not yet found its way into revisions to the South African Standards, particularly SANS 10100-2. However, work is under way to revise the current SA concrete standards, specifically SANS 10100-1 (2000) *Structural use of concrete Part-1: Design* and SANS 10100-2 (2013) *Structural use of concrete Part-2: Materials and execution of works*, and two committees are working to produce drafts, based on the corresponding EN standards. The material that follows refers to the work of these committees, as well as a previous publication (Alexander 2010). (It should be stressed that the views and proposals in this paper are those of the authors).

Figure 1 indicates the framework of the Eurocodes (in relation to their adoption in the UK). For ease of comparison, the figure also shows the corresponding framework of the SA codes. Eurocode 2, i.e. EN 1992-1 (2004) *Design of concrete structures Part 1-1: General rules and rules for buildings* and EN 206-1 are complementary documents, dealing respectively with the details of structural design of reinforced and prestressed concrete, specifications, etc. There are also several other associated documents dealing with testing, execution and materials.

EN 206-1 is an important document when considering concrete durability. However, it is really a framework document and requires further elaboration to make it useful. Therefore it is accompanied in national contexts by 'interpretive' documents or National Annexes that give practical guidance to the design engineer. In the UK, the complementary standards to EN 206-1 are BS 8500-1 (2006) *Method of specifying and guidance to the specifier* and BS 8500-2 (2006) *Specification for constituent materials and concrete* (mentioned earlier).

In South Africa the decision has been taken in principle to adopt the EN concrete

Table 8 Proposed limiting values for concrete composition (for use in revision to SANS 10100-2) (Note: nominal service life or design life assumed to be 50 years; for service life considerably greater or less than 50 years, consult specialist sources)

Exposure category	Exposure class	Max w/c ratio	Min strength class (MPa)	Air content range (%)	Min nominal cover* (mm)	Cement type
XO No risk of corrosion or attack	–	0.70	C20	–	15	Any. For XC3 or XC4 only: i) Any cement with clinker content < 70%: increase minimum nominal cover to 30 mm ii) Any cement with clinker content < 50%: increase minimum nominal cover to 40 mm
XC Carbonation	XC1	0.65	C20	–	15	
	XC2	0.65	C25	–	25	
	XC3	0.55	C30	–	25	
	XC4	0.50	C30	–	25	
XS Chloride from sea water	XS1	0.50	C30	–	40	IIB-S, IIB-V, IIIA, IIIB, IVB-V
	XS2	0.45	C35	–	35	
	XS3	0.40	C40	–	50	
XD Chloride other than sea water	XD1	0.55	C30	–	30	Any, except CEM I
	XD2	0.45	C35	–	35	IIB-S, IIB-V, IIIA, IIIB, IVB-V
	XD3	0.40	C40	–	50	
XF Freeze/thaw attack	XF1	0.55	C30	–	25	Any, except CEM I. For XF3 and XF4 only: do not use IVB-V
	XF2	0.55	C30	4 – 8#	25	
	XF3	0.50	C30	4 – 8#	25	
	XF4	0.45	C30	4 – 8#	25	
XA Aggressive chemical environment	XA1	0.55	C30	–	25	I, IIA-D, IIA-V, IIA-S
	XA2	0.50	C35	–	30	IIA-D, IIA-V, IIA-S
	XA3	0.45	C40	–	40	IIB-V + SR, IIIA-S + SR

Notes:

1. * For every 5 mm additional cover, strength class may be reduced by one level and w/c may be increased by 0.05, subject to a maximum reduction of 2 strength classes (subject to minimum of C30) and increase in w/c up to 0.1 (subject to maximum of 0.55); for example, in the XS2 class, if a cover of 40 mm is used for a CEM IIIB, C30 concrete with 0.50 w/c would be permitted. This clause applies only to exposure classes XS, XD, and XC3 and XC4.
2. # Range given for 19 mm aggregate size; to be changed to 6–10% for 9.5 mm, 5–9% for 13.2 mm, and 3–6% for 37.5 mm nominal maximum aggregate size; for low density concrete, minimum strength class C25, 4–8% air for aggregate size more than 9.5 mm, 5–9% air for aggregate size less than 9.5 mm.

standards where appropriate, and therefore the concrete structural and materials codes will need to be modelled on the Eurocode documents. Eurocodes must be adopted *in toto*, meaning that national or regional emphases must be covered in a 'guidance document', as already indicated. Thus, SANS 10100-1 will be replaced by EN 1992-1 with a 'guidance document' to cover South African conditions. Likewise, SANS 10100-2 will be replaced by EN 206-1, with an accompanying 'guidance document' that will provide SA designers with the needed information. In practice, regarding EN 206-1, only the local 'guidance document' will really be needed by practitioners – the clause numbering of EN 206-1 will be retained, and information will be given interpretive of the corresponding EN 206-1 clauses, but of more value to SA practice. In this way, content in SANS 10100-2 that is felt to be of use and benefit will be retained in some form, while the overall intent of EN 206-1 will remain intact. Similarly, EN 13670 (2009) *Execution of concrete structures* will be adopted, but with a further 'guidance document' to give SA engineers the needed contextual information, and which will also serve as the main reference document in practice. While this may seem cumbersome, it is a simple and practical way to proceed for implementation locally of the Eurocode approach.

