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Testing and Monitoring Concrete using Novel Methods for Predicting their Long Term Behaviour

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Testing and monitoring concrete using novel methods for predicting their long term behaviour

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Abstract
It is widely recognised that durability of concrete depends on its transport properties, viz. absorption, diffusion and permeability. As concrete cover provides the first line of defence against the ingress of many deleterious substances into the concrete, a measure of its transport properties is vital in assessing its long term performance in the given exposure condition. In new structures the rate of ingress of the deleterious substances could be monitored using array of electrical sensors which are embedded in the cover concrete. For structures which are currently in service, two *in situ* permeability apparatuses, viz. Autoclam Permeability System (for measuring gas/water permeability and water absorption) and Permit Ion Migration Test (for determining the ionic diffusion) could be employed. These instruments can be mounted on the concrete surface for carrying out the tests. Typical results are presented for these two novel testing systems to illustrate their usefulness for the condition assessment of reinforced concrete structures.

Keywords: Carbonation, Chloride ingress, Air permeability, Sorptivity, Electrical Resistance Sensors

1. Introduction

The durability of reinforced concrete structures depends on their resistance to: (a) corrosion of reinforcement as a result of carbonation, chloride ingress and leaching, (b) freeze-thaw deterioration, (c) crystallisation of salts in pores, (d) sulphate attack, (e) acid attack, (f) alkali attack, (g) alkali-silica reaction, (h) cracking in both the pre-hardening and hardened states, (i) fire damage and (j) abrasion (Basheer *et al*., 1996 and BCA 1997). As illustrated in Fig. 1, most of these mechanisms of deterioration are related to the microstructure and transport properties of the concrete cover (Basheer *et al*., 1996). This is due to the fact that environmental penetrations which cause damage to the concrete are influenced by the transport properties of the concrete cover. Therefore, it is desirable that concrete is tested non-destructively at the surface in order to assess the quality at the time of construction and the performance in service. Arising out of these need, the Autoclam Permeability System (Basheer *et al*., 1994) for measuring the sorptivity and the permeability and Permit Ion Migration Test (Basheer *et al*., 2005 and Nanukuttan *et al*., 2006) for determining the ionic transport of concrete were developed at Queen’s University Belfast, UK.
Reinforced concrete structures can be made durable by resorting to appropriate design, selection and use of materials and construction practices. If an extremely high

initial quality is achieved, this may lead to a performance history, as shown by curve 1 in Fig. 2. However, for most concretes, the performance history is such that the performance deteriorates gradually with time and not suddenly (and catastrophically) as shown by curve 2, but there is significant deterioration with time, and intermittent maintenance changes the performance level or alters the rate of change of the performance (curve 3). This necessitates the continuous monitoring of the condition of structures on site. That is, the main requirement of a monitoring and testing strategy is to measure the **'state of health'** of the building or the structure **'on completion'**, which can then be checked regularly during its **'life'** by further routine collection of data.

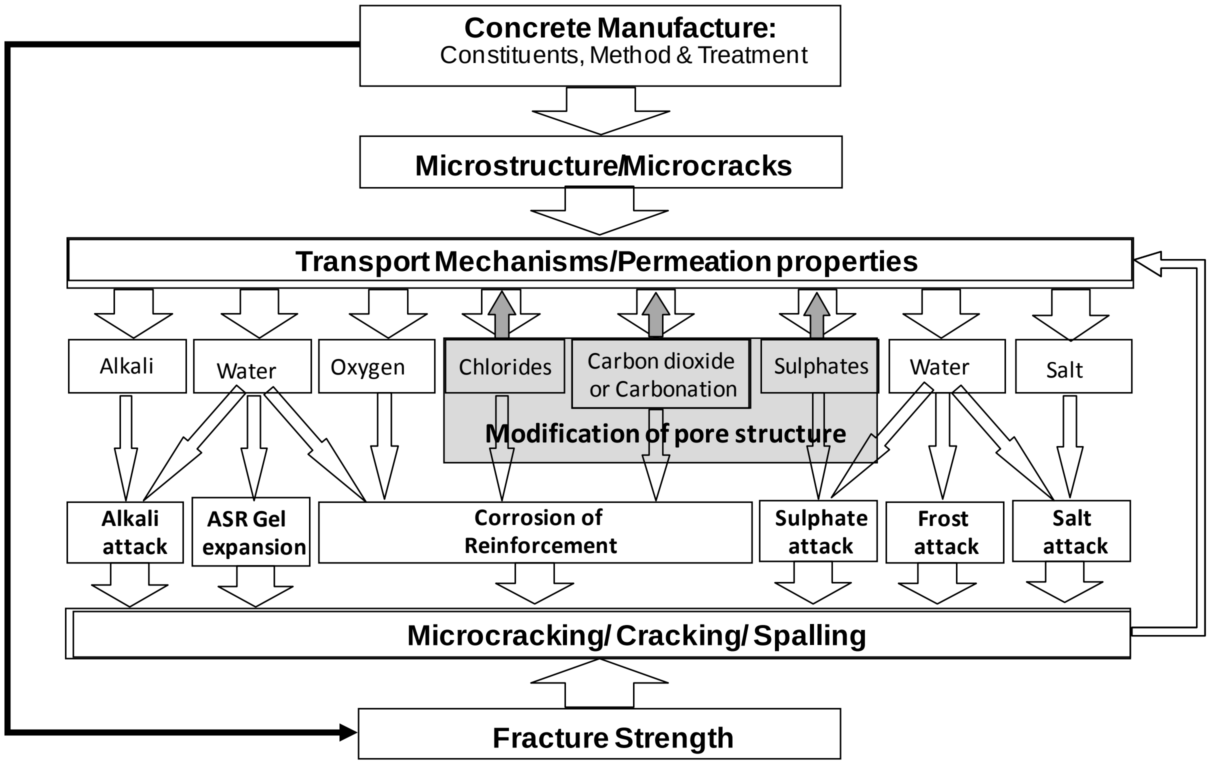


Fig. 1: Dependence of durability of concrete on microstructure and transport mechanisms

Ideally information collected before the extent of the problem becomes severe, i.e. in the initiation period, will be invaluable for the effective maintenance management of civil engineering structures (Fig. 3). The research at Queen's, hence, has considered the use of sensors which can be embedded in new constructions for monitoring the continuous changes of the cover concrete during the initiation period. Details of electrical resistance sensors developed at Heriot-Watt University, Edinburgh (McCarter *et al.*, 1995) and few results is included in this paper.

