Materials and Structures (2008) 41:921–936
DOI 10.1617/s11527-007-9295-0

ORIGINAL ARTICLE

A framework for use of durability indexes in performance-based design and specifications for reinforced concrete structures

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Received: 27 February 2007 / Accepted: 1 August 2007 / Published online: 18 September 2007
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Abstract Durability of reinforced concrete remains a pervasive concern. At present, as-built concrete quality and hence durability is inadequate in many cases. This relates partly to use of prescriptive specifications that do not appropriately address actual quality concerns. Performance-based specifications may offer greater advantages in improving concrete durability, but to be viable require suitable quality parameters to be defined and measured. In South Africa, a 'Durability Index' (DI) approach has been developed to address these concerns. 'Durability indexes' are quantifiable parameters which characterise concrete quality and are sensitive to material, processing, and environmental factors. The approach is based on measurement of transport-related properties of the cover layer of laboratory and in-situ concrete, thus reflecting the dual aspects of material potential and construction quality. Rational durability design and performance-based durability specifications are being developed and in some cases applied in actual construction. The paper presents a framework within which the DI approach is used to craft performance-based specifications, based on service life models that utilise the relevant DI values. Steps to establish appropriate DI test values for a given structure are described, and a procedure for implementing their use as a quality control measure is recommended. The approach is integrated, allowing for continual improvement and modification as additional data become available.

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Resumé *La durabilité des structures en béton armé demeure une préoccupation importante. De nos jours, la qualité du béton, et donc sa durabilité, est encore dans bien des cas inadéquate. Cela est dû entre autre à des spécifications dans les devis qui ne tiennent pas compte correctement des besoins actuels de qualité. Les devis de performance peuvent mener à une amélioration substantielle de la durabilité, mais nécessite la définition et l'estimation de paramètres appropriés. En Afrique du Sud, une approche basée sur un 'indice de durabilité' a été développée pour répondre à ce besoin. Les 'indices de durabilité' sont des paramètres quantifiables qui caractérisent la qualité du béton en tenant compte du matériau, de sa mise en place et de facteurs environnementaux. L'approche est basée sur l'estimation des propriétés de transport de la couche de recouvrement de bétons de laboratoire et de chantier, afin de refléter la qualité de la mise en place et le potentiel du matériau. Les critères de durabilité sont développés* *et dans certains cas appliqués à des structures actuelles. L'article présente une approche dans laquelle les indices de durabilité sont utilisés pour établir des devis de performance, sur la base de modèles de durée de vie utilisant des indices de durabilité pertinents. Les étapes permettant d'établir les indices de durabilité pour une structure donnée sont exposées, et une procédure décrivant leur implantation comme mesure de contrôle de qualité est recommandée. L'approche peut être améliorée de façon continue au fur et à mesure que des données supplémentaires sont disponibles.*

Keywords Durability · Durability indexes · Specifications · Performance · Reinforced concrete

1 Introduction

Durability of reinforced concrete remains a pervasive concern for infrastructure owners and managers. Increasingly, it is realized that improving the quality of new construction reduces repair costs over the long term. More owners are now willing to pay for higher initial quality—provided there is some reasonable guarantee of durability. This can be accomplished through service life design approaches, and appropriate specification of the as-built quality.

Compressive strength is still often used as an indicator of durability, generally within a prescriptive specification framework, possibly with the minimal addition of a maximum w/b ratio [1–3]. However, different methods of achieving similar concrete strength do not all result in the same durability.[1] In addition, strength of fully compacted, properly cured specimens does not account for construction processes such as placing, compaction and curing. These affect the quality of the surface zone of the concrete, which has a direct influence on durability by controlling the movement of aggressive agents from the environment into the concrete. The important deterioration rate-controlling factors are therefore the concrete material constituents, the near-surface quality of the as-built concrete, and the aggressiveness of the environment. It is impractical or impossible to control or modify the exposure conditions, and strategies for improving service life must focus on the materials and the quality of construction. These strategies rely on appropriate service life models—which relate to transport properties of the surface zone of the concrete - and appropriate durability performance specifications [4, 5]. These developments facilitate innovative and responsive durability design.

There are real benefits in moving from prescriptive to performance-based specifications, not least of which is a more rational approach to improving concrete performance [6–8]. Although the general philosophy of performance-based specifications is established [9–12], there remains divergence on appropriate definitions and reliable measurement of quality parameters. For example, alternative test approaches have recently been reviewed by RILEM TC-NEC [13], and further developments in appropriate durability tests can be expected in the future [14]. The FIB Model Code (Service Life Design) [15] categorizes appropriate approaches for service life design as: full probabilistic approach, partial factor design approach, deemed to satisfy approach, and avoidance of deterioration approach. Any of these approaches can be used, although ultimately it is desired to move to a full probabilistic approach. This paper essentially represents a deemed to satisfy approach, but the methodology outlined could also be developed into a fully probabilistic method.

Andrade and co-workers [16] have proposed the use of 'indicators' for the control of durability. Baroghel-Bouny takes the concept further by developing several 'durability indicators' to describe, and hence control, a wide range of deterioration problems [17, 18]. In South Africa, a "durability index" approach has been developed to attempt to improve the quality of reinforced concrete construction. It is based on measurement of appropriate transport-related properties of the cover layer of laboratory and in-situ concrete, which reflect the dual aspects of material potential and construction quality. Key stages in formulating this approach were developing suitable test methods to measure durability indexes, characterising a range of concretes using these tests, studying in-situ performance, and applying the results to practical construction. 'Durability indexes' are quantifiable physical or engineering parameters which

[1] While mindful of the fact that there is a wide range of mechanisms that cause concrete to deteriorate, in the context of this paper, 'durability' mainly refers to avoidance of premature deterioration of reinforced concrete due to reinforcing steel corrosion.

characterise concrete and are sensitive to material, processing, and environmental factors such as binder type, water: binder ratio, type and degree of curing, etc. The approach has progressed to the point that both rational durability design and performance-based durability specifications are being developed and in some cases applied in actual construction [19–22].

These are positive developments for improving the quality of construction, but their usefulness must ultimately be assessed by actual performance of structures built using the indexes for quality control purposes. Long-term studies of performance have been initiated, and preliminary results are encouraging. If correlations between the index values and long-term performance are confirmed, index tests could be used to control covercrete quality through specifying limits to index values at a suitable age. Index tests could then be used as criteria to assess construction quality, and as a partial basis for fair payment.

