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METHODS OF ASSESSING THE DURABILITY AND SERVICE LIFE OF CONCRETE STRUCTURES

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ABSTRACT: Characterisation of cover concrete is often the most viable means for assessing the durability and has become increasingly evident over the past 20 years. A variety of field methods and laboratory techniques exist, which provide a number of properties, such as air permeability index, water absorption rate, water permeability index, chloride diffusivity, electrical resistivity, moisture content and porosity gradient. Most techniques are economical and appropriate for assessing the durability of structures subjected to a single mechanism of deterioration. In reality, structures may face multiple deterioration mechanisms, stress/strains due to both environmental and structural loading and related acceleration of deterioration. Developing an understanding of such multimode deterioration may help in addressing the performance gap between laboratory and field. In this paper, a brief review of some of the ways by which a performance testing strategy could be developed is given so that service life prediction could be more realistic.

Keywords: *in situ* permeation test methods, sensor systems, structural health monitoring, durability assessment

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INTRODUCTION

For the design of concrete structures, durability and service life prediction have increasingly gained importance in recent years. This comes as a result of inadequate durability performance of many reinforced concrete structures built in the past few decades, which places enormous strain on construction budgets worldwide [1]. The dominant cause of premature deterioration of concrete structures is reinforcement corrosion (Figure 1) [2]. Traditional durability design approaches have been based on prescribed limiting values for selected mix design parameters, e.g. European Standard EN206-1 [3] deals with durability of concrete entirely on the basis of prescriptive specification, although it refers to performance-related design methods (in the appendix) as an alternative. However, further development of performance-based specifications has been hampered by the lack of reliable, consistent and standardised test procedures and protocols for evaluating concrete performance [4, 5].

Mehta [6] considered reinforced concrete with discontinuous micro-cracks as the starting point of an holistic model for factors influencing its durability. He considered that environmental factors causes the micro-cracks to propagate until they become continuous, which then results in permeability to influence the transport of moisture and aggressive ions into the concrete. Thereafter, crack growth (which depends on the fracture strength) accelerates the penetration of aggressive substances into the concrete, which in turn activates any one or a number of other mechanisms of deterioration. The interdependence of all these factors and the importance of the permeation characteristics and the strength of concrete can be seen more clearly in the composite diagram in Figure 2 [7].

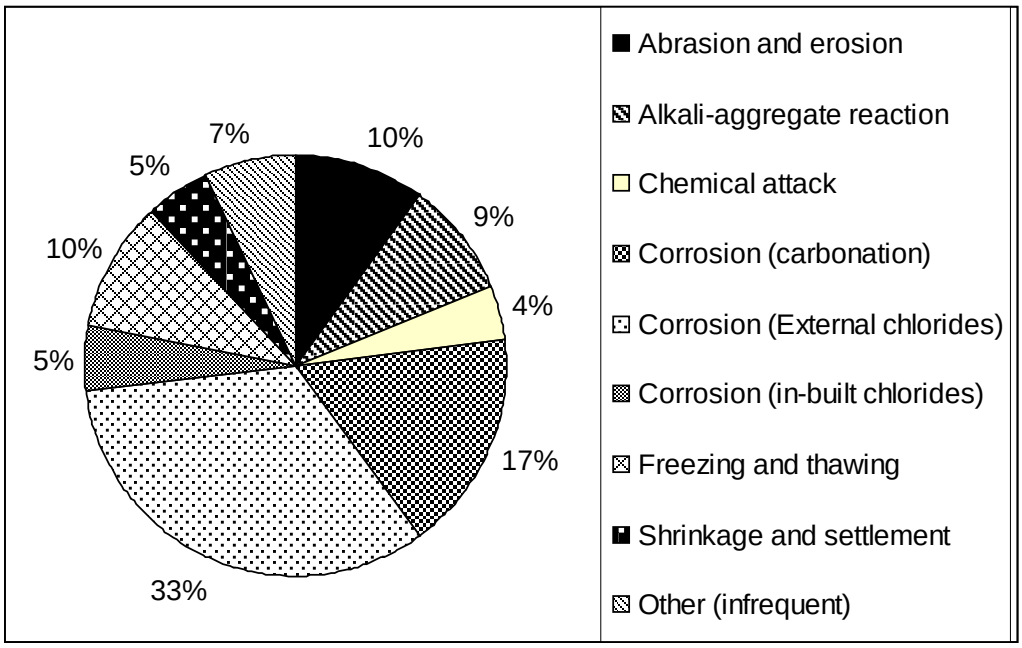


Figure 1: Most frequently reported mechanisms of deterioration of reinforced concrete structures [2]