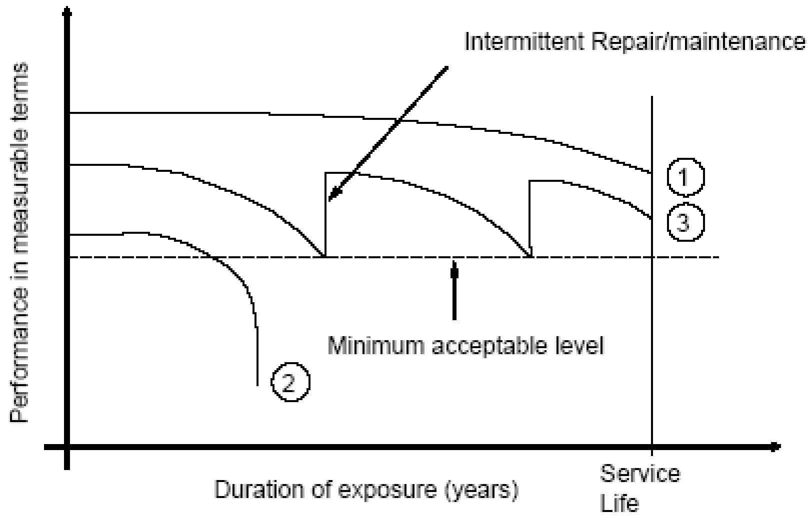


Fig. 2 Service life performance of reinforced concrete structures

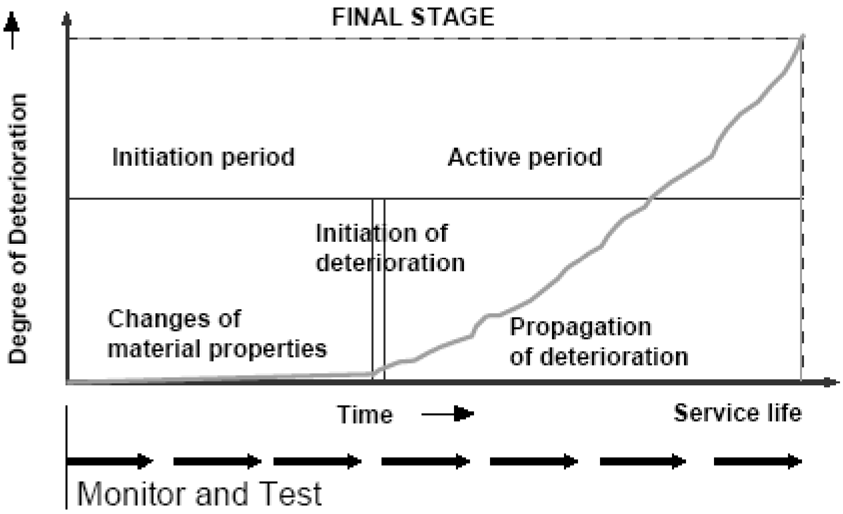


Fig. 3 Need for continuous monitoring of structures

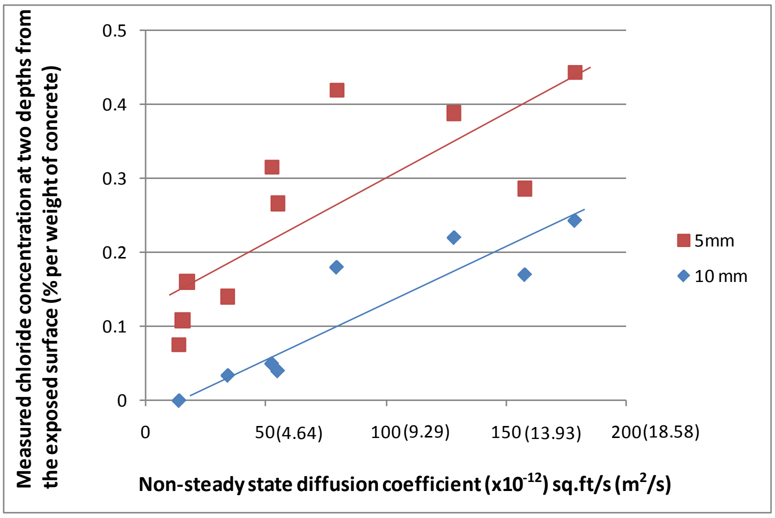
The objective of this paper is to summarise developments in testing and monitoring concrete for durability and illustrate how progress could be made in developing performance-specifications in terms of results from these test techniques.

2. Measurement of resistance to chloride ingress in concrete

Although the primary mechanism of chloride transport through the unsaturated concrete cover is absorption, the accumulation of chlorides in this layer leads to further penetration of chlorides into concrete by diffusion (Nilsson *et al*., 1996). As a consequence, diffusion becomes the most dominant mechanism of chloride transport at greater depths, which can be measured in terms of the coefficient of chloride ion diffusion. Different test methods are available to determine the chloride ion diffusion coefficient, e.g. steady-state and non-steady-state chloride diffusion and migration tests.

3.1. Relationship between depth of chloride penetration and diffusivity measurements from different lab based test methods

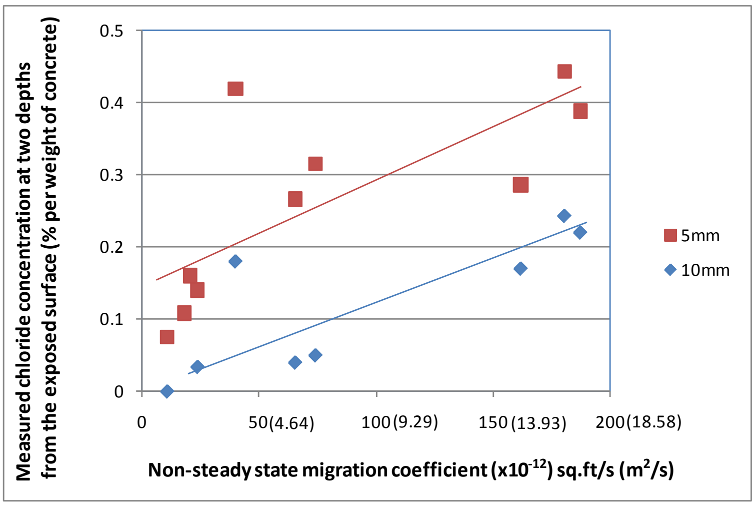
The following graphs shows the diffusivity of concrete assessed using different lab based tests compared against the quantity of chloride ions measured at two depths from exposed surface. Specimens were immersed in 2.8M NaCl solution for 35days. After this period specimens were removed from the exposure solution and dry powder specimens were collected from various depths. Chloride concentration of the dry powder was determined using potentiometric titration procedure. Results presented in Figures 4 to 6 shows that the diffusivity assessed by the different test methods can be used with varying degree of accuracy to predict the quantity of chloride ions at a particular depth.



