

The South African durability index tests in an international comparison

H Beushausen and M G Alexander

Over the last decade, an approach to improving the durability of reinforced concrete construction has been developed in South Africa. The durability index test methods applied in this approach are unique to the country. Internationally, similar trends can be observed and a number of test methods for the quality assessment of hardened concrete, particular the cover zone have been developed world-wide. A group of researchers from different parts of the world carried out comparative tests on the quality of concrete cover, applying the most commonly accepted international test methods. The results indicate that the South African oxygen permeability and chloride conductivity test methods are successful in characterising the concrete cover in respect of important deterioration mechanisms. A good correlation exists between results obtained from these index test methods and those obtained from related test procedures applied overseas.

INTRODUCTION

In reinforced concrete structures, deterioration is often associated with ingress of aggressive agents from the exterior and the near-surface concrete quality largely controls durability. The problem for engineers and concrete producers is how to provide adequate protection to the steel reinforcement by the cover layer, which is subjected to the action of aggressive agents such as chloride ions or acidification from the surrounding environment. What is therefore required is the ability to quantify the quality of the cover layer in terms of engineering parameters that can immediately be useful to designers and concrete practitioners. These quantifiable parameters can then form the basis for crafting performance-based specifications that should help improve overall quality of reinforced concrete construction. Approaches to include such performance-based durability specifications in national standards and/or construction practices, based on appropriate test methods, are being developed world wide.

A performance-based approach to design and specification of concrete structures basically consists of the two main components of (i) appropriate test methods and

(ii) appropriate interpretation of test results obtained. The South African durability index (DI) tests comprise oxygen permeability, chloride conductivity and water sorptivity tests (Alexander *et al* 1999–2007). The durability indices obtained with these test methods have been related empirically to service life prediction models. Index values can be used as the input parameters of service life models, together with other variables such as steel cover and environmental class, in order to determine rational design life. Limiting index values can be used in construction specifications to provide the necessary concrete quality for a required life and environment. Thus, a framework has been put in place for a performance-based approach to both design and specification. In the past years, South Africa has been somewhat ahead of other, similar international developments, and has managed to successfully implement performance-based durability specifications, while other countries are generally still in the state of developing relevant strategies.

In general, it has proven to be a slow process to develop and refine relevant test methods for concrete durability and begin to implement these in practice. International

Table 1 Test conditions investigated in the comparative testing of RILEM TC 189-NEC

Panel	1	2	3	4	5	6
w/b	0,4	0,55	0,6	0,4	0,55	0,55
Binder type	OPC	OPC	OPC	OPC/ slag	OPC/ slag	OPC
Moist curing (days)	7					1
$f_{cu, cube}$ @ 28d (MPa)	62,7	48,5	34,4	52,4	38,2	42,7



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Figure 1 Test panels for the comparative testing

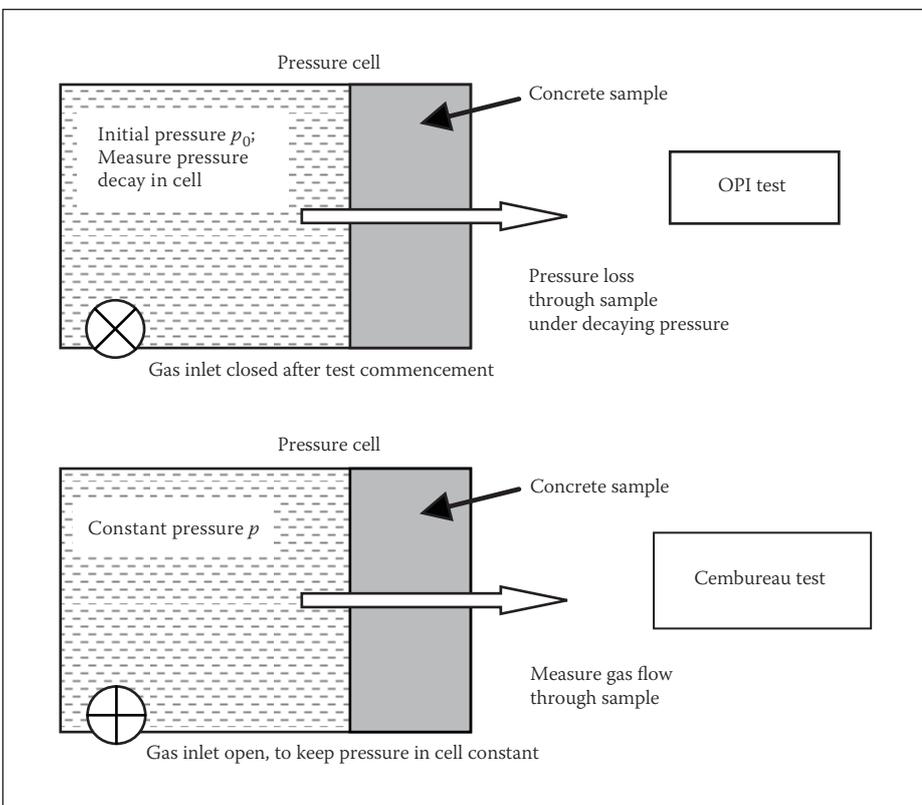


Figure 2 Schematics of the South African oxygen permeability index test (OPI) and the Cembureau permeability test

cooperation and exchange of knowledge and experience can speed up such developments significantly. In today's concrete industry, national research outputs are generally shared and discussed on an international level and cooperation between research institutes of different countries becomes a vital aspect in the progress of concrete technology. Often, different countries work on similar research topics and come up with different solutions to the same problem. Comparison of research results, material properties

and test methods on an international level promotes the development of appropriate technologies for concrete manufacture and specification.

