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Performance-based Testing Methodology for Concrete Durability

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**PERFORMANCE-BASED TESTING
METHODOLOGY FOR CONCRETE DURABILITY**

RILEM TC-PSC MEETING

TOULOUSE, FRANCE

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by

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1 INTRODUCTION

This report presents an overview of performance based testing methodology for concrete durability and work currently underway jointly at Queens University Belfast and Heriot Watt University, Edinburgh, to undertake this research under a EPSRC funded project (EP/G02152X/1).

EN206-1 superseded BS 5328 on 1st December 2003 and allows designers and producers to use a wide range of cements and aggregate types for a variety of exposure conditions. In this new standard, the durability of concrete is specified in terms of the constituent materials of concrete, properties of fresh and hardened concrete, limitations for concrete composition, specification of concrete, delivery of fresh concrete, production control procedures, conformity criteria and evaluation of conformity and verification of these properties. Within this, six basic forms of exposure is also specified, namely XO (no risk of corrosion), XC (Corrosion induced by carbonation), XF (Freeze / thaw attack), XS (Corrosion induced by chlorides from seawater), XD (Corrosion induced by chlorides other than from seawater) and XA (Chemical attack).

According to EN206-1, the performance method adopted should be based on satisfactory experience with local practices in local environments from data obtained from an established performance test method for the relevant mechanism, or using appropriate proven predictive models. Therefore, the methods that may be used include those methods based on:-

- long-term experience of local materials and practices and on detailed knowledge of the local environment.
- approved and proven tests that are representative of actual conditions and have approved performance criteria.
- analytical models that have been calibrated against test data representative of actual conditions in practice. The concrete composition and the constituent materials should be closely defined to enable the level of performance to be maintained.

In order to determine the best methods for assessing concrete durability for performance, it is important to review those methods which have been developed and used in Queens University Belfast and Heriot Watt University to test for permeability, diffusion and absorption as well as electrical methods used to assess if the performance criteria have been achieved in structures using non-destructive testing methods.

Prior to specifying durability performance testing methods, a review of previous projects where limits on permeability, diffusion, electrical resistivity etc, are presented along with the various durability tests used to assess these limits. The examples given are from a number of projects in the UK, Ireland and Europe of varying complexity and size. Due to the relatively small number of such examples in the UK and Ireland, the need for the research presented here is further justified.

The proposed experimental work for the EPSRC project is presented which includes a breakdown of the concrete samples, tests and details of a new marine exposure site on the Northwest coast of Ireland.

Based on the findings of this experimental work and the numerical calibration using the ClinConc model, development of a methodology for testing the concrete durability to assess the performance limits set will be determined. Through this work, the performance methods adopted will satisfy the EN206-1 guidelines above.

2 REVIEW OF EN206-1

2.1 Introduction

In December 2003, EN206-1 Concrete (2000) was launched to supersede the previous standards (BS 5328, 1997) to specify concrete. Concrete designers, producers and users alike now have the opportunity to use a wide range of cement and aggregate types for concretes in various exposure classes. The new code applies to in-situ and precast concrete structures and specifies constituents materials of concrete, properties of fresh and hardened concrete and verification of these properties using appropriate tests (Annex J) for which the EPSRC project is concerned. BS EN 206-1 (2000) now specifies concrete based on its performance against specific deterioration mechanisms as opposed to the prescriptive approach up to now.

In addition, limitations for concrete composition, specification of concrete, delivery of fresh concrete, production control procedures and conformity criteria and evaluation of conformity are also included.

The new exposure class contains six basic forms of exposure, which are also sub-divided as shown:

X0 (No risk of corrosion)

XC (Corrosion induced by carbonation)

- XC1 Dry or permanently wet
- XC2 Wet, rarely dry
- XC3 Moderate humidity
- XC4 Cyclic wet and dry

XS (Corrosion induced by chlorides from seawater)

- XS1 Exposed to air-borne salt
- XS2 Permanently submerged
- XS3 Tidal, splash and spray zones

XD (Corrosion induced by chlorides other than from seawater)

- XD1 Moderate humidity
- XD2 Wet, rarely dry
- XD3 Cyclic wet and dry

XF (Freeze / thaw attack)

- XF1 Moderate water saturation without de-icing agent
- XF2 Moderate water saturation with de-icing agent
- XF3 High water saturation without de-icing agent
- XF4 High water saturation with de-icing agent or sea water

XA (Chemical attack)

- XA1 Slightly aggressive environment
- XA2 Moderately aggressive environment
- XA3 Highly aggressive environment

2.2 Complementary British Standard BS8500 to BS EN 206-1

BS8500 (2006) has been produced as a complementary to EN206-1 (2000) to ease the turnover to EN206-1 (2000) and contains UK provisions on materials, methods of testing and procedures that are outside the scope of EN206-1 (2000) but within UK national experience. For a short period, until Eurocode 2 (2001) replaces the BS 8110 (1997) series, BS 8500 (2006) has to be used with

BS 8110 (1997). Therefore, one has to observe some practical differences in terms of the exposed conditions, where BS 8500 has less onerous requirements. For more severe exposed conditions, the requirements are different and reference may well have to be made to the full BS 8500 standard.

Also, while BS EN 206-1 gives guidance for CEM I concrete, the more comprehensive BS 8500 also includes additional cements (CEM II, III and IV) and provides a flexible trade-off between cover depth and concrete quality.

2.3 Draft Irish National Annex to EN206-1

In December 2003, the Irish Standard for Concrete (IS 326 Part 2(1), 1995) was replaced by the new European Standard IS EN 206-1 (2003). The Irish version comprises the core text of the European standard EN 206-1 (2000), along with the Irish National Annex.

Ireland, compared to other countries in Europe, has substantially more resources per capita of the constituent materials which go into the manufacture of concrete. For this reason concrete is produced on a local basis and generally delivered within a radius of 30 miles.

IS EN 206-1 (2003) is the only current national Irish standard for concrete specification and production since December 2003. Concrete producers are in the process of adapting their quality and production control systems to become fully compliant with the requirements of IS EN 206-1 (2009). Designers and users are required to specify concrete in accordance with the requirements of IS EN 206-1 (2003), to ensure uniformity and clarity in the full construction process. Structural design will continue to be guided by the existing design standards (IS 326/BS8110 etc.) and some disparities may occur in the interim period.