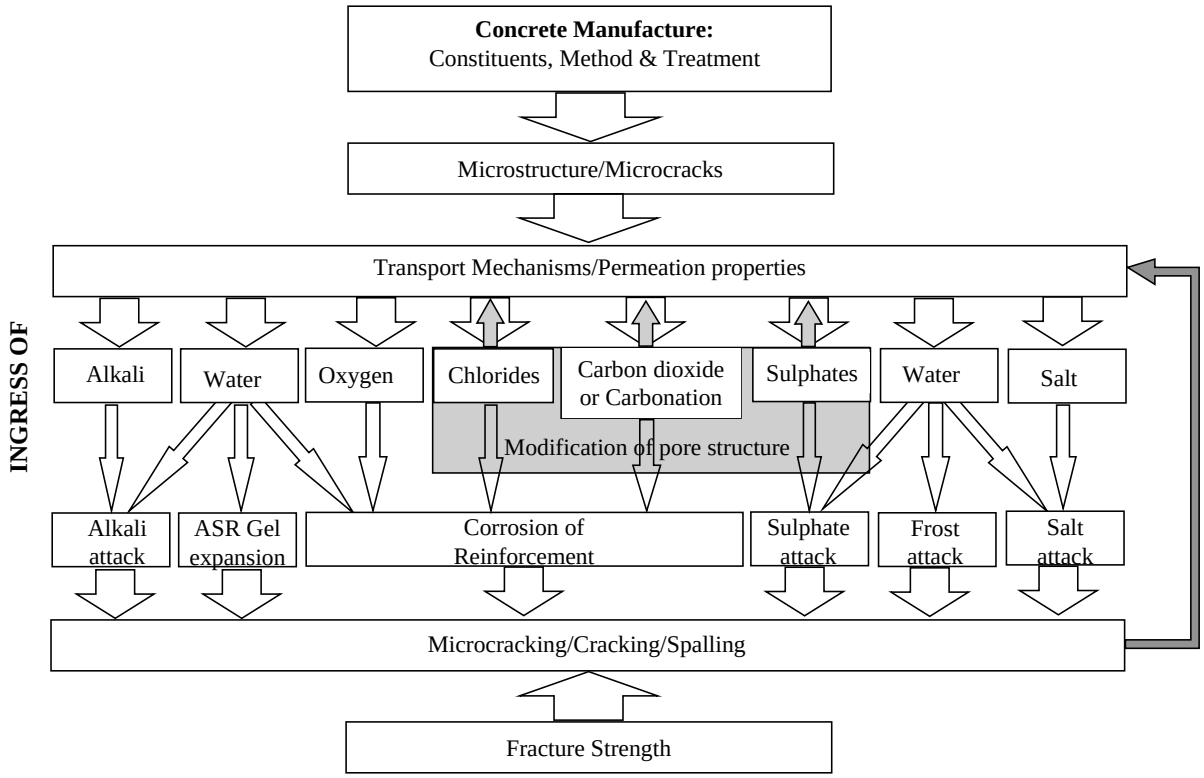


Figure 2: Dependence of durability of concrete on microstructure and transport mechanisms [7]

Figure 2 illustrates that the deterioration of reinforced concrete is related to its microstructure and the transport of the aggressive substances [7]. Thus an assessment of the durability of concrete structures can be made in terms of the measured permeation properties. As shown in the figure, the advance of the chloride front and the carbonation front depends on the permeation properties of the concrete cover. Therefore, a measure of permeation properties of concrete cover enables a good

estimate the durability of reinforced concrete structures. Over the last two decades, many techniques have been proposed for assessing the *in situ* permeation properties of concrete. Amongst these, the assessment of water absorption, air permeability and chloride diffusivity of the near-surface concrete is recognised as a reliable means to qualify and quantify durability performance [8, 9].