SANS 2001-CC1 92 (2007) *Construction works – Part CC1: Concrete works (structural)*, representing a suite of documents each addressing a specific component of construction works, must also be noted. It replaces the older corresponding SABS 1200 G documents. Redrafting of SANS 2001 will need to consider the changes described above to ensure consistency.

With the above in mind, the developments for SA codes regarding concrete durability are as follows:

1. Adopt EN 206-1 and EN 13670.
2. Redraft SANS 10100-2 in the form of two interpretive and elaborative documents, based on the clauses and terminology of EN 206-1 and EN 13670, as indicated above, so as to make them internally consistent. (The new documents will be given new standards numbers or designations).
3. Regarding specifically the clauses for 'Specification of concrete', the new document will allow for:
   a. **Designed concrete:** concrete for which the required properties are specified to the producer who is responsible for designing and providing a concrete conforming to the required properties
   b. **Performance concrete:** concrete for which specific performance requirements are specified. These might include, but not necessarily be limited to, requirements for performance in respect of heat of hydration, water penetration, water absorption, gas permeability, chloride resistance, abrasion resistance, tensile strength, durability, etc. Performance concrete will be specified according to a performance-based specification drawn up by the owner or design engineer, with criteria

to be agreed upon between specifier and producer. In general, performance concrete will require testing to verify compliance with the specified performance requirements

   c. **Prescribed concrete:** concrete for which the precise composition of the concrete and the constituent materials to be used are specified to the producer who is responsible for providing a concrete with the specified composition and with the specified constituent materials
   d. **Proprietary concrete:** concrete which falls outside the scope of designed concrete, specified concrete, or performance concrete, for example specialised concrete for specific applications such as fibre-reinforced concrete, self-compacting concrete, etc.

4. The exposure classes given in EN 206-1 will be adopted for SA, but the 'guidance document' will provide them in a modified form as per Table 5. Requirements for the concrete to withstand the environmental actions are given either in terms of limiting values for concrete composition and established concrete properties (see next section, i.e. "Limiting values for concrete composition"), or the requirements may be derived from performance-related design methods (see section titled "Performance-based methods: durability requirements for new 'guidance document' to be used with EN 206-1"), where 'performance concrete' as defined above can be specified according to a performance-based specification drawn up by the owner or engineer, with criteria to be agreed upon between specifier and producer.

Limiting values for concrete composition

Recognising that performance-based testing and specifications are still under development in SA, the committee felt that the conventional approach for specifying concrete to resist environmental actions should be given in terms of established concrete properties and limiting values of composition. In general this will apply to 'designed' concrete as described above. The proposed requirements for concrete composition for the various exposure classes are given in Table 8, which specifies for each exposure class the maximum water/cement ratio, minimum strength class, minimum nominal cover, air-content range, cement type, and curing.

The requirements in Table 8 are for an intended working life of at least 50 years, and have been derived based on best available SA or other data for deterioration rates under the different exposure conditions; the values given are thus not arbitrary. If the concrete is in conformity with the limiting values, the concrete in the structure shall be 'deemed to satisfy' the durability requirements for the intended use in the specific environmental condition. For shorter or longer service life, less onerous or more severe requirements respectively may be necessary. In these cases, or for specific concrete compositions or specific corrosion protection (e.g. in the case of cover less than that specified in the relevant parts of EN 1992-1 for corrosion protection), special considerations can be made for a specific site, or by using performance-based methods as in the next section.

Performance-based methods: durability requirements for new 'guidance document' to be used with EN 206-1

'Performance concrete' will be allowed in the 'guidance document', which will permit any approach, whether local or international, to be implemented. Recognition is given to the approach that has been developed in SA for reinforced concrete durability (including durability design and specification) – the so-called durability index (DI) approach (Alexander *et al* 2001). This approach has allowed considerable progress towards performance-based standards, with the ultimate aim of having a means of limiting the environmental consequences on the structure to defined acceptable levels (targets) during the service life. The approach is covered in a section in the 'guidance document' headed "Requirements for controlling or preventing corrosion of reinforcing induced by carbonation or chlorides in reinforced concrete", which can be used to specify performance concrete as an alternative. The clauses cover the South African Durability Index approach by way of background, achievement of *as-built* durability, and the specification requirements. These lay responsibility on the concrete producer and constructor whereby the producer might need to achieve 'better' durability index values in comparison with the *as-built* values. At this point, the approach is limited to corrosion of steel in carbonation and chloride environments only.