By way of example, Table 2.1 presents a comparison between the grade of concrete, w/c ratios and minimum cement contents between BS 8110, BS 8500 and the draft Irish National Annex for the carbonation exposure class by way of example for typical cover depths. As may be observed, the main differences between the recommendations are the strengths of concrete with relative agreement between the w/c ratios and minimum cement content.

2.4 References

British Standard Institute (2000) Concrete: Specification, performance, production and conformity, BS EN 206 Part 1

British Standards Institute (1997) Guide to specifying concrete, BS 5328: Parts 1 and 2

British Standard Institute (2006) Concrete: Complementary British Standard to BS EN 206-1, BS 8500

Comité Européen de Normalisation (2001) European 2: Design of Concrete Structures, General Rules for Buildings, prEN1992-1-1.

British Standards Institution (1997) Structural use of concrete: Code of practice for design and construction, BS 8110-1

National Standards Authority of Ireland (1995) Concrete: Guide to Specifying Concrete, IS 326: Part 2.1.

Irish Concrete Federation IS EN 206-1 Summary Documents - Section 8 Guidance on the Application of EN 206-1 Conformity Rules, ICF Technical Committee, 2003.

Table 2.1 Exposure classes, descriptions and examples of exposures for Carbonation durability

Exposure Class BS 8500	Exposure Class BS8110	Cover (mm) assuming a Δc of 5mm	BS8110 (1997) Table 3.3	Draft Irish National Annex values	BS8500 Table A.4
XC1	Mild	25	C30/37 0.65 275	C25/30 0.65 280	C20/25 0.70 240
		30			
		35			
		40			
			↓	↓	↓
XC2	Moderate	25	C45/55 0.50 350	C32/40 0.5 340	NA
		30	C40/55 0.55 325	C28/35 0.6 300	C25/30 0.65 260
		35	C35/40 0.60 300	C25/30 0.65 280	
		40	C35/40 0.60 300	↓	↓
XC3	Moderate	25	C45/55 0.50 350	C35/45 0.5 360	C40/50 0.45 340
		30	C40/55 0.55 325	C30/37 0.55 320	C30/37 0.55 300
		35	C35/40 0.60 300	C28/35 0.6 300	C28/35 0.60 280
		40	C35/40 0.60 300	C25/30 0.65 280	C25/30 0.65 260
XC4	Severe	25	C50/65 0.45 400	C40/50 0.45 400	NA
		30	C45/60 0.50 350	C35/45 0.5 360	C40/50 0.45 340
		35	NA	C30/37 0.55 320	C30/37 0.55 300
		40	C40/55 0.55 325	C28/35 0.6 300	C28/35 0.60 280

3 EXAMPLES OF PROJECTS WITH PERFORMANCE LIMITS FOR CONCRETE DURABILITY

This section will present examples of performance based specifications for concrete durability used on recent projects in the UK, Ireland and Europe. The amount of literature in this area is relatively scarce, which further highlights the needs for research into this area. Table 3.1 gives examples of performance requirements for these projects including tunnels, viaducts, bridges and marine structures.

As shown in Table 3.1, there are more examples of projects using Performance based specifications in Europe than in the UK or Ireland (AFGC, 2007). However, there is a move toward this approach in these areas. The shaded area in Table 3.1 represents the historic prescriptive approach to concrete durability where the concrete type, binder, maximum w/c ratio and minimum cement contents are specified. However, as shown, as well as the prescriptive approach, the performance of the concrete has been specified in terms of the water porosity, water and gas permeability, chloride and oxygen diffusion coefficient and electrical properties.

Other projects such as the Oresund-link Tunnel between Denmark and Sweden also specifies the gas permeability, chloride diffusion coefficient and the electrical properties of the concrete. Also, the Confederation bridge in Canada and the Rion-Antirion Bridge in Greece gives performance criteria for the concrete in terms of the electrical properties.

Table 3.2 outlines the tests performed to assess if these limits have been met for some of the projects listed (AFGC, 2007). As shown, some of the test methods to assess the specification set vary from project to project for the same property being tests. This need for a standard test method for whatever property is being assessed is the aim of the EPSRC project described here to be inserted into the UK and Irish National Annexes.

In Ireland, examples of performance specifications are few but recent additions of ggbs for example is now specified by the National Roads Authority there to improve the durability and the life expectancy of bridges. Performance criteria for a harbour project near Dublin are shown in Table 3.3, where, for the various cements types used, the ranges of acceptable diffusion rates are indicated. Other examples of this type of performance criteria are found in projects including bridges, marine projects, basement structures, multi-storey car-parks and water and wastewater plants.

RILEM reported a review of common tests that measured various concrete durability transport properties (TC 116-PCD, 1999), namely gas and liquid permeability, capillary absorption of water and chloride ion ingress. Using a selection of frequently used methods for these properties suitable for laboratory and on-site testing, an evaluation of the suitability and range of applicability was made, along with proposing improvements and correlating the measured transport parameters for durability characteristics. The transport coefficients investigated are being used as criterion for concrete durability at an early age (during pre-testing of concrete mixes) and routine testing in production control, as well as on material coefficients for numerical modelling.

The experimental programme involved preconditioning of the samples, inter-comparison testing (stages I and II) and evaluation of test methods and durability characteristics.