w/cm Mix detail

0.50 opc
0.45 opc
0.42 opc
0.35 opc
0.40 opc + silica fume
0.42 opc + silica fume
0.42 opc + fly ash
0.45 opc + fly ash
0.42 opc + slag
0.45 opc + slag

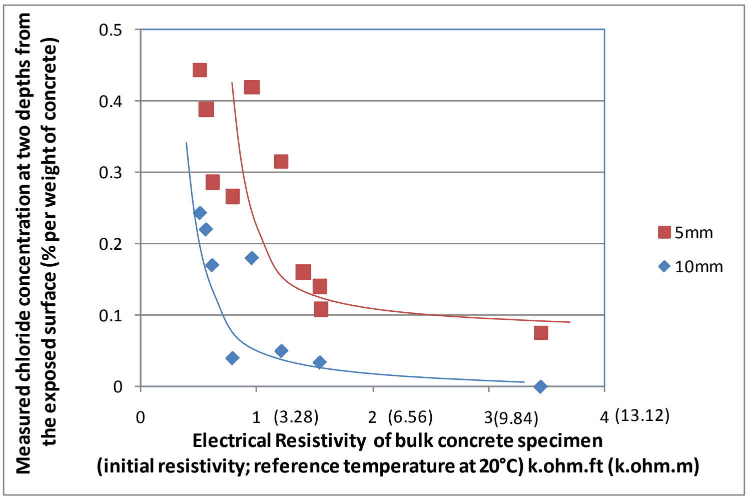
Fig. 4 Concentration of chloride ions versus non-steady state diffusion coefficient for depths 5mm and 10mm from the exposed face of concrete specimens.



w/cm Mix detail

0.50 opc
0.45 opc
0.42 opc
0.35 opc
0.40 opc + silica fume
0.42 opc + silica fume
0.42 opc + fly ash
0.45 opc + fly ash
0.42 opc + slag
0.45 opc + slag

Fig. 5 Concentration of chloride ions versus non-steady state migration coefficient (obtained from NT Build 492) for depths 5mm and 10mm from the exposed face of concrete specimens



w/cm	Mix detail
0.50	opc
0.45	opc
0.42	opc
0.35	opc
0.40	opc + silica fume
0.42	opc + silica fume
0.42	opc + fly ash
0.45	opc + fly ash
0.42	opc + slag
0.45	opc + slag

Fig. 6 Concentration of chloride ions versus electrical resistivity of bulk concrete for depths 5mm and 10mm from the exposed face of concrete specimens

Figures 5 and 6 suggest that useful information about penetration of chloride ions can be assessed using rapid test methods. NT Build 492 requires 24hours to assess the diffusivity of concrete whereas electrical resistivity can be assessed instantaneously. It is also worth noting that the electrical resistivity in this case was obtained from concrete specimens saturated with $Ca(OH)_2$ solution. However, all these tests require concrete specimen of minimum thickness 50mm to be extracted from the structure to perform the test. This will considerably limit the number of test that can be performed and leave the structure badly disfigured.

3.2. Assessing the rate of chloride ingress of concrete on site

The principle of steady state migration test was used to develop an *in situ* ion migration test (PERMIT Ion Migration Test) which can be performed on the concrete surface and therefore does not require a concrete specimen to be removed for testing (Basheer *et al.*, 2005 and Nanukuttan *et al.*, 2006). In this test the chloride ion transport through the cover concrete is used to determine a coefficient of chloride ion migration. The reliability of the test was established by correlating the results with the effective diffusion coefficient from steady state diffusion test and that obtained in 1-D chloride ion migration test using split cells (Basheer *et al.*, 2005 and Nanukuttan *et al.*, 2006).

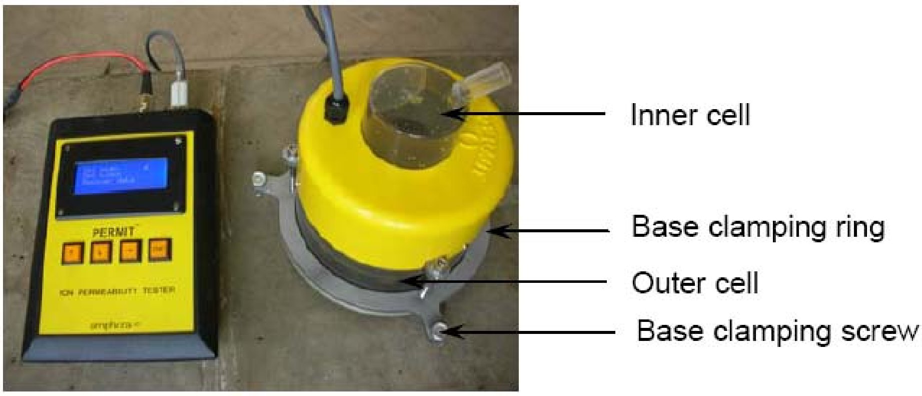


Fig. 7 The Permit Ion Permeability Tester (controller and the main body)

3.3. Relationships between Permit *in situ* migration coefficient and other

measures of chloride transport

The Permit *in situ* migration index (without converting the steady state of chloride flux to a coefficient of chloride migration) was compared with the migration coefficient from the one dimensional chloride migration test, the effective diffusion coefficient from the normal diffusion test and the apparent diffusion coefficient determined from chloride profiles (Nilsson *et al.*, 1996). These relationships were established initially for eight OPC concretes. The main findings of this study were as follows:

- The *in situ* migration coefficient correlated very well (R^2=0.95) with the migration coefficient determined from the one dimensional chloride migration test (Fig. 8).
- A high degree of correlation (R^2=0.95) occurred between the *in situ* migration index obtained from Permit and the effective diffusion coefficient (Fig. 9).