Ideally, performance testing techniques should provide information on the integrated quality of concrete cover as a function of time. Although the quality of concrete cover could be assessed by performance parameters such as sorptivity, depth and rate of water penetration, ionic (and gas) transport resistance, durability depends also on microcracking due to material and exposure characteristics, the moisture loss or residual moisture profile, cyclic and seasonal effects, hydration and pozzolanic effects and electrical properties of concrete. Whilst this list is by no means exhaustive, it does highlight the complex problem of assessing the durability of concrete structures. Various sensors have also been developed to either individually or collectively assess these parameters and this paper offers an overview of one type of sensor system, viz. electrical resistance sensors, in addition to various permeation methods. The usefulness of these techniques for a range of testing conditions is demonstrated so that some of them could be recommended to form the basis of performance based specifications of concrete structures in different service environments.

TECHNIQUES FOR TESTING AND MONITORING PERFORMANCE OF CONCRETE STRUCTURES

Laboratory methods for assessing permeation properties

■ Permeability methods

The techniques to determine permeability of concrete can be broadly divided into two categories, gas (air) permeability tests and water permeability tests. Gas permeability coefficients can be determined by either measuring the flow of gas at a constant pressure or by monitoring the pressure decay over a specified time interval [10]. The rate of outflow is measured for the steady-state gas permeability test. The other type of air test, referred to as falling pressure test, utilises the pressure decay to compute a gas permeability coefficient. Gas permeability tests became popular because of short test duration and the limited effect the test variables have on the pore structure during measurements [11].

Water permeability can be determined by either steady-state or non-steady state water flow measurements as well as water penetration under the influence of an external pressure head [11, 12]. The main difference between them is the test duration. The time required to obtain a steady-state flow varies from a few days to several weeks or months depending on the quality of concrete [13, 14], while the test duration of non-steady state tests is much shorter, generally less than 3 days. The test developed by El-Dieb and Hooton [14] needs to be highlighted due to its novelty. Compared to other methods, it provides a wide range of test pressure from 0.5 MPa to 3.5 MPa and improves the accuracy of the flow measurement. The range of water permeability coefficient determined by Nokken and Hooton [15] varies from 10^{-13} to 10^{-15} m/s, which is in agreement with the results reported by others using similar test arrangements [16, 17]. As the steady state tests require long test duration to achieve the steady state, the depth of water penetration in concrete also has been used to determine the water permeability coefficient for low permeability concretes. This method has been standardised and is outlined by BS EN 12390-8:2000 [18]. Chia and Zhang [19] and Pocock and Corrans [20] found that the scatter of results is quite high and the coefficient of variation of the test results is above 100%. Table 1 gives a summary of typical values and their variance for different test methods.

Table 1 Summary of typical values and variance of permeability coefficients determined by different test methods

Permeability coefficient	Concrete			Variance (CoV)
	Poor	Normal	Good	
K_{gas} (m^2)	$>10^{-13}$	10^{-14}-10^{-15}	$<10^{-16}$	15%-30%
$K_{water\text{-}s}$ (m/s)	$>10^{-11}$	10^{-11}-10^{-13}	$<10^{-14}$	20%-40%
$K_{water\text{-}ns}$ (m/s)	$>10^{-10}$	10^{-10}-10^{-12}	$<10^{-13}$	40%-100%

Note: 1) K_{gas} is the air permeability coefficient determined by the steady-state constant head test; 2) $K_{water\text{-}s}$ is the water permeability coefficient determined by the steady-state constant water head test; 3) $K_{water\text{-}ns}$ is the water permeability coefficient determined by the non-steady-state constant water head test.

■ Ion diffusion

The transport of chloride ions can be assessed by means of an ionic diffusion test [10, 21]. Such tests can be grouped into two categories; diffusion based and migration based methods. The diffusion tests simulate the movement of chloride ions under the influence of a concentration gradient. Traditional set-up includes either diffusion cells (steady-state and non-steady state), the immersion or ponding (non-steady state). In the case of steady state tests, the rate of ionic transport is measured and using Fick's first law of diffusion the diffusion coefficient is calculated. In the case of non-steady state tests, the depth of penetration of chlorides is used to calculate the diffusion coefficient by using Fick's second law of diffusion. The steady state diffusion test typically requires six months or more to achieve a steady state of flow. The duration is short for non-steady state tests. The immersion and ponding tests usually take around 90 days, which can be used to assess chloride resistance for most construction projects if time is available.