The tests undertaken in this study are listed below for the various durability properties:

Gas permeability

- Cembureau method
- Schonlin laboratory method
- Bore holes methods (Parrott, Paulman & Figg)

Table 3.1 Examples of engineering projects with performance based criteria for durability (AFGC, 2007)

Structure	Channel Tunnel (UK-France)	Vasco da Gama Bridge, Lisbon - Portugal	Medway Viaduct (UK)	Millau Bridge (France)	Extension of Condamine Port floating dyke (France)
Construction Period	1987-1992	1995-1998	1998-2001	2002-2004	1999-2002
Specified service life	120 years	120 years	100 years	120 years	100 years
Concrete Type	B45 & B55	B40, B45 and B50	C40 to C60	B60	B54, B65
Type of Binder	CEM I PM (additions permitted)	PM (seawater) cement containing FA	CEM I + slag or CEM I + FA	CEM I 52.5 N PM ES CP2 – no additions	CEM I PM (seawater) + FA + SF
Max w/c ratio	0.32	0.33 to 0.42	0.45 - 0.50	Max. 0.45 W_{eff}/c 0.335	0.35
Min. Cement (kg/m ³)	400 for 425 requested	400	-	420	-
Min. Cement and additions (kg/m ³)	-	-	325 to 350	-	425
Aggregates	NR	NR	-	Class A, NR	Class A, NR
Water porosity	-	-	-	11-13 (piers)	< 12 (B54) < 10 (B65)
Water Permeability (m/sec)	< 10 ⁻¹³	-	-	-	-
Gas Permeability (m ²)	-	< 10 ⁻¹⁷ (at 28 days)	-	<10 ⁻¹⁷ (at 90-days)	< 10 ⁻¹⁶ to 10 ⁻¹⁷ (28-days 80°C drying)
Apparent Chloride Diffusion Coeff.(m ² /sec)	-	< 10 ⁻¹² (at 28-days)	< 10 ⁻¹²	<10 ⁻¹² (at 90-days)	<5x10 ⁻¹² (B54) <1x10 ⁻¹² (B65)
Oxygen Diffusion Coeff.(m ² /sec)	-	-	<5x10 ⁻⁸	-	-
Quantity of electricity (coulombs)	-	<1500 at 28-days < 1000 at 90-days	-	-	100-1000 (B65), 1000-2000 (B54)

Table 3.2 Description of tests used to assess if the performance limits shown in Table 3.1 were met (AFGC, 2007)

Project	Property	Specified durability property	Description of tests	Results
Channel Tunnel	Water permeability (m/sec)	$< 10^{-13}$	Water permeability tests measuring the depth of ingress of water	$0.6-0.7 \times 10^{-13}$ m/sec at 50-days. 1.4×10^{-13} m/sec at 8 months
Vasco da Gama Bridge	Gas Permeability (m^2)	$< 10^{-17}$ at 28 days	Cembureau method	$0.7-0.3 \times 10^{-17}$ m^2 between 28 and 90days. $\leq 0.01 \times 10^{-17}$ m^2 at 18 months
	Apparent Chloride Diffusion Coeff. (m^2/sec)	$< 10^{-12}$ at 28-days	Migration test in non-steady state conditions	$1-4 \times 10^{-12}$ m^2/sec between 28 and 90 days. $0.2-0.8 \times 10^{-12}$ m^2/sec at 18 months
	Quantity of electricity (coulombs)	< 1500 at 28-days < 1000 at 90-days	AASHTO test (ASTM Standard C1202.	
Extension of Condamine Port floating dyke	Water porosity	< 12 (B54) < 10 (B65)	Mercury Intrusion (water porosity). AFPC-AFREM procedure (mercury porosity)	8.8 - 9.4 5.8 - 5.6
	Gas Permeability (m^2)	$< 10^{-16}$ to 10^{-17} (28-days $80^{\circ}C$ drying)	AFPC-AFREM Test procedure	5.54×10^{-19} to 1.25×10^{-18}
	Apparent Chloride Diffusion Coeff. (m^2/sec)	$< 5 \times 10^{-12}$ (B54) $< 1 \times 10^{-12}$ (B65)	Non-steady state (Tang Method)	
	Quantity of electricity (coulombs)	100-1000 (B65), 1000-2000 (B54)	AASHTO test (ASTM Standard C1202.	377 - 401

Table 3.3 Specified diffusion limits for various concrete types in a harbour project in Ireland. Similar limits are used for other projects such as bridges, basements, car-parks and water and waste-water plants.

Cement Type	Diffusion Coefficient (m^2/sec)
CEM I	$7-18 \times 10^{-12}$
CEM II/A	$7-17 \times 10^{-12}$
CEM II/B	$5-10 \times 10^{-12}$
CEM III/A	$2-5 \times 10^{-12}$
CEM III/B	$0.9-3.5 \times 10^{-12}$

Capillary suction

- Ponding test
- RILEM method
- ISA test
- Figg water absorption method

Chloride ingress

- Migration tests
- AASHTO test
- Immersion

The conclusions from this review recommended that the Cembureau method be used for measuring the gas permeability as it was found to be very reliable, easy to handle with good repeatability. The Bore methods were found to frequently fail due to leakage. In terms of capillary absorption, the modified Fagerlund test was recommended as again it was found to be easy to conduct and the results showed very little scatter. However, despite the three tests used, a recommendation to measure the chloride ion diffusion could not be made.

In terms of the air and water permeability, the AutoCLAM apparatus (developed in Queens University) provides a quick and simple non-destructive test that can be easily set-up on any concrete element on site where results can be obtained for each property after 15minutes (see section 4.3) and has shown to give good repeatability and the results showed little scatter.

As stated above, RILEM were unable to recommend a suitable test to measure the chloride ion diffusion test. For this, the PERMIT (developed in Queens University) (see section 4.5) apparatus is a non-destructive test which is easily conducted on site with good repeatability.

Work is underway at Queens University Belfast and Heriot-Watt University on an EPSRC project (EP/G02152X/1) to develop a performance-based testing methodology for concrete durability. As part of this, Heriot Watt University will conduct early age electrical responses in the plastic state and Queens will monitor durability performances in the hardened state using the AutoCLAM and PERMIT apparatus. Electrical methods using embedded arrays will also be undertaken in Queens for measurement of the advancing chloride front which have been developed in Heriot-Watt University. This is outlined in Figure 3.1 below. The aim of this research is to specify which non-destructive method should be used on in-situ and precast concrete to assess limits like those shown in Table 3.1 above in practice subject to various exposures in a marine environment for inclusion in the UK and Ireland National Annexes to EN206-1. These tests will satisfy the requirements in EN206-1 for these tests.

Therefore, a number of concrete samples will be cast and tested in the laboratory and in the field at a new exposure site on the Atlantic Coast of Ireland. More on this experimental work is discussed in Section 5.