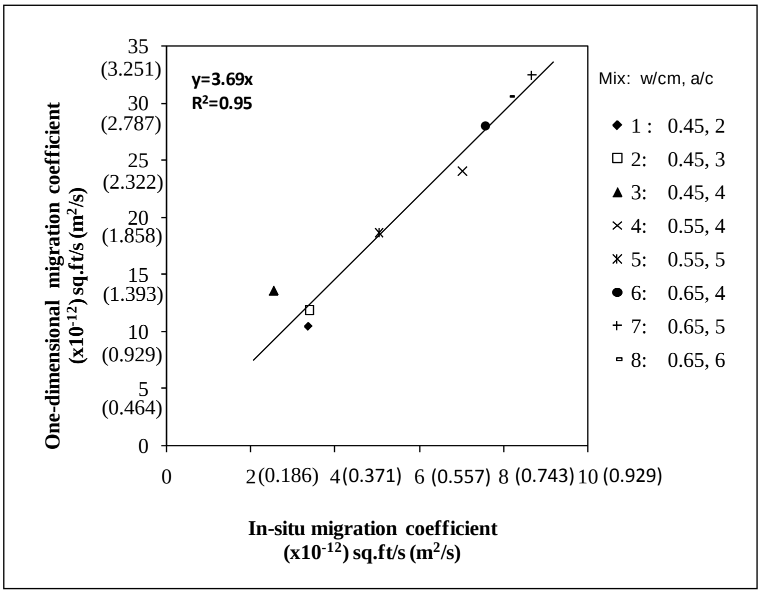


Fig. 8 Correlation between Permit *in situ* ion migration coefficient and 1-dimensional migration coefficient (all ordinary Portland cement mixes; a/c represents aggregate cement ratio)

Another investigation was carried out using nine mixes containing OPC, Pulverised Fuel Ash (PFA), Ground Granulated Blast-furnace Slag (GGBS), Microsilica (MS) and Metakaolin (MK). In this experimental programme, the Permit Ion Migration test was compared with Nordic Test BUILD 492: 1999: Chloride Migration Coefficient from Non-steady State Migration Experiments and 1-Dimensional steady-state migration test.

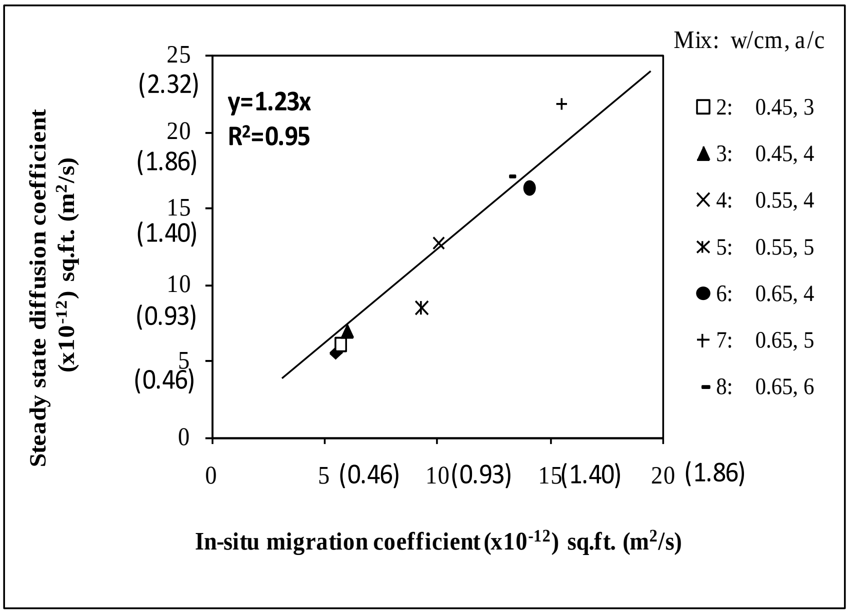


Fig. 9 Correlation between Permit *in situ* migration coefficient and effective diffusion coefficient (all ordinary Portland cement mixes; a/c represents aggregate cement ratio)

<u>*Relationship between Permit in situ migration coefficient and 1-D migration coefficient for concretes containing supplementary cementitious materials*</u>

Figure 11 shows the relationship between Permit *in situ* migration coefficient and the steady state (1D) migration test results. As in the case of ordinary Portland cement concretes (Fig. 12), the results in Fig. 11 demonstrate that the relationship is very good for concretes containing different types of cement replacement materials. Therefore, as an alternative to extracting cores and testing in laboratories, the Permit Ion Migration test can be carried out on site and a reliable estimate of the chloride ion migration coefficient can be made.

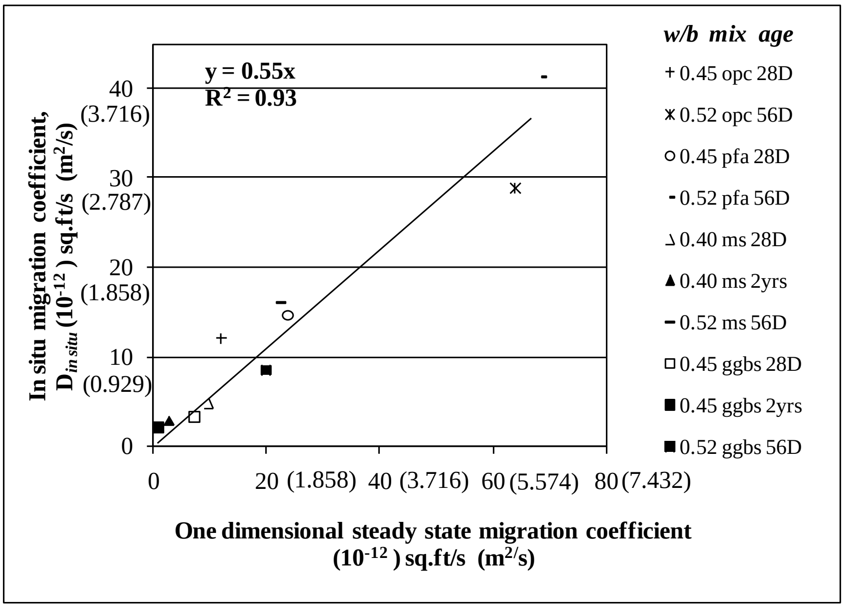


Fig. 11 Permit *in situ* migration coefficient vs 1D migration coefficient for different types of concretes

Relationship between Permit in situ migration coefficient and non-steady state migration coefficient for concretes containing supplementary cementitious materials

The relationship between the migration coefficients obtained from the Permit ion migration test and the non-steady state migration test is shown in Fig. 12. There is a reasonably good relationship between the two (R^2 = 0.85), however, it is not as good as that obtained in the previous case between the two steady state migration tests. This was primarily due to the fact that the data corresponding to 0.45 w/b pfa mix deviated from the rest.