The purpose of this paper is to present a framework within which the durability index (DI) approach can be used to craft performance-based specifications, based on rational service life models that utilise the relevant indexes in their formulations. This paper outlines the steps to establish appropriate DI test values for a specific structure, provides guidance on what these values should be, and recommends a procedure for implementing their use as a quality control measure. It is important to stress the link between DI parameters and their use in service life prediction models. This represents an integrated approach that allows for continual improvement and modification as additional data become available. It also introduces a powerful tool by linking material properties directly with expected service life, and allows decisions to be taken at the construction stage based on measured material parameters, for example whether to implement additional protective measures if the material fails the required DI test values. Finally, it represents a rational approach to ensuring the achievement of concrete quality by being linked to performance-based specifications.

2 Durability index tests and service life models

Durability index tests and service life models have been discussed in previous publications [4, 19–22], and so are only briefly summarized here. Test specimens are 68 mm diameter, 25 mm thick concrete discs, extracted from the cover zone and have their moisture content standardised before testing by conditioning at 50 °C for seven days. The tests can be applied either on lab specimens or on samples from as-built structures. The measured parameters are an oxygen permeability index (OPI), a water sorptivity index, and a chloride conductivity index respectively [23, 24]. OPI indexes are evaluated as the negative log of the D'Arcy coefficient of permeability k (m/s), derived from a falling head permeameter gas test. They are logarithmic values and typically range from 8 to 11, i.e. over three orders of magnitude; the higher the index, the less permeable the concrete. Water sorptivity measures the rate of water uptake by a dry sample, normalized by its porosity. Water sorptivity values vary from approximately 5 mm/hr$^{0.5}$ for well-cured Grade 30–50 concretes to 15–20 mm/hr$^{0.5}$ for poorly cured Grade 20 concretes. The chloride conductivity test measures the electrical resistance of concrete when saturated with a standard, highly ionic chloride solution. The chloride conductivity parameter is related to chloride diffusion properties, and is very sensitive to binder type with blended binders containing, e.g. fly ash, slag, or silica fume, showing superior properties [25]. Values range from 2.5 mS/cm or greater for plain OPC concretes which have low resistance to chloride ingress to 0.5 mS/cm or less for highly chloride-resistant blended binder concretes.

Two corrosion initiation models have been developed, related to carbonation- and chloride-induced corrosion, and derived from measurements and correlations of short-term DI values, aggressiveness of the environment and actual deterioration rates monitored over periods of up to 10 years. The service life models allow the expected life of a structure to be predicted based on considerations of environmental conditions, cover thickness and concrete quality [4, 26]. The environmental classes are related to the EN 206 classes [27], modified for South African conditions, while concrete quality is represented by the appropriate durability index parameter. The OPI is used in the carbonation prediction model, while the chloride model utilises chloride conductivity to represent material quality.

The service life models are normally used during the design and construction phases of new structures. The appropriate combination of concrete quality (DI value) and cover can be selected based on expected environment and desired service life, and the actual concrete quality can be monitored by testing. Alternatively, if concrete quality is known from the appropriate DI value, a corrosion-free life can be estimated for a given environment. This paper concentrates on an approach for using service life models in the design and construction of new structures.

3 Establishing required performance parameters

Required concrete durability must be established with reference to the structure and the environment in which it will be used. The desired end is a durable structure—that is, a structure that will endure for the required life in the design environment with acceptable levels of maintenance. For reinforced concrete structures, this durability relates largely to the quality and thickness of the concrete cover layer, which must be quantified by the owner/designer. DI limits provide such a means of quantification for concrete cover quality.

In practical construction, however, the responsibility for producing a quality structure is shared by the concrete material supplier and the constructor. Therefore, a distinction needs to be made between *material potential* and *as-built durability performance*. The former refers to the potential of the material to be durable (i.e. what can be achieved), while the latter refers to the durability exhibited by the structure using the material in service (i.e. what is actually achieved). Ultimate durability performance will depend on both, and these two separate but related aspects must be appreciated and allowed for in design and construction. As-built durability performance is typically more sensitive to construction processes than as-built strength performance. Construction processes critically influence the cover zone, where the transport of chloride ions and carbonation occurs. Except in cases of gross under-compaction, the internal concrete core, which primarily provides strength, is much less affected by most construction processes.

To establish the required DI values, the designer must consider (i) the exposure conditions, (ii) the service life of the structure, (iii) the materials to be used, and (iv) an appropriate cover. Also, depending on the type of structure, the designer must utilise appropriate service life models that integrate the above factors to arrive at a practical and economic design. In this paper, either a deemed-to-satisfy approach or a rigorous approach is outlined to determine appropriate performance values.

3.1 Environmental exposure conditions

The natural environmental classes according to EN206 are being considered for adoption in South Africa. The environments relevant for reinforced concrete corrosion, i.e. carbonating conditions and marine conditions, are given in Table 1.

3.2 Desired service life

For durability to be appropriately specified, the desired service life of the structure needs to be explicitly established as part of the design process. Required material and construction quality increases with increased service life. The owner determines the design life, but a guideline for typical values is provided by EN 1990 [28], as shown in Table 2. For

Table 1 Environmental classes (Natural environments only) (after EN206)

Designation	Description
Carbonation-induced corrosion	
XC1	Permanently dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity (60–80%) (Ext. concrete sheltered from rain)
XC4	Cyclic wet and dry
Corrosion induced by chlorides from seawater	
XS1	Exposed to airborne salt but not in direct contact with seawater
XS2a*	Permanently submerged
XS2b*	XS2a + exposed to abrasion
XS3a*	Tidal, splash and spray zones
	Buried elements in desert areas exposed to salt spray
XS3b*	XS3a + exposed to abrasion

*These sub clauses have been added for South African coastal conditions

Table 2 Recommended service life for different structure types (after EN 1990)

Design working life category	Indicative design working life (years)	Examples of structures
1	10	Temporary
2	10–25	Replaceable structural parts
3	15–30	Agricultural and similar structures
4	50	Buildings and other common structures
5	100	Monumental building structures, bridges and other civil engineering structures

reinforced concrete structures, the most relevant categories are 4 (Common Structures) and 5 (Monumental Structures), that is 50 or 100 years design life respectively.

3.3 Material (Concrete) quality

Material quality (i.e. quality of the concrete) is one parameter that the designer can specify to achieve the desired service life under the exposure conditions—the other parameter being cover thickness. Increasing material quality means a denser, less permeable concrete which slows the rate of ingress of aggressive chemicals (chloride ions or CO_2). The slower rate of transport extends the time before corrosion begins to occur, and thus extends the service life of a structure before repairs or major maintenance are required.

3.4 Cover thickness

Cover thickness is the other parameter that can be specified by the designer to achieve the desired service life. A greater concrete cover means a longer distance for aggressive agents to travel before they can depassivate the reinforcing steel. Required concrete cover and material quality are not unrelated—higher concrete quality may permit lower concrete cover for similar performance. The balance between material quality and cover thickness is normally determined by practical and economic considerations.