International standardisation of specifications for concrete structures is proceeding, good examples being the planned implementation of the new Eurocode 2 in 2010, the recently established Asian Concrete Code, and the current efforts to establish an African Concrete Code. International standardisation of test methods is important

in these developments. While individual countries will probably retain their own test methods, it is important to be able to compare the results obtained with the various methods to promote the exchange of technical information and experience.

This paper reviews an international research programme on the evaluation of the quality of concrete cover and discusses how the South African Durability Index test methods compare against other internationally accepted test methods. The research reported on in this paper was conducted through RILEM Technical Committee 189-NEC. A comprehensive report on the work of TC 189-NEC was published in 2007 (Torrent & Fernández Luco 2007).

COMPARATIVE TESTS OF DIFFERENT METHODS FOR CONCRETE DURABILITY CHARACTERISATION

Various research institutes and members of the industry from Europe, North America, and South Africa have carried out a joint research project on the quality of concrete cover, concentrating their efforts in RILEM Technical Committee 189-NEC (Non-destructive Evaluation of the Covercrete) (Romer & Fernández Luco 2005; Torrent & Fernández Luco 2007). The objective of the committee is the selection of suitable non-destructive test (NDT) methods for the evaluation of the thickness and quality of the concrete cover, in view of the need for durability of concrete structures.

Comparative tests of different NDT methods to evaluate the 'penetrability' of the concrete cover layer was carried out by RILEM TC 189-NEC. 'Penetrability' is broadly defined as the ease with which different agents (gases, liquids, ions, etc) can move through concrete. It embraces the classical transport mechanisms of permeation, absorption, and conduction. In the following, selected parts of the comparative test programme are discussed, focussing on those test parameters that included the South African DI methods. A more detailed discussion of the comparative tests carried out by RILEM TC 189-NEC can be found in Romer and Fernández Luco 2005; Torrent and Fernández Luco 2007.

In the comparative tests, concrete panels made with different concretes (w/b ratio, binder type, curing, etc, were varied) were prepared at the EMPA laboratory in Zurich, Switzerland (figure 1, table 1). Specialists of several institutions worldwide applied different in-situ NDT to measure the penetrability of the panels. Later, cores were drilled from the panels and sent to several laboratories, in order to perform tests under controlled

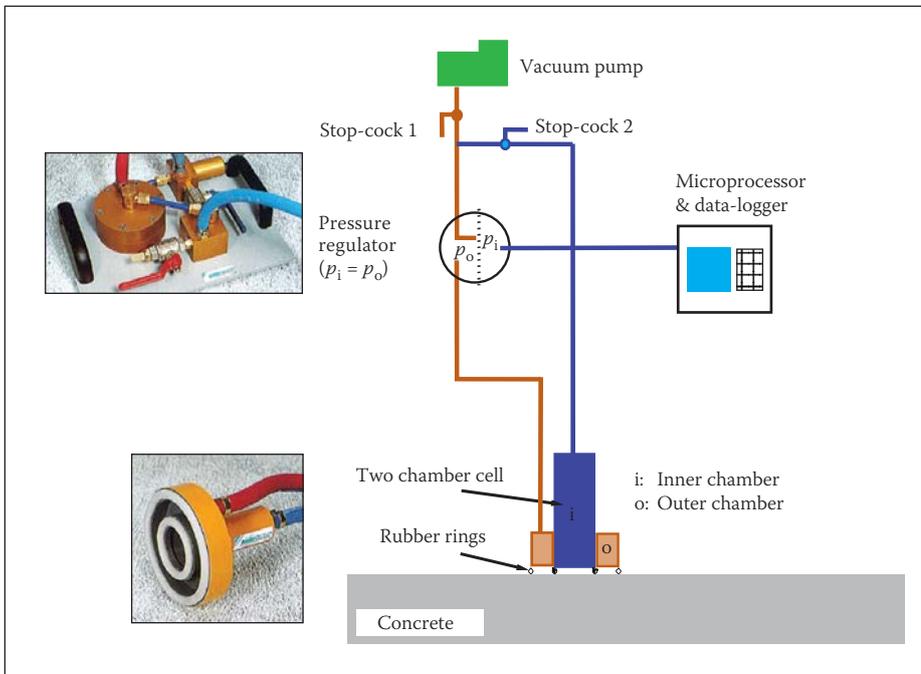


Figure 3 Schematic of the Torrent permeability test (TPT)