3.1 References

Association Francaise de Genie Civil (2007) Concrete design for a given structure service life, Scientific and technical documents

RILEM TC 116-PCD (1999) Recommendation of TC 116-PCD: Tests for gas permeability of concrete - Preconditioning of concrete test specimens for the measurement of gas permeability and capillary absorption of water - Measurement of the gas permeability of concrete by the RILEM - CEMBUREAU method - Determination of the capillary absorption of water of hardened concrete, Materials and Structures, Vol. 32, No. 217.

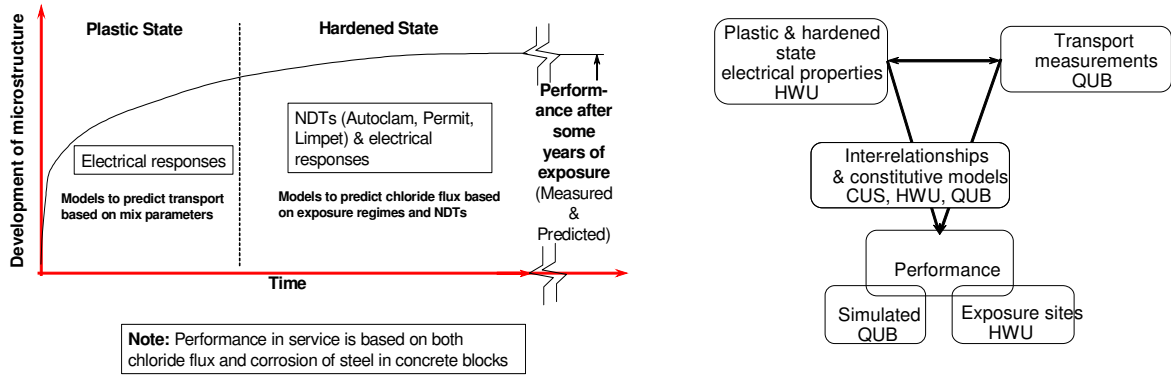


Figure 3.1 Outline of current EPSRC project between Queens University Belfast and Heriot Watt University

4 EXAMPLES OF NON-DESTRUCTIVE DURABILITY TESTS USED TO ASSESS CONCRETE DURABILITY

4.1 Introduction

This section presents a review of the most common non-destructive tests in use to assess concrete durability parameters, such as absorption, permeability (air, gas and water) and migration-based tests.

4.2 Methods for measuring permeation properties

The following are the main transport processes by which the movement of aggressive substances takes place in concrete:

- Adsorption - the process by which molecules adhere to the internal surface of concrete. It can be either by physical forces of adhesion or as a result of chemical bonds.
- Absorption - the process by which concrete takes in liquid by capillary suction to fill the pore spaces available. The rate at which liquid enters the pores is termed as sorptivity.
- Diffusion - the process by which a gas or ion penetrates into the concrete under the action of a molar concentration gradient. It is generally defined by a diffusion coefficient or a diffusivity value.
- Permeability - the property of concrete that describes the resistance to a fluid (liquid or gas) penetration under the action of a pressure gradient. The rate of transport is normally expressed by a coefficient of permeability.

By measuring the permeation properties of concrete, such as absorption, diffusion and permeability, the quality of concrete against the ingress of harmful substances can be assessed. As diffusion is a slow process and determining the diffusion coefficient could take several months, an alternative method of accelerating the flow of ions through concrete by the application of a potential has been developed, which is termed as migration tests. The diffusivity of concrete determined by migration tests conform to the diffusivity obtained from the laboratory-based diffusion tests. Therefore, migration tests which can be performed on site are also included in this section along with other test methods which assess the permeation properties of concrete. A summary of the most common permeation methods suitable for on-site measurement is described below.

4.3 Absorption tests

Initial surface absorption test (ISAT)

In this test the rate of penetration of water into a defined area of concrete (5000mm²) after intervals of 10, 30 and 60 min at a constant water head (200mm height) and temperature (20^oC) is measured. There are specifications for preparing the test area, initial moisture condition, surface area to be in contact with water and the time at which measurements have to be taken. The guidelines on the test method, calibration and sample preparation are available in BS 1881: Part 208 (1996). The main advantage of this test is that it is a quick and simple non-destructive in situ test for measuring the water penetration into a concrete surface. This test method provides reasonably consistent results on oven dried samples. The limitations of this test include the difficulty of ensuring a water tight seal in site conditions, the influence of the moisture condition of concrete on measured property and insufficient water head.

AutoCLAM sorptivity test

The AutoCLAM sorptivity test measures the cumulative inflow of water in the first 15 minutes from a water source of 50mm diameter (i.e. from a base ring of internal diameter 50mm) at an applied pressure of 0.02 bars (approximately 200mm water head). A plot of cumulative volume of water verses square root of time gives a linear relationship and the slope obtained from the graph is reported as a sorptivity index. In the case of less permeable surfaces where flow of water is low, a larger contact area of water source can be used to obtain measurable flow rates. However, the measured data should be normalised to the standard 50mm diameter water source. The moisture content of the concrete surface has been reported to influence the AutoCLAM sorptivity index and it has been proposed that the test should be carried out when the internal relative humidity of concrete at 10mm depth is less than 80% to eliminate this effect. The equipment is portable and easy to use on site. Fixing problems identified for the ISAT have been eliminated for the AutoCLAM.

Figg water permeability (absorption) test

This test involves drilling a 10mm diameter hole in the near surface layer of the concrete to a depth of 40mm. After thorough cleaning, the hole is plugged over the top 20mm depth using a silicon rubber plug, leaving a cavity of 20mm deep in the concrete for carrying out the test. Water is admitted into this cavity at a low pressure head of 100mm and allowed to be absorbed by capillarity. The time required for a certain volume of water to be absorbed is measured in seconds as an absorption index, where a higher absorption index corresponds to better quality concrete. The main advantage of this test method is that it is simple and relatively low cost compared to other test techniques. However, its main disadvantage is that drilling, even at a slow speed, may introduce microcracks, which may defeat the purpose of the test by altering the flow mechanism.