For practical purposes, cover depth is usually restricted to between 25 mm and 80 mm. The actual value must be specified by the designer, but typical minimum cover depths are 30 mm for a carbonating environment and 50 mm for a seawater environment (in the South African context).

For a performance specification for corrosion resistance, the cover depth (both minimum value and variability) actually achieved during construction needs to be one of the performance criteria measured, typically using covermeter surveys. However, the criteria for evaluating covermeter surveys are not considered here.

4 Limiting DI values in performance-based specifications

This paper proposes two alternative approaches to specifying DI values:

- A deemed-to-satisfy approach
- A rigorous approach

The former should be adequate for the vast majority of reinforced concrete construction and represents the simpler method. Its implementation is discussed in this paper. A rigorous approach will be necessary for durability-critical structures, or when the design parameters assumed in the first approach are not applicable to the structure in question. Extensive discussion of an implementation strategy for the rigorous approach is beyond the scope of this paper.

4.1 Deemed to satisfy approach

This approach mimics structural design codes: the designer recommends limiting values which, if met by the structure, result in the structure being 'deemed-to-satisfy' the durability requirements. Durability index values are recommended based upon standard conditions for a limited number of options, which are evaluated using service life models to give the limiting DI values. Models relevant to South African conditions of materials and environment have been developed [29]. Nevertheless, the principles of the method hold wider application possibilities.

4.1.1 Carbonating exposure

A relationship has been developed between the carbonation resistance of concrete and the early age (28-day) Oxygen Permeability Index (OPI) value, although further confirmatory work is still required. OPI values can thus be used as a design parameter to control carbonation. The only environments that require OPI values to be specified are XC3 and XC4 (Table 1). For XC1 and XC2, provided there is a minimum of 30 mm cover, carbonation-induced corrosion is unlikely to occur.

Two typical design scenarios with standard conditions and required minimum OPI values are shown in Table 3. For Common Structures, an OPI of 9.70 and a minimum cover of 30 mm should suffice for a 50 year corrosion-free life. For Monumental Structures, two design options are shown. In the first, the cover is kept at 30 mm and the required concrete quality (i.e. OPI) is increased. In the second, the concrete quality is unchanged but the cover is increased.

4.1.2 Seawater exposure (Chloride conductivity)

The 28-day chloride conductivity value of concrete is related to its chloride resistance, and therefore this index can therefore be used to specify concrete performance in seawater environments. The standard conditions for the two design scenarios are shown in Table 4. These conditions result further in Tables 5 and 6, which give chloride conductivity limits for different binder types. A single chloride conductivity value cannot be specified for equal performance as the relationship between chloride conductivity and long-term performance differs between different binder types. While further research is ongoing to establish the reason for this, it is believed to relate to differences in chloride-binding characteristics between the different cementitious binders and the impact of further hydration beyond 28 days [30]. The horizontal rows in Tables 5 and 6 give approximately equal performance (i.e. chloride resistance) in seawater conditions. Binder types are limited to blended cements for seawater exposure, since concrete made with pure CEM I has been shown to be insufficiently resistant to chloride ingress [31]. In addition, due to

Table 3 Deemed to satisfy values for carbonating conditions

	Common structures	Monumental structures	
		(1)	(2)
Service life	50 years	100 years	100 years
Minimum cover	30 mm	30 mm	40 mm
Minimum OPI[a]	9.70	9.90	9.70

[a] This is the minimum OPI value that must be achieved in the as-built structure, tested on samples removed at 28 days

Table 4 Conditions used to establish deemed-to-satisfy values for seawater exposure

	Common structures	Monumental structures
Service life	50 years	100 years
Minimum cover	50 mm	50 mm

Table 5 Maximum Chloride conductivity values[a] (mS/cm) for different exposure classes and binder types: deemed to satisfy approach—common structures (Cover = 50 mm)

EN206 Class	70:30 CEM I: Fly Ash	50:50 CEM I: GGBS	50:50 CEM I: GGCS	90:10 CEM I: CSF
XS1	3.00	3.50	4.00	1.20
XS2a	2.45	2.60	3.25	0.85
XS2b, XS3a	1.35	1.60	1.95	0.45
XS3b	1.10	1.25	1.55	0.35

[a] These are the maximum values that should not be exceeded in the as-built structure, tested on samples removed at 28 days

Table 6 Maximum chloride conductivity values[a] (mS/cm) for different classes and binder types: deemed to satisfy approach—monumental structures (Cover = 50 mm)

EN206 Class	70:30 CEM I: Fly Ash	50:50 CEM I: GGBS	50:50 CEM I: GGCS	90:10 CEM I: CSF
XS1	2.50	2.80	3.50	0.80
XS2a	2.15	2.30	2.90	0.50
XS2b, XS3a	1.10	1.35	1.60	0.35
XS3b	0.90	1.05	1.30	0.25

[a] These are the maximum values that should not be exceeded in the as-built structure, tested on samples removed at 28 days

Notes to Tables 5 and 6:

Fly Ash = Type F; GGBS = Ground granulated blast furnace slag; GGCS = Ground granulated corex slag; CSF = condensed silica fume limitations in the current state of knowledge, a maximum w/b ratio of 0.55 seems prudent, even when the required index values can be achieved with higher w/b ratios.

4.2 Rigorous approach

As an alternative to the above deemed-to-satisfy guidelines, an explicit approach can be followed to set limiting values. This approach may be needed if the proposed structure has requirements that do not meet the conditions defined for the deemed-to-satisfy criteria. Using this approach, the designer would use the relevant service life models directly and input the appropriate conditions (cover depth, environmental classification, desired life, and material). The advantage of this approach is its flexibility—it allows the designer to use values appropriate for the given situation rather than a limited number of pre-selected conditions. However, it requires more expertise on the part of the user to ensure that the models are being used correctly and the results properly interpreted.[2]

4.3 Establishing water sorptivity limits

The water sorptivity index has not been directly related to deterioration mechanisms at this stage. It is therefore not used as a design specification or parameter. It is, however, sensitive to near-surface properties (i.e. the surface 15 mm or so of cover), and hence it can be used in durability specifications as a site control parameter. The actual sorptivity value achieved is strongly dependent on construction factors, primarily curing, and less dependent on concrete material composition. Its inclusion in specifications can thus serve as a check on construction quality.