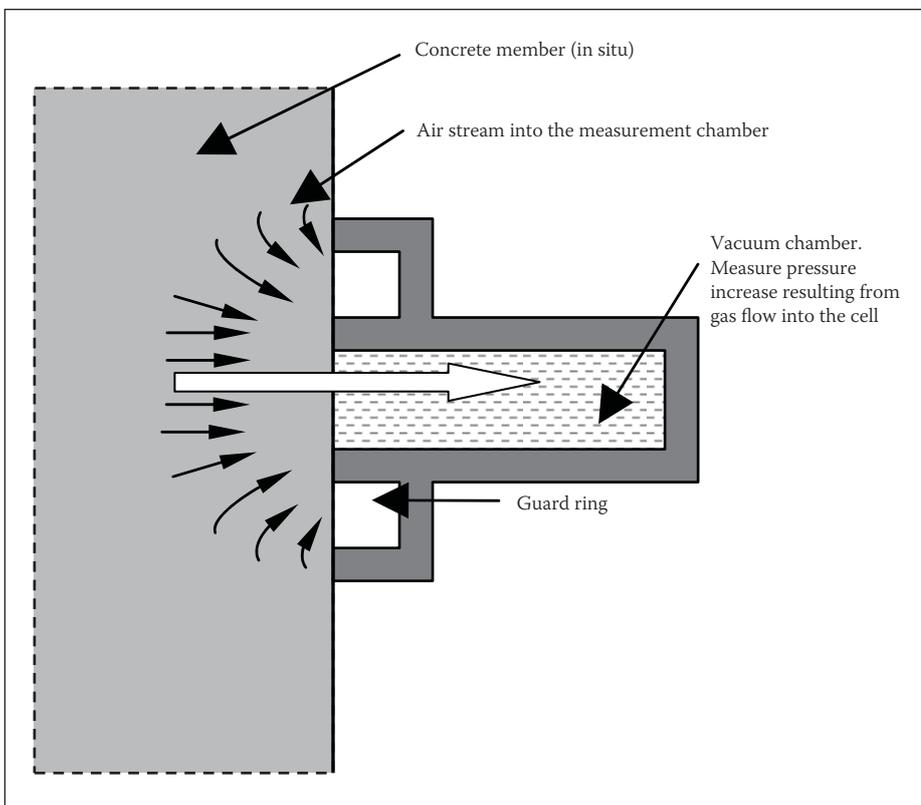


Figure 4 Detail of the air-flow into the vacuum cell of the TPT

laboratory conditions, the so-called reference tests. The reference tests used for determination of chloride resistance were the NT BUILD test (diffusivity) (NTBuild 492 1999), ASTM C1202 (chloride penetration) (ASTM 1997), and the South African chloride conductivity test (Alexander *et al* 1999–2007). Reference tests for oxygen permeability were the Cembureau method (Kollek 1989) and the South African OPI test. Reference tests for water penetrability were the RILEM water absorption test (RILEM TC116-PCD 1999) and the South African water sorptivity

index test. All these methods follow a similar test philosophy in that they mimic transport mechanisms in concrete samples preconditioned under controlled laboratory conditions. Tests with the South African durability index tests were carried out at the University of Cape Town and the other reference tests were performed by LNEC in Lisbon, Portugal.

In the following sections, results obtained with the reference tests are discussed to compare the performance of the South African DI methods with other test

methods. Included in the discussion are results obtained 'in situ' with the Torrent permeability tester as this method represents one of the internationally accepted in-situ procedures for the testing of oxygen penetrability.

TEST METHODS

In the following, the basic principles of the experimental methods that were used in the comparative tests are briefly discussed.

Oxygen permeation tests

Permeation is the process of movement of fluids or gases through the concrete pore structure under an externally applied pressure whilst the pores are saturated with the particular fluid or gas. Permeability is therefore a measure of the capacity for concrete to transfer fluids or gases by permeation. The permeability of concrete is dependent on microstructure, moisture condition of the material, and characteristics of the permeating agent. For the testing of concrete properties, permeation characteristics are commonly identified measuring gaseous flow through a specimen under an externally applied pressure gradient. In terms of durability specifications, gas permeability characteristics are used in predicting the ingress of carbon dioxide into concrete members.

Oxygen permeability index test, OPI

The South African oxygen permeability index (OPI) test method comprises measuring the pressure decay of oxygen passed through a concrete disk (typically 68 mm diameter by 25 mm thick) placed in a falling head permeameter. A pressure gradient is applied across the test specimen and subsequently the pressure decay in the pressure cell is monitored over time (figure 2). Prior to testing, samples are preconditioned by oven-drying at 50 °C for a period of seven days.

Cembureau permeability test

In the Cembureau method, unidirectional gas flow between two parallel surfaces of the test specimen (typically 150 mm diameter by 50 mm thick) is caused by a constant absolute pressure difference of the test gas between the two surfaces (Kollek 1989). Therefore, in contrast with the OPI test method, the Cembureau method measures the gas flow through the concrete sample under a constant pressure gradient. The schematics of the two test methods are presented in figure 2. In both methods, the gas flow depends on the pressure difference, testing area, specimen thickness and open porosity, and the viscosity of the test gas.