The DI performance-based approach is still in development and much work remains to bring it to a more robust state. Nevertheless, this approach will continue to develop and mature as more specifiers adopt and use it in practice.

The DI approach to durability specifications is best suited to more sophisticated concrete structures, particularly major civil infrastructure where extended service lives are required and where expenditure from the public purse demands longevity and durability from the structures. Other concrete structures such as commercial buildings, low-rise and clad concrete frame buildings, certain light industrial buildings, etc, may not need the sophistication of the performance-based approach. Nevertheless, specifications for such structures should at least reflect a hybrid approach in which 'deemed to satisfy' provisions are given that relate rationally to service life design models against which they are calibrated. This will give some assurance for actual durability.

In summary, both prescriptive and performance alternatives will be permitted in the new 'guidance document'. This is appropriate for the current stage of development in technology and in the specification framework. Indeed, at this point it would be inappropriate and premature for performance specifications to completely replace prescriptive specifications. They may not be suitable for every project at every location, or suit specific durability problems, such as alkali silica reaction, abrasion, aggressive chemicals and so forth. In particular, they are unsuitable in cases where the test methods for evaluating performance are unavailable, expensive, time-consuming, or have high variability. In these cases, prescriptive specifications govern and should therefore be retained in the standard with greater emphasis on performance through innovation.

Proposed methodology for developing durability specifications in the South African concrete industry

Concrete durability specifications require a change of mindset with respect to the roles and responsibilities of the stakeholders involved. Such roles and responsibilities have been described in several publications (Bickley *et al* 2006; CSA A23.1/23.2 2009; Carino *et al* 2010), particularly for the performance-based approach. From these publications, a broad methodology for developing durability specifications in the South African concrete industry that cover prescriptive, hybrid and performance-based approaches is proposed below.

- ***Stage 1: Specifications:*** These require input from the client's team, i.e. client, specifier, and/or client's testing agency. The client should define the project in measurable terms, e.g. service life, level of performance, etc. The specifier should establish required specifications, i.e. prescriptive, performance, or hybrid, and should specify exposure classes and, where appropriate, standard test methods and parameters to be measured, service life models to be used, and construction methods. The client's team should specify the frequency of testing and limits for acceptability. Generally, the client's team should define conformity and non-conformity criteria and recommend appropriate measures, e.g. a bonus-penalty system.

- ***Stage 2**: **Construction and testing**:* This phase involves the concrete producer and contractor, each with their own responsibilities, working together. The producer prepares a mix design with the requisite properties required by the specifications, and conducts pre-qualification tests. The contractor should determine the means and methods required to ensure that the fresh concrete can be taken from the delivery point, and the needed quality retained in the hardened state, after undergoing construction practices such as compaction and curing. The producer and contractor should conduct a quality control plan, and prepare documents that demonstrate compliance with the specified requirements determined in Stage 1. Field tests will usually be necessary, e.g. strength and durability tests which evaluate concrete with respect to the requirements of the specification.
- ***Stage 3**: **Verification**:* The client should verify that the durability requirements have been or will be satisfied during construction. The consequences of compliance or non-compliance, which may involve bonus or penalty, may be applied at this stage.

Generally, committed and knowledgeable stakeholders are required in order to implement this methodology. Regardless of the type of specifications, key elements to be considered are structural safety, cost considerations, and constructability, as well as availability of local laboratories to carry out the tests to the desired precision.

CONCLUSIONS AND FUTURE OUTLOOK

This paper provides a review of durability requirements for RC structures in selected international design standards. It concludes that most standards and specifications are prescriptive, with a few having some performance elements; these performance requirements are, however, 'hybrid' since they still present some prescriptive requirements. The 'hybrid approach' may be useful in moving practice forward, and may be effective in providing simple ways for extending service life of RC structures.

Following international trends, the paper discusses re-drafting and implementing durability requirements of the current South African Standards, particularly the replacement for SANS 10100-2: both prescriptive and performance alternatives are suggested, as it is inappropriate and premature to completely replace prescriptive specifications. A performance approach based on the DI approach developed in South Africa is proposed; however, much work still remains to bring it to a more robust state so as to give specifiers assurance for actual durability. A methodology for developing durability specifications is also proposed.

The paper also covers issues related to environmental exposure conditions, material compositions and proportions for durability. Much work is still required to cover various durability aspects in a broader perspective. Included among the issues that need attention in the future are: categories of the structure based on proximity to the sea to characterise the degree of corrosion damage, a concrete corrosive map of South Africa indicating corrosion-prone areas, and a client durability service manual for future monitoring of the structure. Such developments may provide the ultimate basis for achieving a more controlled durability and service life of RC structures in South Africa.

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