The required sorptivity value for construction needs to be established by an internal standard in each project. During the mix qualification stage, concrete samples should be prepared and cured in a standard fashion which represents desired construction quality—for example seven days of curing. They can then be stored for the additional time to 28 days of age in controlled laboratory conditions (23 ± 2°C, 50–60% R.H.) and the sorptivity test performed on specimens from these cubes, to provide a material potential (characteristic) value. This value should be increased by a factor of 1.10 (see Appendix for justification) to become the basis of the acceptance criterion for the as-built structure. Nevertheless, an absolute maximum value of 12 mm/hr$^{0.5}$ should be required on the basis of experience with this test in practice. If this value cannot be achieved for the concrete during the qualification stage, the concrete mixture is unsuitable for providing durable structures for the given curing.

5 Evaluating compliance with durability requirements

As mentioned earlier, there are two key aspects for the production of durable concrete in as-built structures—the concrete supplied and the on-site processing. The various construction processes (transporting, placing, compacting, curing, etc) influence the durability properties of the final product more strongly than strength, and therefore both these aspects must be evaluated.

5.1 Material potential quality

To evaluate the material potential, standard specimens (e.g. cubes) should be prepared from the concrete supplied. These should be kept in the mould for one day, and then stored in a water bath (23 ± 2°C) for an additional period. (At present, the proposal is to make this an additional 6 days giving a total of 7 days of moist curing, which is considered to represent a 'best-case scenario' for site curing). The specimens should then be stored for the additional period up to 28 days of age in controlled laboratory conditions (23 ± 2°C, 50–60% RH), at which time they can be tested.

As a general rule, concrete in the as-built structure may be of lower quality compared with the same concrete cured under the controlled laboratory

[2] The service life models are available on the UCT website: http://www.civil.uct.ac.za, follow links to Research Groups, Concrete and Cement-based Materials. The developers of the models should be consulted prior to the models being used. Contact information of the model developers is included on the website.

conditions described above. To account for the improved performance of laboratory concrete over site concrete, the characteristic values for the durability indexes of the laboratory concrete should be:

(a) For OPI: a margin of at least 0.10 greater than the value determined in Sect. 4.1.1 or 4.2
(b) For chloride conductivity: a factor of no greater than 0.90 times the value determined in Sect. 4.1.2 or 4.2

The Appendix outlines the rationale behind the use of these factors. As the sorptivity test is primarily a measure of the influence of site processing, it is not a necessary test for the supplied concrete. The material supplier may elect to perform this test on standard specimens, in which case the characteristic value should be that obtained during the testing outlined in Sect. 4.3, without the factor of 1.10 applied.

5.2 As-built quality

To evaluate the combined effects of material potential and on-site processing, samples should be taken from the structure between 28 and 35 days of age, and tested for the durability indexes.

The characteristic values of these indexes should:

(a) For OPI: equal or exceed the value determined in Sect. 4.1.1 or 4.2
(b) For chloride conductivity: equal, or less than the value determined in Sect. 4.1.2 or 4.2
(c) For water sorptivity: equal, or less than the value determined in Sect. 4.3

5.3 Testing frequency

The testing frequency should be project-specific, and therefore could vary. It is suggested that initially, testing frequency should be greater. Once it has been establihed that the criteria are being consistently achieved, the testing frequency can be decreased. For example, initially one set of tests may be required for every 50 m^2 of in-situ concrete surface area placed, with a minimum of one test for each element.[3] This could reduce subsequently to, say, one set of tests for every 150 m^2 of in-situ concrete surface area, or possibly a greater value. In selecting the locations within the structure at which cores are taken for testing, small areas with obvious physical defects should be avoided. Furthermore, unavoidable spatial variations in concrete quality across a section (eg. vertical variations in a single pour height of a wall) should be acknowledged, for example by not taking cores from the very top or bottom of a single lift of a wall or column.

6 Conformity criteria for DI values

The values required for material potential (as established in Sect. 5.1) are characteristic values, not target (average) values. The owner requires this level of performance for the structure so that the desired service life is achieved with an adequate probability of success. The inherent variability in concrete performance needs to be considered when interpreting test results and evaluating concrete mixture designs, similar to the approach that is adopted with strength specimens. Thus, it is proposed that two criteria be used to allow for this variability, such that:

(a) the average of any three consecutive test results must be 'better' than the required characteristic value, and
(b) no single test result is "poorer" than the characteristic value by more than a specified magin.

The material supplier should aim at target values that will achieve the required characteristic values with adequate probability. Since durability is a serviceability criterion, the limitations may need to be less stringent than for strength. According to ACI 318 [2], current limitations for strength imply a 1 in 100 chance that the average of three consecutive tests would be below the required characteristic value, and a 1 in 100 chance that an individual test value would be 3.45 MPa or more below the required value. At this stage, it is proposed that a 1 in 10 chance be adopted for the durability index tests with a margin of 0.3 below for OPI, 0.2 mS/cm above for chloride conductivity, and 1.0 mm/$hr^{0.5}$ above for sorptivity. This results in Eqs. 1–7 below for determining target durability index test values. (These equations are more completely developed in the Appendix).

[3] Note that a valid test result is the mean value from a minimum of 3 (preferably 4) individual determinations, i.e. from 3 (or 4) concrete disc specimens.

6.1 Small Number of Results (<30 results)

At present, the use of durability indexes is at an early stage, and an extensive data base on variability both in terms of material potential and in-situ quality is not available. Some initial trials have been done, however, to evaluate the variability of a limited range of nominally identical ready-mix concrete batches [32]. In the absence of other information, the coefficients of variation (C.O.V.) determined in this work are used to establish the target average test value so as to meet the acceptance criteria in Sect. 7.

OPI: The target average index value based on the desired characteristic value should be:

$$OPI_{Target} = OPI_{Char,Mat'l\ Potential} + 0.22 \quad (1)$$

(Note that for the OPI, the logarithmic transformation results in a constant factor being added to the characteristic value. Also, the subscript "Char, Mat'l Potential" refers to the required characteristic value for material potential).

Chloride Conductivity: The target average value (in mS/cm) based on the required characteristic value should be the lesser of:

$$CC_{Target} = 0.90CC_{Char,Mat'l\ Potential} \quad (2)$$

$$CC_{Target} = 0.82CC_{Char,Mat'l\ Potential} + 0.2 \quad (3)$$

(Sorptivity is used (at this stage of development) as an internal standard in construction, if desired. Guidance on the appropriate values can be obtained from Sect. 4.3, and in the Appendix in Sect. A2.3 and Table A.3).