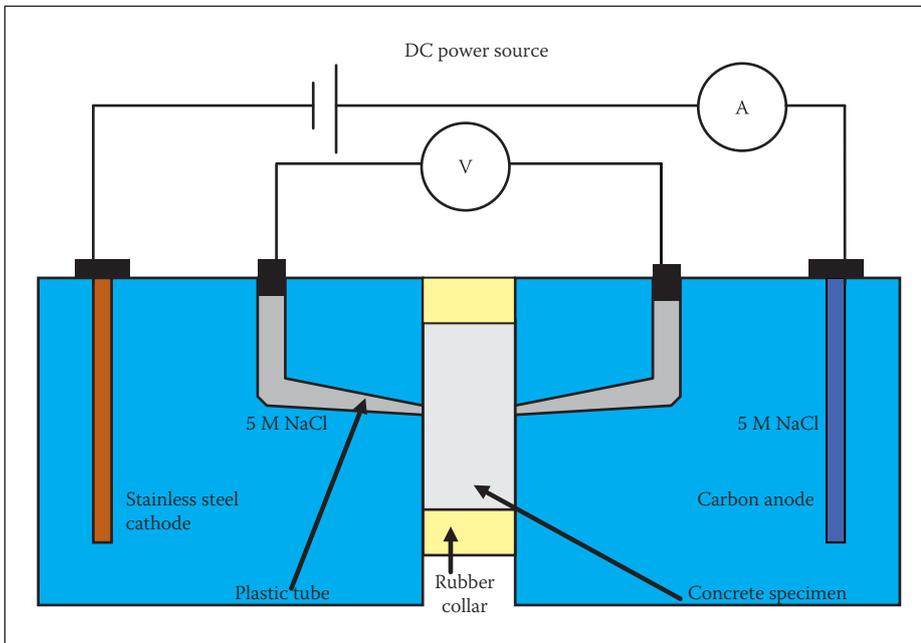


Figure 5 Schematic of the chloride conductivity index test

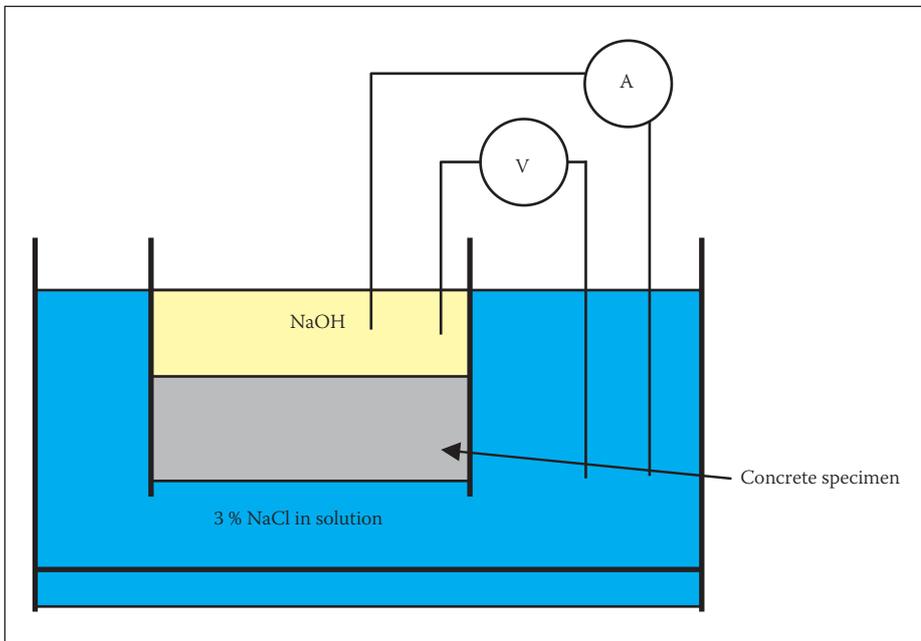


Figure 6 Schematic of the rapid chloride permeability test ASTM C 1202

Torrent permeability test, TPT

In some European countries, oxygen permeability characteristics are determined in situ using the Torrent permeability tester, TPT (Torrent 1992). The characteristic features of the TPT test equipment are a two-chamber vacuum cell and a regulator that balances the pressure in the inner (measuring) chamber and the outer (guard-ring) chamber (figures 3 and 4). The outer guard ring prevents air from the surrounding areas from flowing into the pressure measurement chamber, which would influence the test results. During the test, the cell is placed on the concrete surface and a vacuum is produced with the pump. Owing to the external atmospheric pressure and the rubber rings the cell is pressed against the surface and thus both chambers are sealed. The rate at

which the pressure rises in the inner chamber is recorded and this rate is related to the permeability of the underlying concrete. This test was recently adopted in the recommendations of the new Swiss Standard SIA 261/1: 2003 on 'Concrete Structures' (Swiss Standard SIA 262 2003).