4.4 Permeability tests

AutoCLAM water and air permeability tests

The AutoCLAM water permeability test involves a procedure similar to that used for the AutoCLAM sorptivity test. The main difference is in the test pressure used, i.e. a pressure of 1.5 bar is used for the AutoCLAM water permeability test compared to 0.02 bar for the AutoCLAM sorptivity test. The inflow of water through a test area of 50mm diameter through a surface-mounted ring is measured at this pressure for a period of 15 minutes. From a linear plot of the cumulative inflow verses the square root of time, the slope is determined and reported as the AutoCLAM water permeability index, in $\text{m}^3/\sqrt{\text{min}}$. As the inflow is measured in this test, the test location has to be dry to obtain meaningful data. The AutoCLAM permeability system, which enables the AutoCLAM sorptivity and water permeability test to be carried out, is used to determine the AutoCLAM air permeability index of concrete.

The AutoCLAM air permeability test depends on the measurement of pressure decay in a test reservoir mounted on the surface of concrete from a pressure of 1.5 bar over a period of 15 min and plotting the natural logarithm of the pressure against time, yielding a straight line graph. The slope of this graph is reported as the AutoCLAM air permeability index. Although moisture influences the test results, it has been shown that the quality of concrete can be classified in terms of the AutoCLAM air permeability index if measurements are taken when the internal relative humidity in a cavity in concrete at a depth of 10mm from the surface is less than 80%. The main advantage

of this test is that it is portable, quick and simple to perform. However, as in the case of the AutoCLAM sorptivity test, this test provides air and water permeability indices rather than coefficients of permeability.

Figg air permeability test

This test, which is also commercially known as Poroscope, uses a similar set-up to that used for the Figg water test. However, instead of admitting water into the cavity, a pump is used to reduce the pressure in the cavity to 55kPa below atmospheric. As air flows into the cavity, the pressure increases and the time taken for the pressure to increase by 5kPa, to a cavity pressure of 50kPa, is recorded using a stopwatch and this is reported as the air permeability index. A higher air permeability index value corresponds to a less permeable concrete. The advantages and disadvantages of the Figg water absorption test also apply to the Figg air permeability test.

Torrent test

This test is very similar to the Schonlin air permeability test and uses a surface-mounted reservoir to apply a vacuum to the test surface. Although the concept of the Torrent test is similar to that of the Figg air permeability test, damage caused by drilling a hole in the concrete is avoided. The Torrent test uses an annular reservoir along with the central test reservoir in an attempt to direct the flow of air into the test reservoir in a unidirectional manner. Using this assumption of unidirectional flow of air, a permeability coefficient is reported from measurements taken. It is claimed that the electrical resistivity of concrete can be used to adjust the readings from the Torrent test to take account of the moisture variations in concrete.

There are several other non-destructive test methods for evaluating air and water permeability of concrete and details of which can be found in published literature elsewhere.

4.5 Migration-based tests

Rapid chloride permeability test (RCPT)

The Rapid chloride permeability tests (RCPT) is based on the same principle as the laboratory test (ASTM C1202), where the charge passed through concrete cores taken from the in-situ concrete during the first six hours after the application of a potential across the specimen is used to characterize the concrete for chloride penetration. A detailed description of the test instrument is available elsewhere. Whiting (1981) suggested that the test should be carried out at a potential difference of 80V for a period of six hours. The total charge passed is used as an index to characterize concrete for chloride diffusivity. The disadvantages of this test technique are the same as that for the laboratory version, namely:-

- The test result is influenced by the conductivity of the pore solution, which can be highly variable on site.
- The temperature rise due to the high voltage (80V) will significantly affect the charge passed during the test.
- The depth of concrete cover will affect the test results. For example, if a cover of 50mm is assumed, results may vary as much as 25% if the actual cover varies by 25mm from this value.

In addition, unlike the laboratory-based test specified in ASTM C1202, it has been difficult to saturate the test area prior to carrying out the RCPT on site. Although Whiting (1981) proposed a vacuum saturation technique, this was not entirely satisfactory for yielding reliable and repeatable results. de Rooji *et al* (2007) reports that this test is too slow and too expensive and a faster, cheaper and preferably non-destructive test is preferred to assess durability in terms of chloride diffusion rates.

Permit ion migration test

This is a unique non-destructive test which is capable of determining the chloride migration coefficient of cover concrete. Detailed descriptions of the instrument, test technique and test area preparation are available elsewhere. Extensive testing using the PERMIT ion migration test on different concrete samples has indicated that the in situ migration coefficient from the PERMIT ion migration test correlates well with the conventional laboratory-based steady state diffusion and migration coefficients. The main advantage of this test is that it can provide a migration coefficient without having to remove cores from the structure. The main disadvantage of the test is that it introduces chloride ions into the test surface. However, the chloride ions within the test area can be effectively removed by reversing the test voltage, which may take up to four days. It is also noted that the test area will be slightly stained by deposition of the ferrous by-products of the electrochemical reaction. However, if this deposit is washed off immediately after the test, the extent of the staining can be reduced.

RILEM tests on methods to determine chloride transport parameters in concrete

Castellote and Andrade (2006) reported the results of a Round-Robin test series to determine chloride transport parameters where 27 different laboratories around the world, using 13 different methods, in triplicate, for 4 different mixes with different binders. Natural diffusion methods, migration methods, resistivity methods and colourimetric methods were tested. However, the results were not statistically representative as only a few of the laboratories undertook the tests where the majority of the natural diffusion tests, one of the two resistivity tests and no laboratory undertook the colourimetric test. However, a statistical analysis of the remaining tests was performed according to international standards in terms of the trueness, precision, relevance and convenience along with several sub-indicators.

The authors summarized that the best method to measure the steady state diffusion coefficient for the three importance factors used is the Resistivity method which measures the resistivity of a water saturated specimen. In terms of measuring the natural diffusion, it was found that the natural diffusion ponding method gives a better global behavior. For calculation of the non-steady state diffusion coefficient by migration methods, the best method observed was the multi-regime method.

4.6 Comparison and selection of test methods

The selection of appropriate permeation test technique (or penetrability test) for assessing the condition of concrete in structures basically depends on the associated transport mechanism that causes deterioration. However, most of the test methods have common limitations and it is essential to overcome the limitations by understanding the factors causing them. These common limitations include sensitivity to moisture and temperature condition in concrete, changes in transport mechanism during the test and influence of drilling on measured values. A detailed

experimental study to compare different non-destructive testing (NDT) techniques for measuring penetrability characteristics of cover concrete and thereby detecting the changes in quality of concrete was carried out by RILEM committee 189 (Romer, 2005).