6.2 Large number of results (>30 results)

When a large number of test results on similar concrete mixtures is available (>30), the results can be analysed statistically and the determined standard deviation (s) used to set the target value. The resulting equations are:

OPI: The target average value should be the greater of:

$$OPI_{Target} = OPI_{Char,Mat'l\ Potential} + 0.75s \quad (4)$$

$$OPI_{Target} = OPI_{Char,Mat'l\ Potential} + 1.30s - 0.3 \quad (5)$$

Chloride Conductivity: The target average value should be the lesser of:

$$CC_{Target} = CC_{Char,Mat'l\ Potential} - 0.75s \quad (6)$$

$$CC_{Target} = CC_{Char,Mat'l\ Potential} - 1.30s + 0.2 \quad (7)$$

7 Acceptance criteria

For acceptance of a set of test results, the obtained values must be compared with the required characteristic values for Material Potential (Sect. 5.1) and for as-built quality (Sect. 5.2). Thus the oxygen permeability test results are considered satisfactory if both

(1) the average of any three consecutive test results exceeds the characteristic value 90% of the time, and
(2) no single test result is less than the characteristic value by more than 0.3

The chloride conductivity test results are considered satisfactory if both

(1) the average of any three consecutive test results is less than the characteristic value 90% of the time, and
(2) no single test result is greater than the characteristic value by more than 0.2 mS/cm

The sorptivity test results are considered satisfactory if both

(1) the average of any three consecutive test results is less than the characteristic, and
(2) no single test result is greater than the characteristic value by more than 1.0 $mm/hr^{0.5}$.

(The characteristic value for sorptivity is that determined in Sect. 5.2 for the as-built quality.)

A flowchart illustrating the various steps and necessary durability index values for each step is given in Fig. 1. It allows the designer to follow the processes described to arrive at the final acceptance criteria.

8 Practical example

An example of how the procedures can be implemented may assist in making the previous discussion clear. (The example also refers to the equations presented in the Appendix.) The desired quality of the

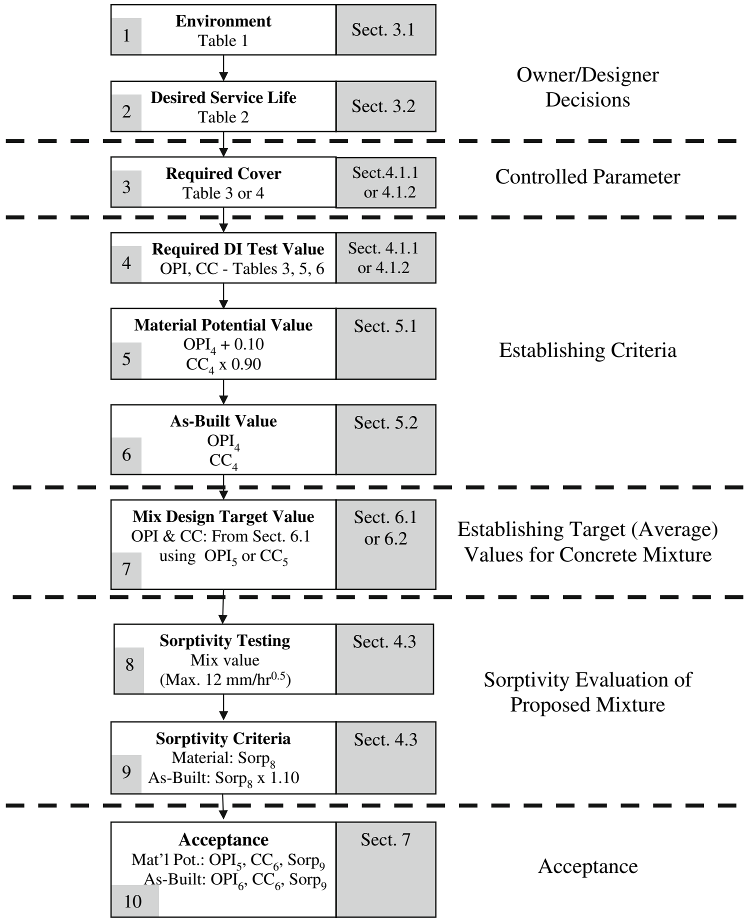

Fig. 1 Flowchart illustrating establishment of acceptance criteria, assuming deemed-to-satisfy approach (Subscripts refer to the step in the process in which the relevant value was derived)

structure must first be established in terms of the performance criteria. This can be done using the deemed-to-satisfy approach (Sect. 4.1) or more rigorously using service life models, considering environment, concrete cover and desired life (Sect. 4.2). In this example, assume that for chloride resistance a maximum chloride conductivity value of 1.35 mS/cm is required, and a minimum OPI of 9.70 is required for carbonation resistance. (Both values need not necessarily be specified for a single structure, and should be based on the environment and the expected deterioration mechanism.) These are the *characteristic* values that must be achieved by the as-built structure, and the average of any three consecutive test results from the structure must pass these values 90% of the time.

Regarding sorptivity, assume that tests on the proposed mix indicate a material potential value (*characteristic*) of 10 mm/hr$^{0.5}$. Therefore, the as-built value from the actual structure should achieve values of no greater than (10 $\times$ 1.1 =) 11mm/hr$^{0.5}$ (Eq. A.12 and Sect. 4.3).

The materials supplier must meet more stringent criteria. For chloride conductivity, the material potential value as determined on laboratory specimens must be no greater (i.e. better quality) than that determined from equation A4 (see also Sect. 5.1)—that is no greater than (1.35 $\times$ 0.90) = 1.22 mS/cm. For the OPI, the material potential value must be not less than that determined from Eq. A8 (see also Sect. 5.1) —that is no less than (9.70 + 0.10 =) 9.80.

The materials supplier, in order to achieve these values at the required level of certainty, must target better values on average. These are calculated using Eqs. A13 and A14 for chloride conductivity, and Eq. A15 for OPI, using the previously calculated characteristic values for material potential (see also Sect. 6.1). This results in target values of (0.90 $\times$ 1.22=) 1.10 mS/cm for chloride conductivity and (9.80 + 0.22=) 10.02 for OPI. For sorptivity,

Table 7 Summary of values for example

Parameter	Responsibility	Chloride conductivity (mS/cm)	OPI	Sorptivity (mm/h$^{0.5}$)
Required quality limit	Designer/Owner	1.35	9.70	–
As-built quality: characteristic value	Constructor	1.35	9.70	11.0
Material potential: characteristic value	Materials supplier	1.22	9.80	10.0
Material potential: target value	Materials upplier	1.10	10.02	9.0

the target concrete value to be aimed at by the supplier should be (0.90 × 10=) 9 mm/hr$^{0.5}$ (equation A17). These values are summarized in Table 7.

9 Closure

The paper has discussed the approach being developed and implemented in South Africa to improve the quality of reinforced concrete construction—in particular, to prevent premature corrosion of reinforcing steel. The approach is based on use of DIs, which represent a measure of durability. DIs can be measured on both laboratory specimens and samples from as-built structures, allowing an assessment of the dual contributions of the material itself, and the effects of construction processes. The paper suggests DI values for the various phases of design and construction, involving as-built values and also material potential and target values, based on present experience and statistical formulations.