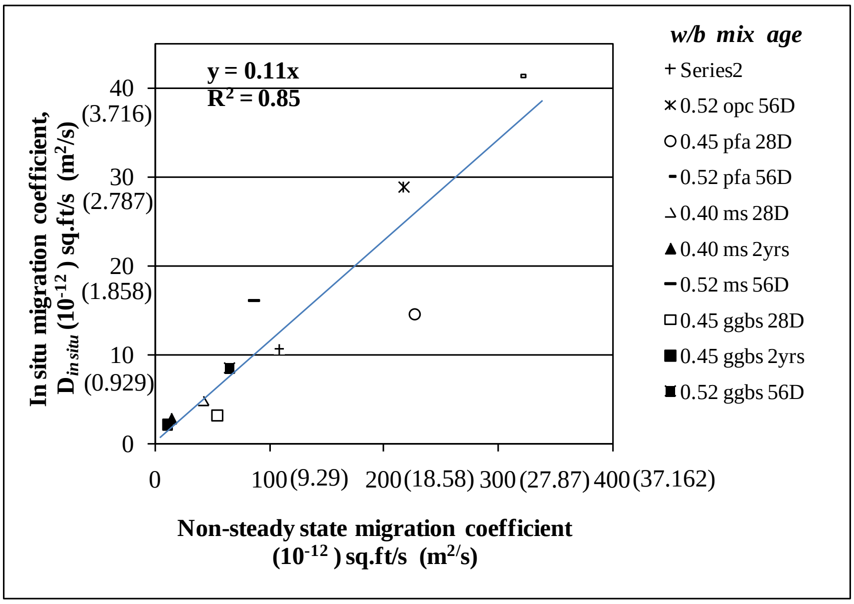


Fig. 12 Permit *in situ* migration coefficient vs NT build 492 for different types of concretes

3.3. Relationship between current and flow of chloride ions in a migration test

The initial current obtained in a migration test (or ASTM C1202) gives an indication of the conductivity of the pore fluid and not that of the bulk concrete. Hence this parameter is not expected to have a good correlation with the migration coefficient. As shown in Fig. 13 the relationship between initial current and *in situ* migration coefficient obtained from PERMIT is not strong. As the test progress, current increases and eventually reaches a maximum value (termed as peak current). Immediately prior to the peak current, a steady flow of chloride ions to the anolyte is observed. This observation is common for steady state migration test and the PERMIT, as these two tests are carried out under a constant potential difference. During a migration test, the ingress of chloride ions decreases the resistivity of the set-up and this result in an increase in the current value (as the voltage remains constant). At this stage, chloride ions are responsible for a portion of the charge flow governed by its transference number. Therefore, it is logically correct to identify a relationship between the chloride migration coefficient and the peak current. The data presented in Fig. 14 confirms this logic and shows that the peak current can be used to estimate the *in situ* migration coefficient, with 82% degree of determination.

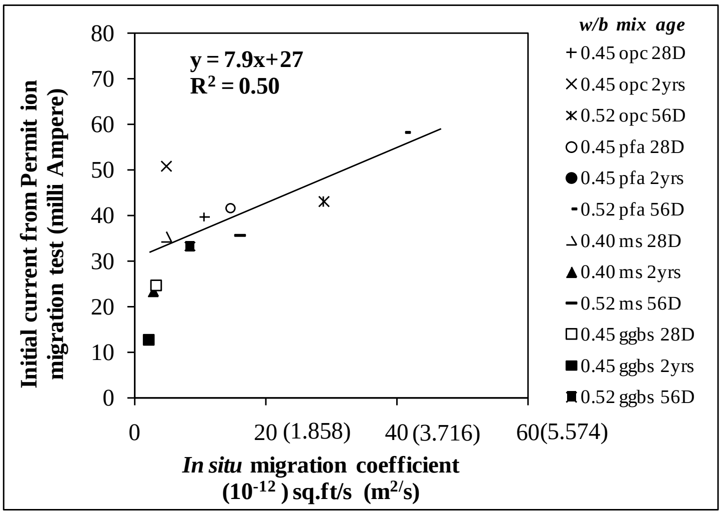


Fig. 13 Shows the initial current measured during Permit ion migration test plotted against *in situ* migration coefficient. A similar trend was obtained for one-dimensional steady state migration test.

Nanukuttan et al [2] showed that there is a linear relationship between the rate of change of charge passed (during steady state) and the rate of change of chloride concentration. This would mean that if charge passed is the only parameter assessed in a migration test, it is still possible to arrive an equivalent chloride flow. This finding is similar to that reported by Yang [6], where the author found that the charge passed during steady state flow is more representative of the chloride penetration resistance of concrete than the first 6 hours charge passed. The above discussion highlights that the charge passed during the steady state is a better measure of the chloride penetration resistance of concrete than any absolute values, such as charge passed during the first 6 hours.