Chloride penetration tests

Chlorides are able to enter the concrete microstructure in three main ways, namely capillary absorption, permeation, and diffusion. Of these, diffusion is the primary means of ingress and might easily allow ions to reach the level of the reinforcing steel within the life span of the structure. Diffusion is the process by which liquid, gas or ions move through a porous material under the action of a concentration gradient.

It occurs in partially or fully saturated concrete and is an important internal transport mechanism for most concrete structures exposed to salts, for example in the marine environment. High surface salt concentrations are initially developed by absorption, and the salt migrates by diffusion towards the low concentrations of the internal material. This salt migration process can be seen as diffusion of chloride ions. As diffusion is a slow process, rapid chloride tests have been developed to accelerate the diffusion process. Most of these methods rely on electrical acceleration of the ions.

Chloride conductivity test

The South African chloride test involves the measurement of a sample's electric conductivity. A concrete specimen (typically 68 mm diameter by 25 mm thick) is dried in an oven and vacuum pre-saturated with a 5 M NaCl solution. A conduction cell is used, in which the sample is placed between two cells containing 5 M NaCl solution (figure 5). A potential difference is applied across the sample, causing a movement of chloride ions, and the corresponding current is used to calculate the concrete's conductivity, which in turn can be related to the concrete's resistance to chloride ingress. This procedure gives an instant reading.

Rapid chloride permeability test ASTM C 1202

The North American rapid chloride permeability test according to ASTM C 1202-97 (ASTM 1997) involves placing a water-saturated 50 mm thick 95 mm diameter sample in a migration cell and applying a 60 V DC current for six hours (figure 6). One cell of the migration device is filled with 3,0 % NaCl solution and the other with 0,3 M NaOH solution, creating a chloride concentration difference between the two exposed faces of the sample. The total charge passed is then determined and used to give a concrete rating. In this method, ionic flux is caused by both diffusion and conduction, as opposed to the South African chloride conductivity test, which is solely based on the conduction of chloride ions.

Bulk diffusion test (NordTest NTBuild)

In this Scandinavian test (NTBuild 492 1999), samples are saturated with limewater and then sealed on all sides except the top face, and submerged in a 2,8 M NaCl solution (figure 7), for a minimum of 35 days. After this time chloride profiling is done, by grinding off 0,5 mm portions of the sample and measuring the amount of chlorides at different depths. The chloride concentration profile is then used to determine the

Table 2 Compared sets of concretes, expected penetrability rating, and significance of test methods (++) highly significant, + significant, o not significant, -- wrong)

Transport mechanism investigated	Compared sets	1-2	2-3	1-3	4-5	2-6
	Variable tested	w/b	w/b	w/b	w/b	Curing
		OPC	OPC	OPC	OPC/slag	
	Expected penetrability rating	2 > 1	3 > 2	3 > 1	5 > 4	6 > 2
Test	Differentiation capability (significance)					
Gas permeability	Coefficient of O ₂ permeability (Cembureau) (Kollek 1989)	++	++	++	++	++
	Coefficient of O ₂ permeability (South Africa, OPI test)	++	++	++	++	++
	Torrent permeability tester, TPT (Torrent 1992)	++	++	++	o	++
Chloride ingress	ASTM C1202 – Cl ⁻ electromigration	++	++	++	++	++
	Cl ⁻ electromigration BT – ‘diffusivity’ (NTBuild 1992)	++	++	++	+	++
	Chloride conductivity (South Africa)	++	++	++	++	++
Water penetrability	Absorption rate and 24h absorption (RILEM 1999)	++	++	++	++	++
	Water sorptivity (South Africa)	++	--	++	+	o

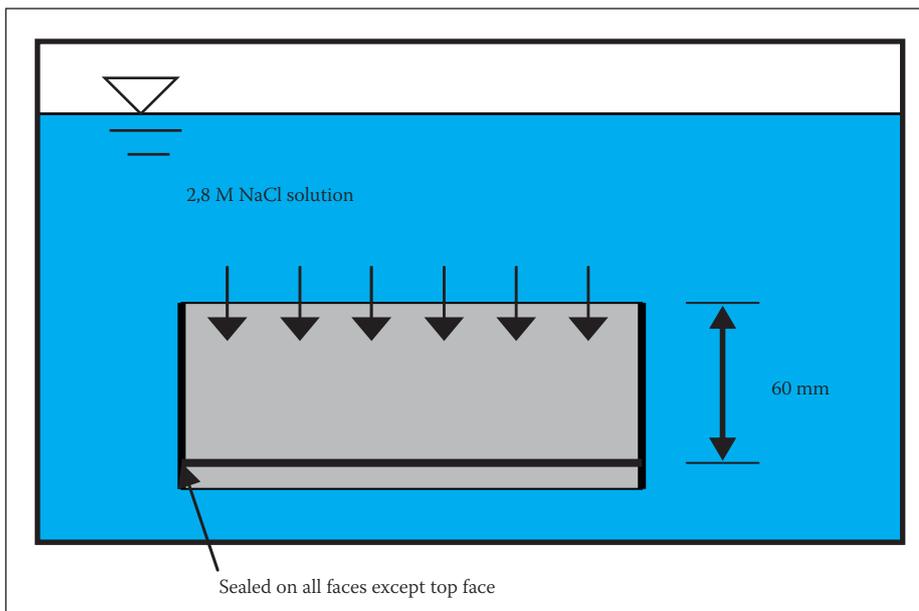


Figure 7 Schematic of the bulk diffusion test (NordTest NTBuild)

diffusion value and surface concentration. The bulk diffusion test is considered the most fundamental test and is not affected by the unknown implications of using an electrical field to accelerate the diffusion process, as done in the tests described above. As the test is time consuming it is generally not suitable for quality control purposes. However it has been used to calibrate most other test methods.