Currently the statistical factors required to determine target values by the material supplier so that the constructor can be expected to meet as-built requirements are only provisionally established and need further investigation before full implementation. Also, the approach contained in this paper needs to be validated with further practical experience on various construction sites over time. The proposed provisions should therefore be used developmentally. Realistic limiting values should be set with due cognisance of the uncertainties inherent at present. Possible use of this approach should be discussed at the pre-bid stage. A process of advocacy and education of all concerned needs to be implemented in the construction sector, and realistic limiting values should be the subject of ongoing discussion and agreement between all parties.

The values given in the paper are 'best-estimates' based upon present experience. It is inevitable, and indeed desirable, that the values should be modified with time as experience grows and greater insight is gained into the practicalities of the proposed methods. It is important, however, that a start should be made to collect information from laboratory results, in-situ results and relevant site parameters (e.g. curing type and duration, temperature, humidity, site location, etc.), and this information be made available. Work is currently underway to establish a protocol to accomplish this within the South African construction industry. As information becomes available, the values can be reviewed and more appropriate margins can be established. There is thus a need for an evolutionary approach to the development of this approach to durability specification.

Appendix—Derivation of equations

This Appendix gives additional background and the statistical basis for the derivation of the various durability index values discussed in the main paper.

A1 Relationship between material potential and as-built characteristic values

A1.1 Definition of characteristic value

At this stage in the development of the method and since we are dealing with serviceability parameters, it is recommended that a 1 in 10 chance that the average of any three consecutive tests will fail the required limiting values be accepted as the appropriate confidence level.

A1.2 Differences between material potential and as-built values

The effect of site processing would be expected to be two-fold—a reduction in average quality and increased variability. Thus, the absolute differences in average values between the as-built and material potential specimens, as well as their variances, are required in order to establish the margin between material potential and as-built values. This has not been extensively studied, with one reference available examining this phenomenon in terms of South African durability indexes [21]. Gouws studied the quality of as-built structures and associated site-cast cubes from nominally identical concrete batches, using the South African DI tests. Regarding average values, the results were mixed. As-built values were generally worse, but occasionally better than the laboratory specimens. The occasional reversals were attributed to the methods of finishing; for example when considerable densification was given to the surface of well-cured ground slabs. In view of uncertainties, accounting for differences in average performance is therefore neglected at this stage. This issue is returned to later. Gouws et al. [21] reported variances for the laboratory (material potential) and as-built conditions. The coefficients of variation (COV) are shown in Table A1.

A1.3 Derivation: chloride conductivity values

If average values are assumed to be the same for both as-built and material potential specimens (in the absence of better information), the situation is as shown in Fig. A1, where characteristic values represent poorer quality (i.e. higher numerical values), as is the case for the chloride conductivity test. The relationship between the characteristic value and average value is thus:

$$CC_{Char} = \left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV\right) CC_{Average} \quad (A1)$$

where $Z_{90\%}$ refers to the one-sided 90% probability value from the standard normal distribution (=1.30), COV represents the coefficient of variation, CC_{Char} represents the characteristic chloride conductivity value, and $CC_{Average}$ the average value. (The $\sqrt{3}$ is required in Eq. A1 because the relationship between characteristic and average value is for the average of 3 tests, but the COV is related to the variability of single test results.)

Equation A1 holds for both material potential and as-built values. Thus the ratio between the characteristic values for material potential and as-built quality can be determined as:

$$\frac{CC_{Mat'l}}{CC_{As-Built}} = \frac{CC_{Average}\left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{Mat'l}\right)}{CC_{Average}\left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{As-Built}\right)} \quad (A2)$$

where 'Mat'l' represents Material Potential throughout

Substituting the values from Table A1:

$$CC_{Mat'l} = 0.94\ CC_{As-Built} \quad (A3)$$

The desired material potential value is calculated as a function of the required as-built value, since the as-built value is the key value used in service life models and performance-based specifications.

In the absence of better information, Eqs. A2 and A3 were calculated assuming that the average as-built quality was the same as for the laboratory specimens representing material potential. This is unlikely to be the case. When coupled with the limited data used to derive the relationships, it is considered prudent to increase the margin between the as-built value and the material potential. Thus, as an interim measure the recommended relationship is:

$$CC_{Mat'l} = 0.90\ CC_{As-Built} \quad (A4)$$

A1.4 Derivation: oxygen permeability values

The procedure for developing the relationship between material potential and as-built quality for OPI is similar to that given above, but with this difference: the OPI value is the negative logarithm of the coefficient of permeability. Thus, OPI values cannot be assumed to be normally distributed, and therefore Eqs. A1 and A2 do not apply. However, these equations can be used for the coefficient of permeability, k, which decreases with increasing quality as for the chloride conductivity value. Equation A2 expressed for k becomes:

Table A1 Single-operator coefficients of variation [21]

Note: k is the D'Arcy coefficient of permeability in m/s units; OPI is the negative log of k

Condition	Chloride conductivity (%)	COV for:		
		Sorptivity (%)	Oxygen perm.	
			OPI (%)	k (%)
Laboratory (Material potential)	5	7	1	23
As-built	14	13	2	50

$$\frac{k_{Mat'l}}{k_{As-Built}} = \frac{k_{Average}\left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{Mat'l}\right)}{k_{Average}\left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{As-Built}\right)} \quad (A5)$$

Taking the logarithms of both sides, and substituting OPI for –log (k) results in:

$$OPI_{Mat'l} = OPI_{As-Built} - \log\left[\frac{1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{k,Mat'l}}{1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{k,As-Built}}\right] \quad (A6)$$

Coefficients of variation for k of 23% and 50% are equivalent to the coefficients of variation of 1% and 2% for material characteristic and as-built conditions respectively, for OPI [21]. Substituting these values and solving:

$$OPI_{Mat'l} = OPI_{As-Built} + 0.07 \quad (A7)$$

Transforming the k values to OPI values results in the margin becoming a fixed value, rather than proportional to the required value as was the case for chloride conductivity. Again it is deemed prudent to increase the margin, resulting in the proposed relationship:

$$OPI_{Mat'l} = OPI_{As-Built} + 0.1 \quad (A8)$$

A1.5 Derivation: sorptivity values

The procedure for sorptivity is identical to that for chloride conductivity. The relationship between average and characteristic values is:

$$Sorp_{Char} = \left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV\right) Sorp_{Average} \quad (A9)$$

The relationship between material potential and as built quality is thus similarly:

$$\frac{Sorp_{Mat'l}}{Sorp_{As-Built}} = \frac{Sorp_{Average}\left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{Mat'l}\right)}{Sorp_{Average}\left(1 + \frac{Z_{90\%}}{\sqrt{3}} COV_{As-Built}\right)} \quad (A10)$$