4.7 Choice of Test Methods

BS1881-201 (1986) has outlined a number of key parameters that should be considered when a non-destructive test is being decided upon. Essentially the test equipment should be portable in most cases and all tests should be rapidly carried out, although some tests will require some preparation. Important considerations when deciding the choice of tests include:

- Test locations – position in the structure, depth of reinforcement, effect of local influences such as carbonation and the depth below the surface the results apply to.
- Effect of damage – effect of the test on the surface appearance and the possibility of structural damage to the structure as a result of the test.
- Size of the member – the area that the test occupies should be as small as possible to ensure it is applicable in as many situations/locations as possible.
- Testing accuracy – depending on the purpose, the accuracy required will vary and will depend on the test method, the number and location of the measurements and the accuracy of available calibrations.
- Economic and social factors – delays in construction due to carrying out the test(s) and remedial works/making good required following the test,

The code provides a summary of test methods and gives a breakdown of the principal applications, properties assessed, surface damage and type of equipment. It must be noted, however, that this code is somewhat dated and developments over the 23 years since it was published are not included.

4.8 Concluding remarks

From the point of view of using the tests for different site applications, it may be noted that some of them can be used for more than one purpose. With no two investigations being the same, it is the investigator who has to select the best approach and which tests are to be used. The need to have a thorough understanding of the deterioration mechanisms and the causes of distress cannot be overstated in order to select the most appropriate tests. Furthermore, there is a need to understand the principle of operation of each of the test methods and their limitations in order to apply the various methods either independently or in combination in an effective manner. Quite often the equipment available to the engineer decides the testing procedure. However, work at Queens and Heriot-Watt is being currently undertaken to specify test should be used to assess the air and water permeability (through the AutoCLAM apparatus), chloride ion migration rate (through the PERMIT apparatus) and electrical properties. Other factors influencing the testing programme are the cost of the various tests in relation to the value of the project, the cost of delays to construction and the cost of possible remedial works.

4.9 References

British Standard Institute (1996) Methods for the determination of initial surface absorption, BS 1881: 208.

ASTM C1202. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, Philadelphia, PA: American Society for Testing and Materials.

Whiting D (1981). Rapid Measurement of the Chloride Permeability of Concrete, Washington, DC: Federal Highway Administration, FHWA/RD-81/119.

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Castellote M and Andrade C (2006) Round-Robin test on methods for determining chloride transport parameters in concrete, Materials and Structures, (39), 955-990.

British Standard Institute (1986) Testing concrete – Part 201: Guide to the use of non-destructive methods of test for hardened concrete, BS 1881: 201.

5 PROPOSED EXPERIMENTAL WORK

5.1 Experimental Tests proposed

Table 5.1 presents the various work packages as outlined in a project current being jointly undertaken between Queens University Belfast and Heriot Watt University. The project is funded by the EPSRC research council (Project No. **EP/G02152X/1**) and is entitled 'Development of a Performance-based testing methodology for Concrete Durability'. Its aim is to specify which non-destructive apparatus/tests be used to assess the performance limits set for concrete structures when set.

Table 5.1 Experimental Tests proposed

Work Package No.	Title (from application)	Proposed experimental work
WP1	Electrode configuration and test cells	Development of test-cells, electrode geometry and electrode/concrete contacting system
WP2	Prediction of electrical conductivity	Evaluation of electrical conductivity in concrete
WP3	Experimental determination of transport properties of the concrete cover	<u>Test Series 1</u> Design and cast concrete blocks for suitable exposure classes in EN206 using suitable CEM I, II, III, IV and V concretes within the limits in EN197. Tests will include typical laboratory and field methods for sorption, diffusion and permeability using the AutoCLAM and PERMIT apparatus. In parallel, water and salt absorption tests will be carried out in the laboratory using conventional diffusion and migration cells.
WP4	Determination of the rate of hydration	<u>Test Series 2</u> The rate of hydration is required for the numerical study. Concrete samples from test series 1 will be used to conduct isothermal calorimetric studies and differential scanning calorimetric studies.
WP5	Determination of the durability of concretes	<u>Test Series 3</u> Reinforced concrete blocks (cast along with Test Series 1) with varying cover depths will be tested in parallel using an embedded electrode array to determine the advance of chloride within a salt-spray cabinet and a traditional ponding test.
WP5	Determination of the durability of concretes	<u>Test Series 4</u> As Tests Series 3 is ongoing, the initiation and rate of corrosion will be carried out. In parallel, the chloride profile and total chloride through the concrete will be measured
WP6	Field testing of concrete blocks (fresh concrete)	<u>Test Series 5</u> A number of concrete blocks will be located on the west coast of Co. Donegal on the North West coast of Ireland. Tests will include chloride ingress, water and salt absorption analysis, the advancing chloride front, initiation of corrosion (if any) and rate of corrosion (if any).
WP7	Field testing of concrete blocks (>10 years old)	<u>Test Series 6</u> In-situ testing of existing concrete samples in Dornock Firth exposure site. Tests to be undertaken to follow on from those taken to date and on-going monitoring of tests in place (embedded electrode arrays and corrosion monitoring).

5.2 Concrete samples

Table 5.2 presents the proposed cement types to be made as part of this project. As shown, 11 cement types will be cast with 3 w/c ratios (0.3, 0.4 and 0.5) and concrete strengths of C35/45 and C40/50 will also be specified for both the laboratory and exposure tests.

The size of the samples for the salt-spray tests are proposed to be 150mm thick x 250mm wide x 1000mm high. This allows suitable dimensions to perform AutoCLAM and PERMIT tests at the same time on opposite faces of the sample. The size of the samples for measurement of the advancing chloride front using electrical arrays in a series of Ponding tests are to be 250x250x150mm thick. 3No. 100mm diameter x 50mm thick cores are required for the numerical model calibration and for NT Build 492 (1999) tests. The samples are shown in Figure 5.1.