Many techniques have been proposed since 1980 that applies an external electrical field to accelerate the ingress of chloride ions. Some of the tests even utilised a higher concentration of chloride source solution to further expedite the movement [21]. One of the first tests in this category is the Rapid Chloride Permeability Test (RCPT) and this was adopted as a standard test by AASHTO T277 [22] and ASTM C1202 [23]. In this test, the resistance of concrete against chloride is categorised by the total charge passing through the specimen in the first 6 hours. As charge is carried out by other ions as well as chlorides during the test, this test has been criticised by some researchers [24]. Latest in the series is the steady-state migration test. The test arrangement is similar to RCPT, but the chloride concentration of the anolyte is measured, instead of the charge passed. The migration coefficient is calculated using a modified Nernst-Planck equation [21]. Tang and Nilsson proposed a rapid test based on the non-steady state chloride migration theory, known as the rapid chloride migration (RCM) test [25]. The chloride migration coefficient is calculated from the chloride depth and using a modified Nernst-Planck equation. Currently, this method is included in the Nordic standards [26]. Due to short test duration and simplicity, the three migration based methods have an advantage over diffusion based tests for determining the chloride transport resistance of concrete. However, as stated earlier, the RCPT has several inherent problems. It is reported that this method measures conductivity of the pore solution, rather than chloride transport properties [24, 27]. The temperature rise due to the high voltage can significantly affect the conductivity of ions and, hence, the final result in Coulombs. Therefore, the RCPT cannot provide a reliable indication of chloride migration. The typical results of ionic diffusion/migration coefficients are given in **Table 2**.

Table 2 Summary of typical values and variance of ion diffusion/migration coefficients determined by different test methods

Diffusion coefficient	Concrete			Variance (CoV)
	Poor	Normal	Good	
D_s (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-12}$	15%-25%
D_{ns} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-13}$	20%-35%
D_{ms} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-13}$	20%-35%
D_{mns} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-13}$	20%-35%

Note: 1) D_s is the ion diffusion coefficient determined by the steady-state test; 2) D_{ns} is the ion diffusion coefficient determined by the ponding or immersion test; 3) D_{ms} is the ion migration coefficient determined by the steady-state migration test; 4) D_{mns} is the ion migration coefficient determined by the non-steady-state migration test.

Field methods

■ In situ permeability tests

Air permeability tests have gained popularity due to their short test duration and the fact that concrete pore structure is unaffected during the test. Schonlin and Hilsdorf [28] developed a surface-mounted air permeability test method that could measure the pressure drop to calculate an air permeability index. This falling pressure method is extremely fast and can be performed by a single operator. Later, numerous researchers modified the setup and theory of this technique. This type of surface-mounted air permeability tests can identify the effects of w/b, curing duration and curing temperature on permeability under controlled test conditions. However, it should be noted that in order to yield reliable results, the concrete should be in a moisture state equivalent of 21 days of drying in an oven at 40 ºC. This can be ensured by achieving a relative humidity of less than 60% in the near-surface region of approximately 40mm thickness [10, 11].

The above moisture condition is not easy to achieve *in situ*, especially in most parts of northern Europe, where annual rainfall averages from 80 to 110 times [29]. Therefore, it is logical that concrete in structures should be tested when it is in a saturated condition rather than in a dry state. *In situ* water permeability tests are preferable to air permeability tests for assessing the quality of concrete in these regions. The CLAM test, first reported by Montgomery and Adams [30], for measuring the water permeability of *in situ* concrete was modified by Basheer *et al.* [31], which is currently available as Autoclam Permeability System (Figure 3). It is a constant head permeability test and the water permeability is estimated either by the steady state or non-steady state flow theory. In the latest version, a test pressure of 7 bar could be selected to assess high-performance concrete and improve the repeatability and accuracy of the measurements [11, 32].