Water penetration tests

Absorption is the process whereby fluid is drawn into a porous, unsaturated material under the action of capillary forces. Water absorption caused by wetting and drying at

the concrete surface is an important transport mechanism in near-surface regions. The rate of movement of a wetting front through a porous material under the action of capillary forces is defined as sorptivity.

Both the South African water sorptivity index test and the method for determination of the capillary absorption of water of hardened concrete suggested by RILEM (RILEM TC116-PCD 1999) are based on measuring the unidirectional ingress of water into a preconditioned concrete sample. For this, the concrete samples are sealed on the circumferential surfaces and exposed to a few millimetres of water with the test surface facing downwards. Both methods measure

the mass change of the specimens over time, determining the amount of water absorbed into the concrete. The difference between the two methods lies in the analysis of test results. In the RILEM method, test results are expressed in terms of mass of water absorbed over test area and time (kg/m²/√h). In the water sorptivity index method, the porosity of the sample is considered in the analysis to establish the rate of water sorption, that is, the speed at which water is absorbed into a certain depth of the member, resulting in the unit (mm/√h). The South African test effectively normalises the results for porosity, and at the same time provides a useful measure of concrete porosity.

EXPERIMENTAL RESULTS

Ability of test method to differentiate between different parameters

The object of the comparative testing was to determine whether the tests designed to measure the penetrability of the concrete cover are capable of detecting differences in w/b ratio, binder type, and curing condition. Statistical analysis was applied to establish if a certain method was able to differentiate between mixes on a ‘highly significant’, ‘significant’, or ‘non-significant’ level (Romer & Fernández Luco 2005; Torrent & Fernández Luco 2007). If the results were in reverse order than expected, the response of the test was deemed ‘wrong’. Details on the statistical procedure used are presented in (Torrent & Fernández Luco 2007). Test results are presented in table 2.

For measurements of gas permeability and chloride ingress, the results obtained with the reference tests were very consistent. With just a few exceptions, the tests managed to differentiate between different mixes at a highly significant level. Similarly, the TPT method was able to differentiate between the mixes on a highly significant level, the only exception being the slag concrete. It can thus be concluded that the methods investigated facilitate the assessment of concrete cover quality and are valuable for specification and prediction of concrete durability both in terms of gas permeability and chloride ingress.

Note that for the evaluation of the OPI test the actually measured coefficient of permeability k (m/s) was used, not the OPI value commonly applied in durability specifications. The OPI value, used for its practical convenience, is the negative logarithm of the k value and therefore yields less significant numerical differences between different concretes. For example, a k value of 5×10^{-11} corresponds to an OPI value of 9,00 while a 20

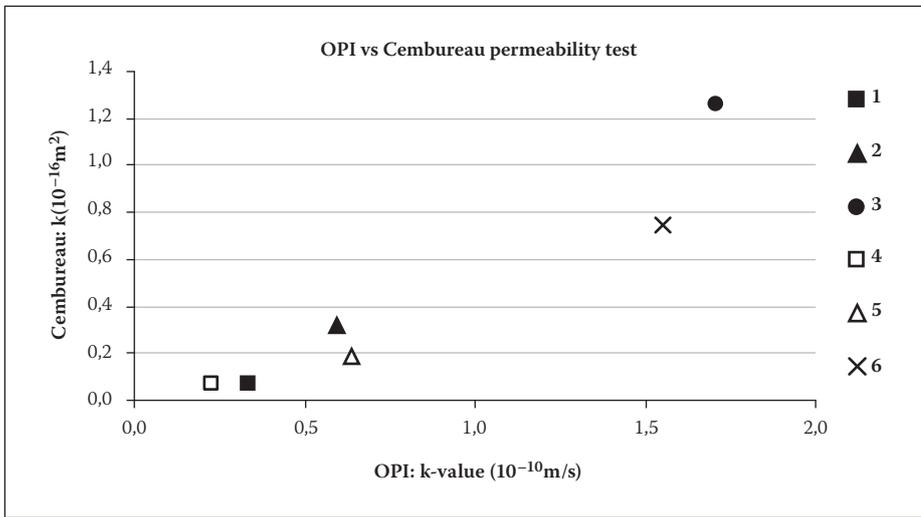


Figure 8 Correlation between test results obtained using the OPI method and the Cembureau method