5.3 Exposure Site on Atlantic Coast

As part of this project, it is proposed to locate a number of concrete samples on the Atlantic Coast of Ireland in Co. Donegal, as shown in Figure 5.2 for exposure testing. These samples will be tested using the AutoCLAM and PERMIT apparatus to assess the air and water permeability, absorption and chloride ion diffusion rates respectively. In addition to this, the advancing chloride front will be measured using embedded electrical arrays attached to the reinforcement in the samples. This will be similar to the existing exposure site at Dornoch Firth, Scotland which has been set up by Heriot Watt University where ongoing monitoring of various durability properties have been carried out over the past 7-years (Nankuttan *et al*, 2008). Photographs of this site are shown in Figure 5.3, along with the roadside and urban exposure sites also developed by Heriot Watt University (McCarter *et al*, 2001).

A summary of the proposed tests are shown in Table 5.3.

Table 5.2 Proposed Concrete mixes

Main Type	Notation		Cement Type
CEM I	Portland Cement	CEM I	Portland Cement
	Sulphate Resistant Cement	CEM I/SR	Sulphate Resistant Cement
CEM II	Portland slag cement	CEM II/A-S	Portland Slag, 85% clinker content, 15% Slag
	Portland slag cement	CEM II/B-S	Portland Slag, 70% clinker content, 30% Slag
	Portland Silica Fume cement	CEM II/A-D	Portland Silica Fume, 90% clinker content, 10% Silica
	Portland Fly ash cement	CEM II/A-V	Portland fly-ash, 85% clinker content, 15% PFA
	Portland Fly ash cement	CEM II/B-V	Portland fly-ash, 70% clinker content, 30% PFA
CEM III	Blastfurnace Cement	CEM III/A	Blastfurnace cement, 50% clinker content, 50% GGBS
		CEM III/B	Blastfurnace cement, 25% clinker content, 75% GGBS
CEM IV	Pozzolanic Cement	CEM IV/A	Pozzolanic cement, 75% clinker Content, 25% Pozzolanic
		CEM IV/B	Pozzolanic cement, 55% clinker Content, 45% Pozzolanic