(a) CLAM water tester (b) Autoclam permeability test system

Figure 3: Different versions of CLAM permeability tests

■ *In situ* chloride migration tests

The steady state diffusion tests are not suitable for *in situ* application due to the long test duration. An external electric field can remarkably accelerate the ion transport and, hence, some migration tests have been designed as field test techniques. Three methods can be found in the literature, which are the Coulomb test [33], the *in situ* rapid chloride migration test (RCM test) [21] and the PERMIT ion migration test [34].

Whiting [33] developed the Coulomb test on the basis of the RCPT method. The charge passed is considered as an index to assess the diffusivity of concrete. As discussed before [22], the Coulomb test provides an estimate of the charge carried by all ions and not just chlorides. Moreover, this technique does not provide a migration coefficient. The second field method was developed by Tang and Nilsson, as reported by Tang *et al.* [21] based on the rapid chloride migration (RCM) test. An external potential voltage is applied through the reinforcement bar and cathode in the chamber. After the measurement, a core is taken from the test position and the chloride penetration front is examined by the colorimetric technique. The cores are needed for the *in situ* RCM and, hence, there is no obvious advantage compared with laboratory methods.

The PERMIT ion migration test (Figure 4) was developed by Nanukuttan *et al.* [34]. Both the anolyte and the catholyte chambers are in the form of concentric cylindrical reservoirs. The chloride ions move from the catholyte towards the anolyte through the concrete due to the application of an electric field. The chloride movement is monitored by conductivity of the anolyte solution and the in situ migration coefficient is evaluated by a modified Nernst-Planck equation. Validation of the PERMIT has been carried out by comparing the coefficients from Permit test against the one-dimensional chloride migration test, the effective diffusion coefficient from the normal diffusion test and the apparent diffusion coefficient determined from chloride profiles [27, 34]. The results show that for a wide range of concrete mixes, a high degree of correlation exists between the *in situ* migration test and the laboratory based tests, the results of which are given in Figure 5.

Figure 4: The PERMIT ion migration test apparatus

Electrical resistivity sensors

The electrical resistance of concrete is a function of several factors, including the geometrical configuration of the measuring electrodes, the tortuosity of the capillary pores, degree of pore saturation, and the concentration and mobility of ions in the pore solution [35, 36]. It can be used to monitor moisture movement, chloride ingress, carbonation and the likelihood of corrosion. The concrete resistance can be measured either with direct current (d.c.) or alternating current (a.c.). Due to electrode polarisation problems in dc mode, the current and potential electrodes are separated and a

four-point (or Wenner) configuration is used, while for ac measurements only two electrodes are required. The use of an a.c. signal normally reduces spurious electrode polarization effects and a frequency in the region of 5 kHz, in most circumstances, is sufficient to reduce such polarization problems to minimal proportions [36].