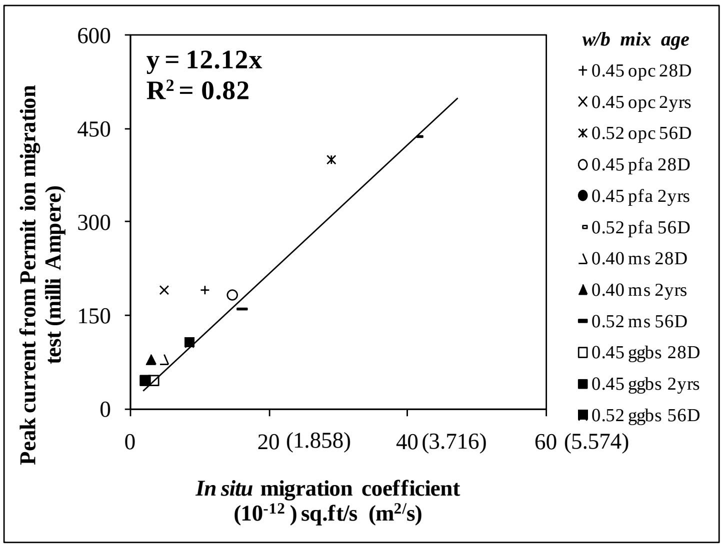


Fig. 14 Shows the peak current measured during Permit ion migration test plotted against *in situ* migration coefficient. A similar trend was obtained for one-dimensional steady state migration test.

3.4. Calculating migration coefficient from peak current value in a migration test

The chloride flux at steady state according to Nernst-Planck equation can be expressed as (adapted from reference [1]):

$$J_{Cl} = t_{Cl} \frac{I_{peak}}{Z_{Cl} F} = \frac{Z_{Cl} FE}{RTL} D_{mig} C_{Cl} \qquad \text{Eq. 1}$$

where, J_{Cl} = flux of chloride (mol/cm^{2}s), t_{cl} = transference number of chloride ion, I_{peak}= peak current density(A/cm^2), Z_{Cl} = electrical charge of chloride ion, F= Faraday constant (C/eq), C_{Cl} = concentration of chloride ions, R= Universal gas constant (8.31 J/K/mol), E = Electrical potential applied between the anode and cathode, L = length of the concrete specimen and D_{mig} is the migration coefficient (theoretically calculated).

Therefore, D_{mig} can be rewritten as

$$D_{mig} = \frac{RTL}{EF^2} \cdot \frac{I_{peak}}{Z_{Cl}^2 C_{Cl}} \cdot t_{cl} \qquad \text{Eq. 2}$$

Using relationship presented in Fig. 6 and Eq. 2, the value of t_{cl} can be calculated for PERMIT as t_{cl} = 0.251.

For PERMIT the parameters are: F = 96500 C/eq , Z_{Cl}=1, C_{Cl} = 0.55mol/l, Ipeak = Peak Current(Amperes)/ Area (in m^2); L/A = 3.76m^{-1}; T = 300K (Average temperature)

The experimental value of t_{Cl} obtained is 0.251. This would suggest that if $I_{peak,}$ C_{CL} and t_{Cl} are known, D_{mig} value can be calculated using Eq. 2. However, t_{Cl} value obtained is lower than that reported by Andrade (0.338) [1]. This could be due to the variations in the test set-up used by Andrade. As suggested by Prince et al [7] the value of transference number and hence the migration coefficient will vary depending on the type of electrolytes and test set-up used. So the above mentioned t_{Cl} value is only for a test set-up similar to PERMIT. However, for the ASTM C1202 test a similar t_{cl} could be found which could then be used to evaluate a migration coefficient using just the peak current.

2. *In situ* measurement of air permeability and sorptivity

The movement of gases, liquids and ions through concrete, generally called penetration, occur due to various combinations of air or water pressure differentials, humidity differentials and concentration or temperature differences of solutions. Depending on the driving force of the process and the nature of the transported matter, different transport processes for deleterious substances through concrete are distinguished as diffusion, absorption and permeation. The Autoclam Permeability System (Fig. 4) could be used to measure the gas and water permeability and water absorption (sorptivity) of concrete *in situ*. The relationships between permeation properties obtained with the Autoclam Permeability System and various durability measures are summarised in this section.

Fig. 4a Autoclam Permeability System, with bonding type base ring

Fig. 4b Bonding type ring

Fig. 4c Bolt on type ring

2.1. Dependence of durability parameters on Autoclam air permeability index

Figure 5 demonstrates an excellent relationship between the Autoclam air permeability index and intrinsic permeability, which was obtained by carrying out steady state air permeability test, for 27 different concrete mixes.

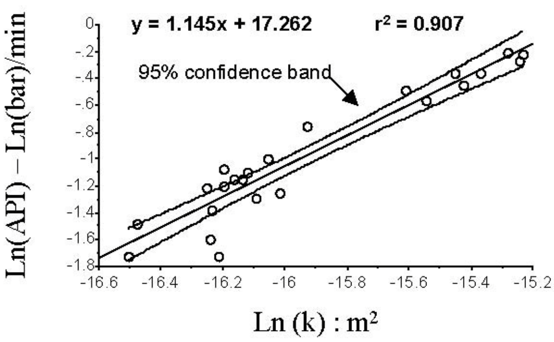


Fig. 5 Relationship between Autoclam air permeability index and intrinsic air permeability

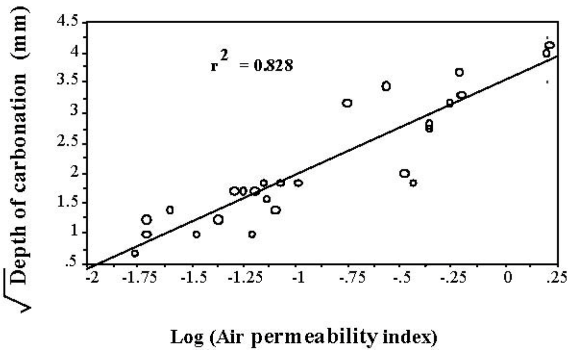


Fig. 6 Relationship between Autoclam air permeability and depth of carbonation

The depth of carbonation, salt scaling and the freeze-thaw deterioration are related to the Autoclam permeability index in Figs. 6, 7 and 8 respectively. Please note that in Fig. 8, the Autoclam water permeability is used instead of the Autoclam air permeability index because a better correlation was obtained with the water permeability index in the case of freeze-thaw deterioration. For the range of mixes investigated, there is a very high degree of correlation between the permeability indices and the durability parameters in Figs. 6-8. As all the durability parameters included in these figures are related to both the paste microstructure and the interfacial transition zone (i.e. the immediate region of the cement matrix around aggregates which has a higher porosity and different microstructure characteristics than the rest of the cement matrix) in concrete, it is natural to expect a very high correlation with the Autoclam permeability index, because the latter also depends on both these properties of the microstructure of the concrete. This means that an early prediction of the susceptibility to carbonation, salt scaling or freeze-thaw deterioration can be obtained by carrying out an *in situ* permeability test on the concrete, when the average relative humidity of concrete within 10mm depth from the surface is less than 80%.