In this case, the known value will be the material potential and not the as-built value. Substituting values from Table A1:

$$Sorp_{As-Built} = 1.04\ Sorp_{Mat'l} \quad (A11)$$

For similar reasons as for the chloride conductivity test, it is considered prudent to increase this margin, resulting in the recommendation of:

$$Sorp_{As-Built} = 1.10\ Sorp_{Mat'l} \quad (A12)$$

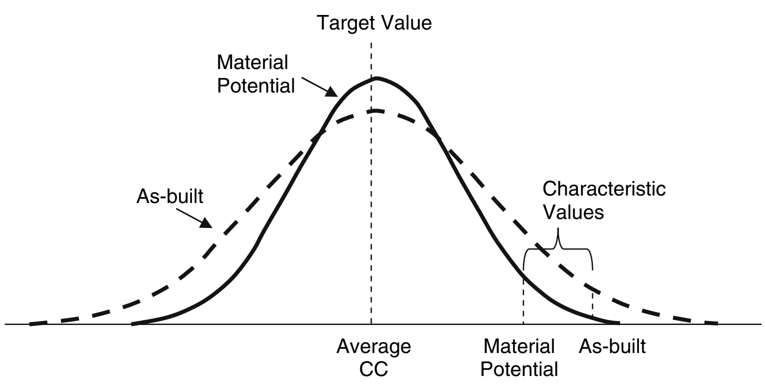

Fig. A1 Conceptual relationships between material potential and as-built test distributions for chloride conductivity test. differences between average quality neglected

Table A2 Between-batch coefficients of variation [32]

Condition	Chloride conductivity (%)	Sorptivity (%)	Oxygen perm. (%)	
			OPI	k
Between-batch variability	13.6	13.6	3.8	53.2

A2 Establishing target values

The materials supplier must establish target values so that the characteristic values are met consistently. Target values can be calculated by a method similar to that proposed for strength [33], except for the less stringent criterion of 1:10. Only chloride conductivity and oxygen permeability limits are used to control the mix design, and not the sorptivity. Relationships are thus derived only for these two tests. Between-batch coefficients of variation for the tests, that is the coefficient of variation of the average of multiple sets of samples taken from a single batch, are required. For the situation with a small number of batches, these were taken from [32], see Table A2.

For a large number of batches, the operator can choose to use the coefficient of variation from the actual test history to establish limits. The equations given in Sect. 6 were derived as given below for a small number of specimens.

The requirement that no single test result should fail the target value by more than some absolute limit was also adopted. The proposed limits are suggested as 0.2 mS/cm for the chloride conductivity test and 0.3 for the OPI, based upon the judgement of the authors (see Sect. 7).

A2.1 Chloride conductivity values

Here, the calculations are straightforward. Using the COV of 13.6% from [32] and that no single test is above the absolute maximum by more than 0.2 mS/cm, results in:

First Criterion: (average of three consecutive test results not less than target value):

$$\begin{aligned} \mathrm{CC_{Target}} &= \mathrm{CC_{Char}} - \frac{1.30}{\sqrt{3}}\left(\frac{13.6}{100}\right)\mathrm{CC_{Char}} \\ &= 0.90\ \mathrm{CC_{Char}} \end{aligned} \quad \text{(A13)}$$

and the second criterion (no single test result is 0.2 mS/cm more than target value):

$$\begin{aligned} \mathrm{CC_{Target}} &= \mathrm{CC_{Char}} - 1.30\left(\frac{13.6}{100}\right)\mathrm{CC_{Char}} + 0.2 \\ &= 0.82\ \mathrm{CC_{Char}} + 0.2 \end{aligned} \quad \text{(A14)}$$

where 'Char' values refer to Material Potential values.

The more stringent of these two limits controls.

A2.2 Oxygen permeability values

For the OPI values, the concept is similar, although complicated by the logarithmic transformation. Again this is satisfied by developing the expressions for k values and then transforming. For the first criterion, and using a COV for k of 53% [32]:

$$\begin{aligned} \mathrm{k_{Target}} &= \mathrm{k_{Char}} - \tfrac{1.30}{\sqrt{3}}\mathrm{COV_k k_{Char}} = \mathrm{k_{Char}}\left(1 - \tfrac{1.30}{\sqrt{3}}\mathrm{COV}\right) \\ -\log \mathrm{k_{Target}} &= -\log\left[\mathrm{k_{Char}}\left(1 - \tfrac{1.30}{\sqrt{3}}(0.53)\right)\right] \\ \mathrm{OPI_{Target}} &= \mathrm{OPI_{Char}} + 0.22 \end{aligned} \quad \text{(A15)}$$

For the second criterion, a margin of 0.3 for the OPI was deemed satisfactory. This results in:

$$\begin{aligned} -\log(\mathrm{k_{Target}}) &= -\log(\mathrm{k_{Char}}(1 - 1.30\ \mathrm{COV})) - 0.30 \\ \mathrm{OPI_{Target}} &= \mathrm{OPI_{Char}} - \log(1 - 1.30(0.53)) - 0.30 \\ \mathrm{OPI_{Target}} &= \mathrm{OPI_{Char}} + 0.51 - 0.30 \\ \mathrm{OPI_{Target}} &= \mathrm{OPI_{Char}} + 0.21 \end{aligned} \quad \text{(A16)}$$

where 'Char' values refer to Material Potential values.

Therefore the second criterion will always result in a lower value and can be discarded.

A2.3 Sorptivity values

For the water sorptivity test, using the COV of 13.6% [32] and taking that no single test is above the absolute maximum by more than 1 mm/hr$^{0.5}$, results in:

Table A3 Equations for calculated values

	Chloride conductivity	OPI	Sorptivity
As-built Limit (Characteristic)	$CC_{As\text{-}built}$ From Service Life Model	$OPI_{As\text{-}built}$ From Service Life Model	$S_{As\text{-}built} = 1.10S_{Mat'l\ Pot'l}$
Mat'l Pot'l Limit (Characteristic)	$CC_{Mat'l\ Pot'l} = 0.90CC_{As\text{-}built}$	$OPI_{Mat'l\ Pot'l} = OPI_{As\text{-}built} + 0.10$	$S_{Mat'l\ Pot'l}$ Established on site mix
Material Target Value (Average)	Lesser of: 0.90 $CC_{Mat'l\ Pot'l}$ 0.82$CC_{Mat'l\ Pot'l}$ + 0.20	$OPI_{Mat'l\ Pot'l} + 0.22$	Lesser of: 0.90$S_{Mat'l\ Pot'l}$ 0.82$S_{Mat'l\ Pot'l}$+1.0

First Criterion: (average of three consecutive test results not less than target value):

$$S_{Target} = S_{Char} - \frac{1.30}{\sqrt{3}}\left(\frac{13.6}{100}\right)S_{Char} = 0.90\ S_{Char} \tag{A17}$$

and the second criterion (no single test result is 1 mm/hr$^{0.5}$ more than target value):

$$S_{Target} = S_{Char} - 1.30\left(\frac{13.6}{100}\right)S_{Char} + 1.0 = 0.82\ S_{Char} + 1.0 \tag{A18}$$

where 'Char' values refer to Material Potential values.