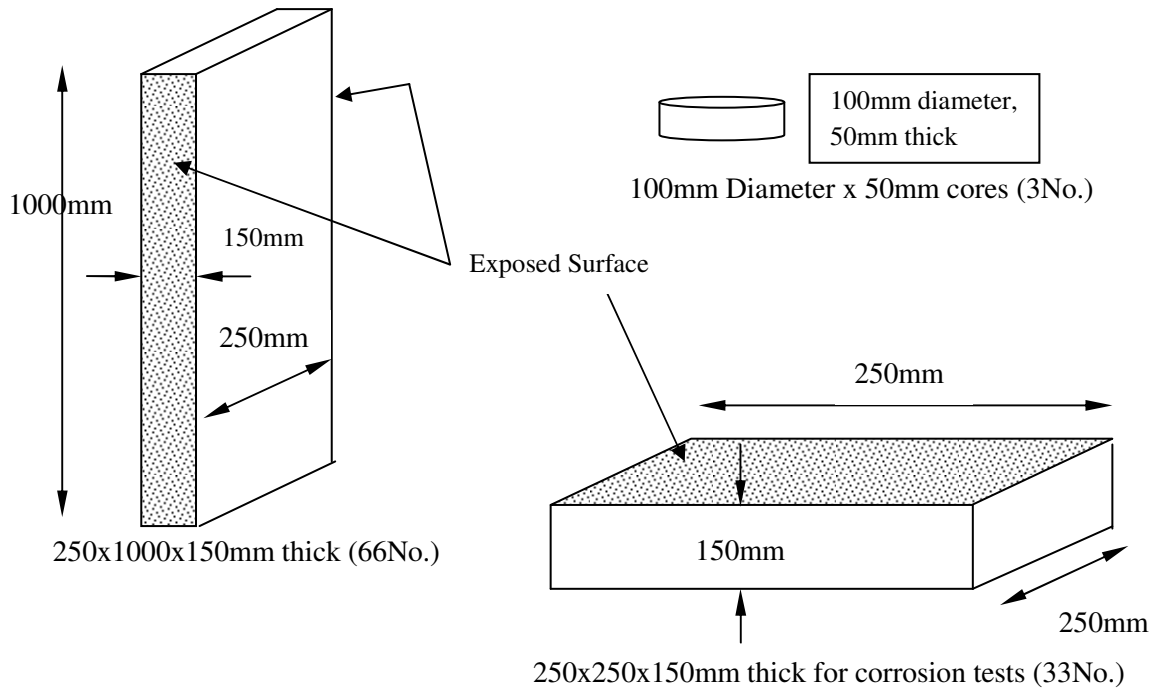


Figure 5.1 Proposed Concrete Samples

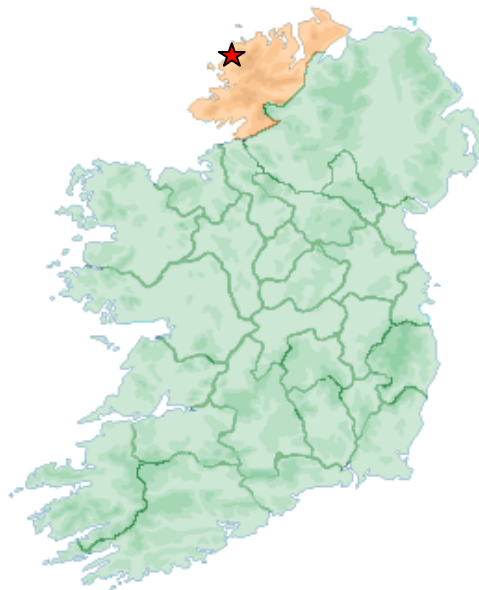


Figure 5.2 Proposed location of exposure site in Co. Donegal

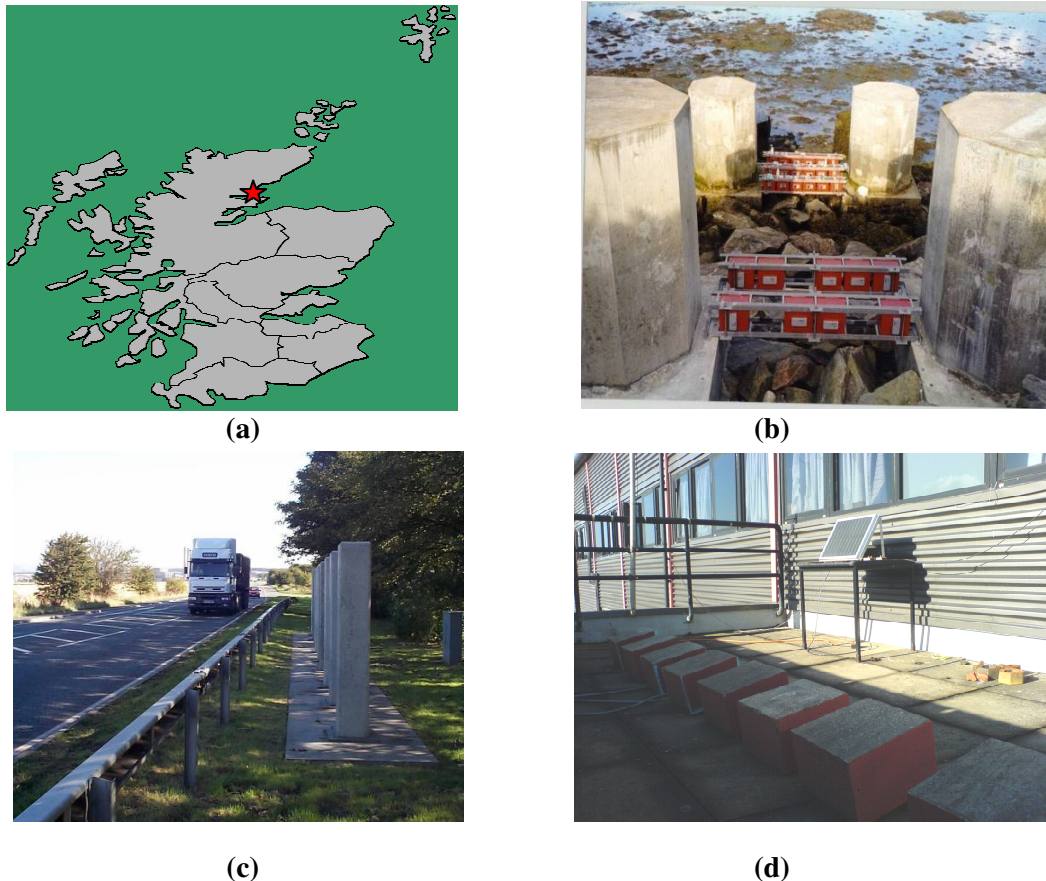


Figure 5.3 (a) Location of Marine exposure site in Dornoch Firth, Scotland. (b) full-scale concrete pier-stems and concrete blocks allowing XS1, XS2 and XS3 exposure zones in Dornoch Firth. (c) Concrete monoliths used in simulated roadside environment (salt-spray) and (d) concrete blocks for urban environment.

Table 5.3 Testing Details

Work Package No.	Title (from application)	Proposed concrete samples
WP3	Experimental determination of transport properties of the concrete cover	<u>33No. 250x1000x150mm thick concrete samples</u> Salt-spray cabinet testing <u>Testing:</u> AutoCLAM, PERMIT and migration cell tests
WP5	Determination of the durability of concretes	<u>33No. 250x250x150mm thick concrete samples</u> Chloride Ponding tests Embedded electrode array at cover depths up to 85mm to determine the advance of chloride in the laboratory
WP6	Field testing of concrete blocks (fresh concrete)	<u>33No. 250x1000x150mm thick concrete samples</u> On-site on the west coast of Donegal (see Figure 5.2) <u>Testing:</u> Embedded electrode array at cover depths up to 85mm to determine the advance of chloride in the Donegal site. AutoCLAM & PERMIT
WP4	Determination of the rate of hydration	Pastes from the above concretes will be tested using isothermal calorimetric and differential scanning calorimetric studies at set times during hydration of the concrete samples.

5.4 References

NT Build 492 (1999), Nordtest Method: Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady migration experiments.

Nankuttan S.V., Basheer P.A.M., McCarter W.J., Basheer L. and Robinson D.J. (2008) Full-Scale Marine exposure tests on treated and untreated concrete: initial 7-year results, *ACI Materials Journal*, (105) 81-87.

W.J. McCarter, A. Butler, T.M. Chrisp, M. Emerson, G. Starrs and J. Blewett (2001), Field trials on covercrete monitoring sensors, *Proceedings of the Institution of Civil Engineers, Structures & Buildings* (146), 3, 295-305.

6 CONCLUSIONS

The above has presented examples of projects in the UK, Ireland and Europe where performance specifications for concrete durability have been used. A summary of the most common non-destructive tests to assess the durability of the concrete, namely the permeability, chloride ion diffusion, absorption and electrical properties, has also been discussed.

Work is currently underway in Queens University Belfast and in Heriot Watt University in Edinburgh to develop a performance based testing methodology for concrete durability as part of an EPSRC funded project. This project will specify which non-destructive apparatus be used to assess the various performance limits for the concrete durability and inserted into the UK and Irish National Annex of EN206-1. The apparatus to be used in this project will be the AutoCLAM, PERMIT and embedded electrode arrays at various depths at early age and over time. These apparatus have been shown to give accurate results, repeatability and easy to use in any concrete element. Additional tests in the project will include accelerated corrosion methods such as salt-spray cabinets and traditional ponding tests.

In addition to the laboratory based tests, a number of samples will be located on the Northwest Atlantic coast of Ireland to assess the advancing corrosion front in the concrete in an exposed marine location. The results from these tests will be compared to existing concrete samples located in Northeast Scotland which have been in place for 10-years.

In addition to the physical tests, evaluation and modifications to the existing NIST hydration models and ClinConc prediction model will be made that are based on both simulated and field studies. A methodology will be proposed for performance-based specifications within the context of this project.

Through this approach, the recommendations in EN206-1 will be met as they must satisfy the following requirements:

- long-term experience of local materials and practices and on detailed knowledge of the local environment.
- approved and proven tests that are representative of actual conditions and have approved performance criteria.
- analytical models that have been calibrated against test data representative of actual conditions in practice. The concrete composition and the constituent materials should be closely defined to enable the level of performance to be maintained.