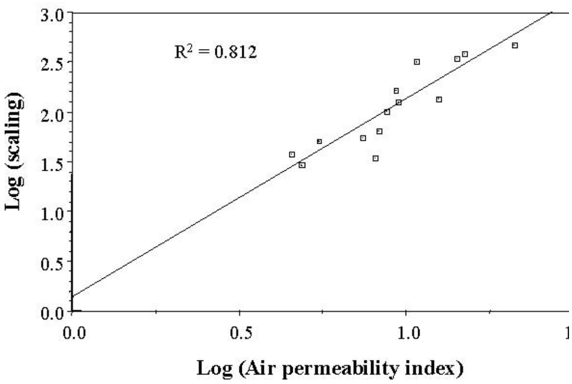


Fig. 7 Relationship between Autoclam air permeability and salt scaling

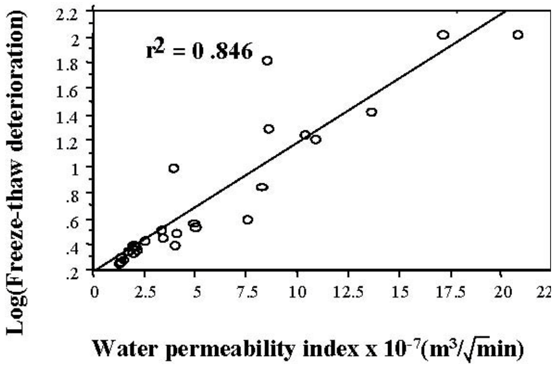


Fig. 8 Correlation between Autoclam water permeability and freezing and thawing deterioration

2.2. Dependence of durability parameters on Autoclam sorptivity index

Figures 9 and 10 present the relationships between the Autoclam sorptivity index and various durability parameters obtained. In Fig. 9, there is very high degree of correlation between the sorptivity index and the chloride penetration. This is considered to be because the chloride exposure regime for the data in Fig. 9 consisted of a wetting and drying cycle, for which the chloride penetration depended on the absorption characteristic of the concrete. From a practical point of view, the results in Fig. 10 are very encouraging because here a very good dependence of the corrosion initiation time on the sorptivity was obtained. The effect of the depth of cover on this relationship also can be seen in this figure.

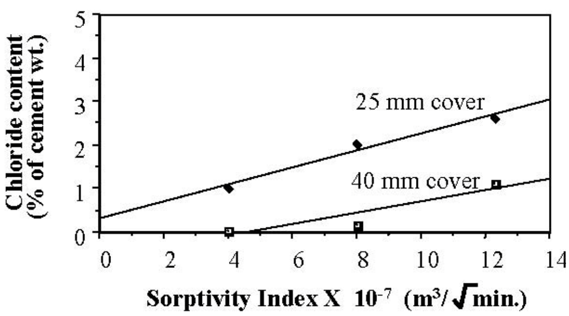


Fig. 9 Correlation between Autoclam sorptivity and chloride penetration

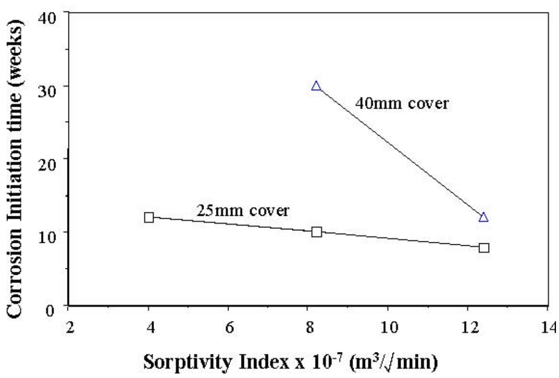


Fig. 10 Correlation between Autoclam sorptivity and corrosion initiation

On the basis of correlations found between various durability parameters and the Autoclam permeation indices, a set of classification criteria for normal quality concretes was developed (Table 1). A project recently funded by the UK Engineering and Physical Sciences Research Council aims to develop performance-based testing methodology for high performance concretes (McCarter and Basheer, 2008).

Table 1 - Protective Quality Based on Autoclam Air Permeability Index

Protective Quality	Autoclam Air Permeability Index (Ln(Pressure)/min)	Autoclam Sorptivity Index (m3 /√min) x 10-7

Very good	≤ 0.10	≤ 1.30
Good	> 0.10 ≤0.50	> 1.30 ≤ 2.60
Poor	> 0.50 ≤ 0.90	> 2.60 ≤ 3.40
Very poor	> 0.90	> 3.40

5. Electrode array sensors for monitoring changes in concrete cover

The covercrete electrode array (Fig. 19), developed by McCarter *et al.* (1995), was used in many projects in which the resistance to both chloride ingress and carbonation were studied (Basheer *et al*., 2002 and Basheer *et al*., 2006). The electrode array was also used in a marine exposure study carried out jointly between Heriot-Watt University Edinburgh and Queen's University Belfast (Fig. 20). Here the concrete blocks of size 300x300x200mm and concrete monoliths were exposed to the marine environment at Donarch in Scotland.

In Fig. 21, the normalised resistivity is presented for electrodes at five different depths from the exposure face of a block tested in a laboratory study. As can be seen from this figure, the resistance ratio decreased with time for all the electrode pairs, but the most affected electrodes were those nearer to the exposure face. Figure 22 shows the conductivity values of ggbs concrete blocks exposed to the marine environment. In this figure the as measured conductivity values, after correcting for the temperature variations, are presented, instead of the resistivity values. Here the conductivity decreased with time, i.e. the resistivity increased with time, unlike the data in Fig. 21. This indicates that not only the ggbs concrete provided resistance to the chloride ingress in the marine environment, but also the continued pozzolanic reaction had resulted in an improvement in its electrical resistance. Therefore, a greater level of corrosion protection could be expected from this concrete.