The more stringent of these two limits controls.

The resulting equations are summarized in Table A3.

References

1. SANS 10100-1 (2000) The structural use of concrete, part I: design. South African National Standards, Pretoria
2. ACI Committee 318 (2005) Building code requirements for structural concrete (ACI 318-05) and commentary (318R-05). American Concrete Institute, Farmington Hills, MI, 430 pp
3. ACI Committee 301 (2005) Specifications for structural concrete (ACI 301–05). American Concrete Institute, Farmington Hills, MI, 49 pp
4. Mackechnie JR, Alexander MG (2002) Durability Predictions Using Early-Age Durability Index Testing. In: Proc. Ninth Durability and Building Materials Conference, Australian Corrosion Association, Brisbane, Australia, 11 pp
5. Alexander MG, Stanish K (2005) Durability design and specification of reinforced concrete structures using a multi-factor approach. In: Mindess Symposium, Third Int. Conference on Construction Materials, Vancouver, August 2005, CD ROM, University of British Columbia, Vancouver, 10 pp
6. Simons B (2004) Concrete performance specifications: New Mexico experience. Concr Int 26(4):68–71
7. Day KW (2005) Perspective on prescriptions. Concr Int 27(7):27–30
8. Bickley JA, Hooton D, Hover KC (2006) Performance specifications for durable concrete. Concr Int 28(9):51–57
9. Lobo C, Lemay L, Obla K (2005) Performance-based specifications for concrete. Indian Concr J 79(12):13–17
10. AS3600-2001 Concrete Structures. Incorporating Amendments No. 1 and 2, Standards Australia, Sydney, NSW, 165 pp
11. CAN/CSA-A23.1-04/A23.2-04 (2004) Concrete materials and methods of concrete construction/methods of test and standard practices for concrete. Canadian Standards Association, Toronto, 516 pp
12. Harrison TA (1995) Framework for durability performance specifications for concrete used in normal construction. In: Proc. XIth European ready-mixed concrete congress, Turkey
13. Recommendation of RILEM TC 189-NEC Non-destructive evaluation of the concrete cover: Comparative test—Part I: Comparative test of 'penetrability' methods (2005) Mater Struct (284)
14. Hooton D, Mindess S, Roumain J-C, Boyd AJ, Rear K (2006) Proportioning and testing concrete for durability. Concr Int 28(8):38–41
15. FIB Model Code for Service Life Design (2006) *fib* Bulletin 34, *fib*, EPFL Lausanne, 116 pp
16. Andrade C, Izquierdo D (2005). Benchmarking through an algorithm of repair methods of reinforcement corrosion: the repair index method. Cement Concr Compos 27(6):727–733
17. Baroghel-Bouny V (2002) Which toolkit for durability evaluation as regards chloride ingress into concrete? Part II: Development of a performance approach based on durability indicators and monitoring parameters. In: Andrade C, Kropp J (eds) Proc. 3rd Int. RILEM workshop: testing and modelling chloride ingress into concrete, Madrid, Spain, 2004, Bagneux: RILEM Publ., PRO 38:137–163
18. Baroghel-Bouny V (2004) Durability indictors: a basic tool for performance-based evaluation and prediction of RC durability. In: Sato R, Fujimoto Y, Dohi T (eds) Proc. Int.

seminar on durability and life-cycle evaluation of concrete structures, Japan, 2004. Univ. of Hiroshima, 13–22
19. Alexander MG, Mackechnie JR, Ballim Y (1999) Guide to the use of durability indexes for achieving durability in concrete structures. Research Monograph No 2, Department of Civil Engineering, University of Cape Town, 35 pp
20. Alexander MG, Mackechnie JR, Ballim Y (2001) Use of durability indexes to achieve durable cover concrete in reinforced concrete structures. In: Skalny JP, Mindess S (eds) Materials science of concrete, vol. VI. American Ceramic Society, pp 483–511
21. Gouws SM, Alexander MG, Maritz G (2001) Use of durability index tests for the assessment and control of concrete quality on site. Concr Beton 98:5–16
22. Raath B (2004) Practical Issues of Concrete Specification. Concrete Society of Southern Africa, National Seminar: Specifying Concrete for Durability—State of the Art of South African Practice, Presented at Johannesburg, Durban, Port Elizabeth and Cape Town, South Africa, 2004
23. Alexander MG, Ballim Y, Mackechnie JR (1999) Concrete durability index testing manual. Research Monograph No. 4, Department of Civil Engineering, University of Cape Town, 33 pp
24. Alexander MG, Streicher PE, Mackechnie JR (1999) Rapid chloride conductivity testing of concrete. Research Monograph No. 3, Department of Civil Engineering, University of Cape Town, 35 pp
25. Mackechnie JR, Alexander MG (2000) Rapid chloride test comparisons. Concr Int 22(5):40–46
26. Mackechnie JR (2001) Predictions of reinforced concrete durability in the marine environment. Research Monograph No. 1, Department of Civil Engineering, University of Cape Town, 28 pp
27. EN 206 (2000) Concrete—Part 1: Specification, performance, production and conformity. British Standards Institution: 70 pp
28. EN 1990 (2002) Eurocode: Basis of structural design. British Standards Institution
29. Mackechnie JR, Alexander MG (2002) Durability predictions using early-age durability index testing. Proceedings, 9th durability and building materials conference. Australian Corrosion Association, Brisbane, 11 pp
30. Gardner T (2006) Chloride transport through concrete and implications for rapid chloride testing. MSc (Eng) Thesis, University of Cape Town
31. Alexander MG, Mackechnie JR (2003) Concrete mixes for durable marine structures. J South Afr Inst Civil Eng 45(2):20–25
32. Mwandla S (2004) Variation of the durability index test values between nominally identical ready-mix concrete batches. BSc Thesis, Department of Civil Engineering, University of Cape Town
33. ACI Committee 214 (1995) Recommended practice for evaluation of strength test results of concrete, ACI manual of concrete practice, Part 2. Construction practices and evaluation, pavements. American Concrete Institute, Farmington Hills, MI