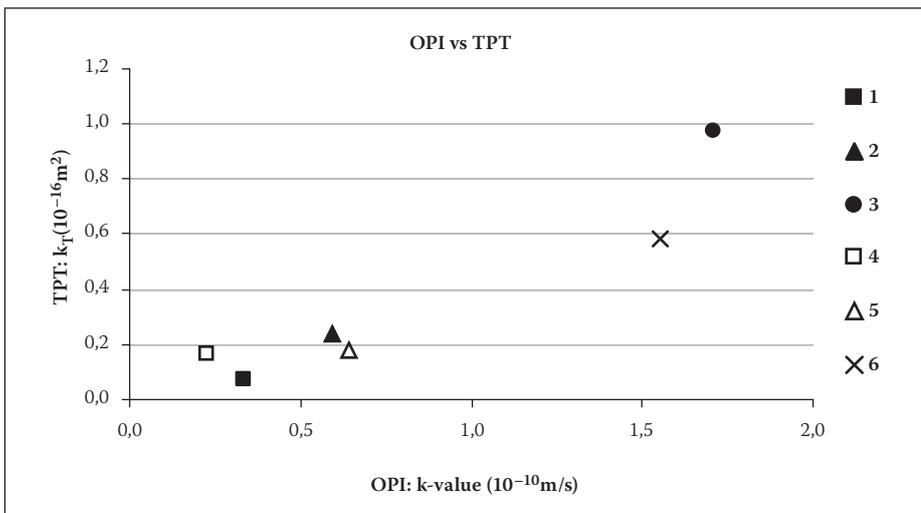


Figure 9 Correlation between test results obtained using the OPI method and the torrent permeability tester, TPT

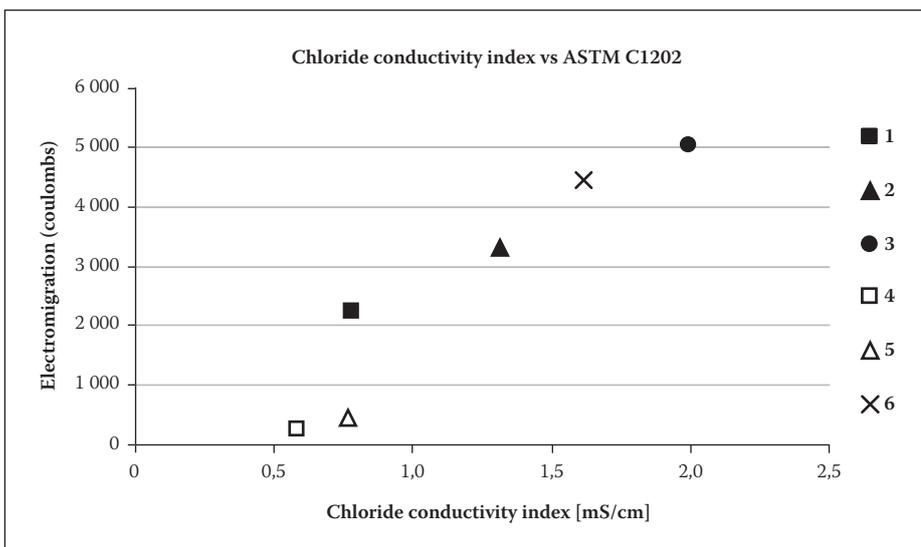


Figure 10 Correlation between test results obtained using the chloride conductivity index method and the rapid chloride permeability test ASTM C 1202

times higher k value (1×10^{-9}), indicating a concrete 20 times as permeable, corresponds to an OPI value of 10,30. The statistical significance of different permeability values can therefore better be evaluated using the coefficient of permeability k .

For the measurement of water penetrability, the RILEM method was successful, for all test parameters in differentiating between mixes at a highly significant level. By contrast, the water sorptivity index test method failed to yield satisfactory results.

This was largely due to an abnormal value obtained for test condition 2 (OPC concrete, $w/b = 0,55$), which conflicted with the comparison between test conditions 2 and 3, as well as 2 and 6. The abnormal water sorptivity values obtained for test condition 2 could not be explained, and are generally not consistent with other experience with this test.

Correlations between different test methods

To compare the test results obtained with different methods it is best to consider specimens of the same 'group', for example Specimens 1, 2, and 3 (w/b ratios of 0,40, 0,55, or 0,60, respectively; same curing conditions (seven-day water cured), same binder type (OPC)), or Specimens 4 and 5 (w/b ratios of 0,40 or 0,55, respectively; same curing conditions (seven-day water cured), same binder type (OPC / GGBS)). Specimen 6 should be compared to Specimen 2 (same w/b and binder, different duration of curing (one and seven days, respectively)). In basic terms, a good correlation exists between different test methods if the curve produced from all single comparisons, for a certain parameter, is near linear. This can be investigated by comparing results for Specimens 1, 2, and 3 (at least three results are needed to draw a relevant correlation curve).