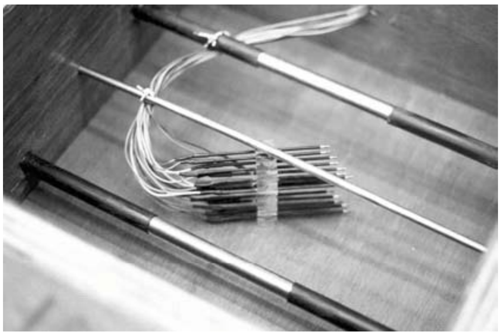


Fig. 19. Covercrete electrode array

Fig. 20. Laboratory exposure

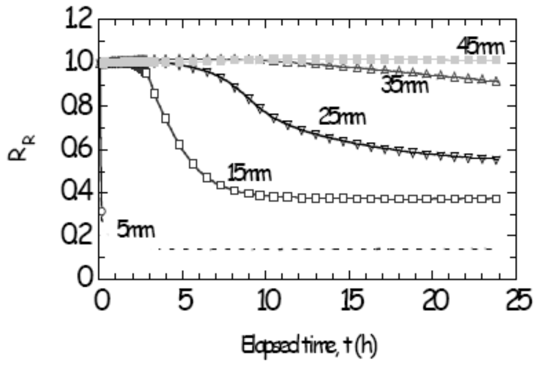


Fig. 21. Resistivity ratio for electrode pairs at different depths from the exposure face of a concrete block (OPC Concrete) (Y-axis resistivity ratio and X-axis elapsed time in hours)

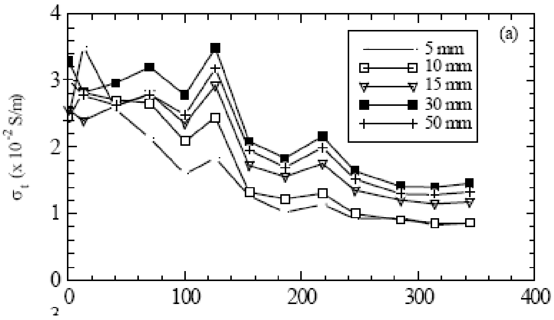


Fig. 22. Change of conductivity of ggbs concrete in the marine environment (Y-axis conductivity 10^{-2}S/m and X-axis time in days)

The current efforts are to use the electrode array sensors for monitoring early age properties of concrete, which could be used along with *in situ* testing of transport properties as a means of specifying concrete in terms of its performance. The recently awarded research grant (McCarter and Basheer, 2008) between Heriot-Watt University Edinburgh and Queen's University will be aiming to achieve this objective.

6. Concluding Remarks

In this paper, it has been demonstrated that *in situ* permeability tests, such as the Autoclam Permeability Test and Permit Ion Migration, could effectively be used to assess the durability of concrete structures on site. In addition, it was found that the fibre optic pH sensor probe could be used to monitor the pH (i.e. the effect of carbonation) in concrete.

Embedded sensors are useful during the initiation phase in Fig. 3. In the active or propagation stage, it is highly unlikely that monitoring devices may be of any significant benefit because they measure factors causing deterioration and not the extent of the deterioration, the latter is needed in the propagation stage. However, *in situ* test techniques could be used effectively, as illustrated by the strong correlations between permeation measurements and durability assessments. However, it is to be remembered that a combination of different types of non-destructive tests may be needed to assess the degree of deterioration in the propagation stage.

There was a good relationship between the *in situ* migration coefficient and the peak current. The theoretical relationship between the two also suggests that the two parameters are related using the transference number of the ionic species. Therefore, the *in situ* migration coefficient can be estimated from the peak current, which would make the test simpler for site applications.

The need for applying combinations of embedded sensors and *in situ* permeability tests to develop performance-based specification for concrete structures in different exposure conditions has been identified. Queen's University Belfast, Heriot-Watt

University Edinburgh and City University London aim to address this through various joint research projects.

References

Basheer, P.A.M., Chidiac, S. and Long, A.E., (1996) Predictive models for deterioration of concrete structures, *Construction & Building Materials*, Vol. 10, No. 1, pp 27-36.

British Cement Association, (1997) Development of an holistic approach to ensure the durability of new concrete construction, *BCA Research Report*, C/21.

Basheer, P.A.M., Long, A.E. and Montgomery, F.R., (1994) The Autoclam - a new test for permeability, Concrete, *Journal of the Concrete Society*, July/August, pp 27-29.

Basheer, P.A.M., Andrews, R.J., Robinson, D.J. & Long, A.E., (2005/4), 'PERMIT' ion migration test for measuring the chloride ion transport of concrete on site, *NDT & E International*, vol. 38, no. 3, pp. 219-229.

Nanukuttan, S.V., P.A.M. Basheer and D.J. Robinson, (2006) "Further developments of the Permit Ion Migration test for determining the chloride diffusivity of concrete", *Structural Faults and Repair-06*, Edinburgh, Eds: M.C. Forde, Vol. CD Rom, Engineering Technic Press, June, pp 14 pages.

McCarter ,W. J., Emerson, M. and Ezirim, H., (1995) 'Properties of concrete in the cover zone: developments in monitoring techniques', *Mag. Conc. Res.*, Vol. 47, No. 172, pp243-251.

McCarter, W.J., Basheer, P.A.M. et al, (2008-2011) Development of a Performance-based specification for assessing concrete durability, EPSRC EP/G02152X/1 and EP/G025096/1.

Nilsson, L.-O., Poulsen, E., Sandberg, P., Sorensen, H.E. and Klinghoffer, O., (1996)HETEK, *Chloride penetration into concrete, state-of-the-art-, transport processes, corrosion initiation, test methods and prediction models*, Report No. 53.

Basheer, P.A.M., Gilleece, P.R.V., Long, A.E. and McCarter, W.J., (2002) Monitoring electrical resistance of concretes containing alternative cementitious materials to assess their resistance to chloride penetration., *Cement and Concrete Composites*, Special Issue on Electrical Monitoring and Characterisation of Cementitious Systems, 24 (5), pp 437-449, Invited contribution. ISSN 0958-9465.

Basheer, P.A.M., Russell, D., Andrews, R. and McCarter, W.J., (2006) Monitoring internal changes in concrete during carbonation and chloride ingress using a covercrete electrode array, *Structural Faults and Repair-06*, Edinburgh, Eds: M.C. Forde, Vol. CD Rom, Engineering Technic Press, 2006 June, pp 13 pages.

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