The correlations between the oxygen permeation test results obtained using the OPI test and the Cembureau permeability test / the TPT method were very good (figures 8 and 9 – near linear relationship for Specimens 1, 2, and 3), indicating that all of these common methods have similar merit in assessing concrete cover quality. The three methods use the same basic principle of applying a pressure gradient to a concrete specimen and measuring the resulting flow of gas through the specimen. Differences in sample preconditioning, pressure application (positive or negative pressure, constant or decaying pressure), magnitude of initial pressure applied, test duration, and specimen size did not result in significant differences in the experimental outcome.

Similarly, the cross-correlations between the various methods for testing the likelihood of chloride ingress were very good (figures 10 and 11 – near linear relationship for Specimens 1, 2, and 3). The three methods that were investigated use fundamentally different test philosophies and are based on different electrochemical and physical transport mechanisms. It is interesting to observe that all these methods nonetheless result in comparable results and that they have similar merit in assessing the quality of the concrete in salt-rich environments.

CONCLUSIONS

The test results indicate that the South African chloride conductivity and oxygen permeability test methods are generally successful in evaluating concrete durability characteristics and have similar merit in establishing material properties as other internationally accepted methods. Results obtained with these DI test methods can be directly compared to results obtained with test methods used overseas. This facilitates the exchange of knowledge and experience between the South African and international concrete industries. In view of international specifications this can help in establishing correlations between local and international durability prediction and service life design models. This in turn can greatly assist in the efforts to establish reliable prediction models for the durability of concrete structures.

The water sorptivity index test did not perform as expected and failed to reliably differentiate between certain concrete mixes. A comparison between local and international test methods for water absorption based on the discussed test programme was therefore difficult. Further work is necessary to clarify this aspect.

Future efforts should aim at establishing a reliable correlation between South African and international durability test methods for a range of concrete mixes. Through utilisation of international research data this would enhance the locally available pool of information for concrete specification and service life modelling.

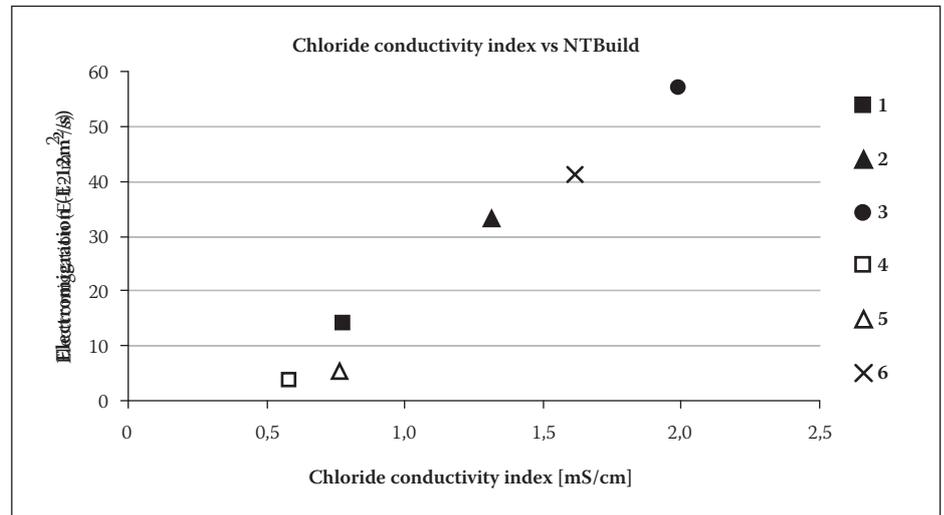


Figure 11 Correlation between test results obtained using the chloride conductivity index method and the bulk diffusion test (NordTest NTBuild)

REFERENCES

- Alexander, M G *et al* 1999–2003. Series of monographs published by University of Cape Town and the University of the Witwatersrand.
- Alexander, M G and Beushausen, H 2007. Performance-based durability design and specification in South Africa' *Proceedings International Concrete Conference and Exhibition ICCX Cape Town*, January.
- ASTM C 1202 2007. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. USA: ASTM.
- Kollek, J J 1989. The determination of the permeability of concrete to oxygen by the Cembureau method - a recommendation. *Materials & Structures*, 22(129):225-230.
- NTBuild 492 1999. Chloride migration coefficient from non-steady state migration experiments. *Nordtest*, Espoo, Finland.
- RILEM TC116-PCD (Permeability of Concrete as a Criterion of its Durability) 1999. Recommendations, 'Determination of the capillary absorption of water of hardened concrete'. *Materials and Structures*, 32(4):178-179.
- Romer, M and Fernández Luco, L 2005. RILEM TC 189-NEC, Non-destructive evaluation of the concrete cover: Comparative test - Part I: Comparative test of 'penetrability' methods. *Materials & Structures*, 38(284):895 - 911.
- Swiss Standard SIA 262:2003. Concrete structures. Switzerland.
- Torrent, R 1992. A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site. *Materials & Structures*, 25(150):358-365.
- Torrent, R and Fernández Luco, L 2007 (eds). *Non-destructive evaluation of the penetrability and thickness of the concrete cover. State-of-the-art report of RILEM TC 189-NEC*. Bagneux, France: RILEM.