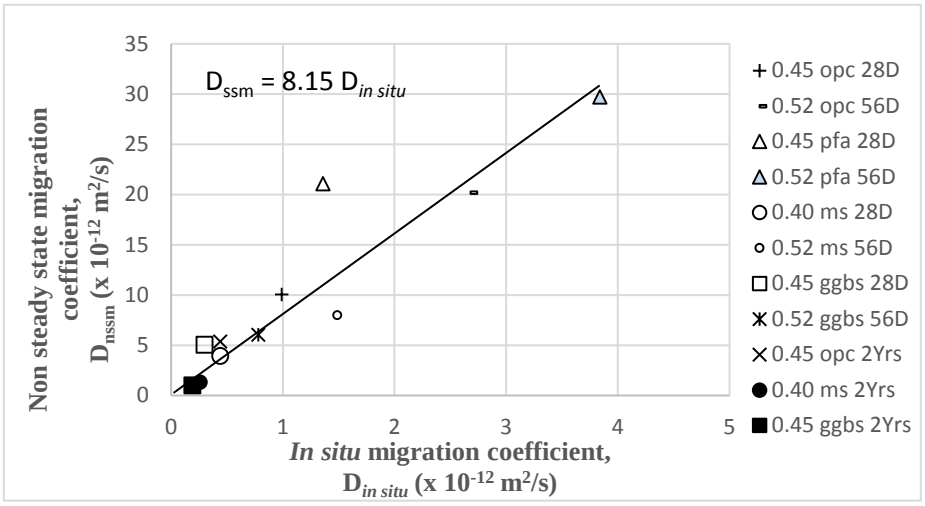


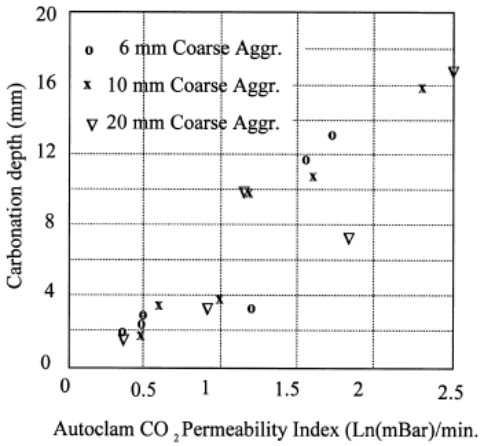
Figure 5: Correlation between Permit in situ migration coefficient and non-steady state migration coefficient for different types of concrete [34]

The temperature of the concrete at the time of measurement is also important. Therefore, it is normal to present resistivity data at a predefined reference temperature, normally 25 ^{o}C, and temperature compensation formulae can be applied to the measured resistance data. This will assist in distinguishing changes in resistivity due to temperature and those due to changes in ionic concentration in the pore fluid and degree of saturation of the concrete. Miniature, multi-electrode (and thermistor) arrays embedded within the cover zone allow monitoring of the electrical properties (and temperature) of concrete at discrete depths from the exposed surface [37]. This can then be used to provide information on continuing hydration and pozzolanic reaction, wetting and drying effects, ionic ingress and the effectiveness of surface treatments.

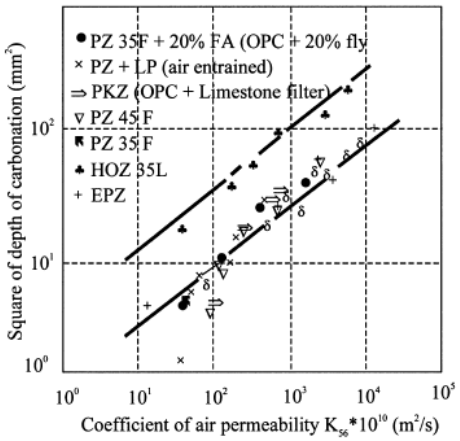
RELATIONSHIP BETWEEN PERMEATION TEST METHODS AND MEASURES OF DURABILITY

Relationship with carbonation

Several researchers attempted to establish the relationship between carbonation and both air permeability and water absorption. Figure 6 shows some of the results from the literature. It can be seen that there is a strong relationship between them in all these cases. Dhir *et al.* [38] also reported similar observations between Figg air permeability and depth of carbonation. However, the relationships were built based on empirical analysis and were dependent on the methods used. Therefore, it is safe to conclude that concretes with high air permeability will carbonate more, but precise prediction is still questionable, as no unique relationship exists at present for the whole range of concrete types and strength class used in structures.



(a) Air (CO_2) permeability index (Autoclam) vs carbonation depth [10]



(b) K_{air} VS (carbonation depth)$^{0.5}$ [38]

Figure 6: The relationship between carbonation and air permeability

Relationship with chloride induced corrosion

Basheer *et al.* [39] reported the evidence of links between chloride ingress, corrosion initiation time and sorptivity. In their study, cyclic ponding was carried out weekly to allow the chloride transport into concrete and the total test duration was 44 weeks. The chloride content and corrosion initiation time were measured and the effects of water cement ratio (0.45, 0.55, 0.65) were determined. The relationship between sorptivity (determined with Autoclam) and the chloride content is given in Figure 7, where 25 mm and 40 mm represent the depth from the surface subjected to ponding. It can be seen that a fairly strong relationship exists and as expected the chloride content is lower at greater depths, suggesting that water absorption index can serve as a quick indicative approach. This trend needs to be verified for concrete containing supplementary cementitious materials so that the influence of binding, if any, can be considered in the relationship.

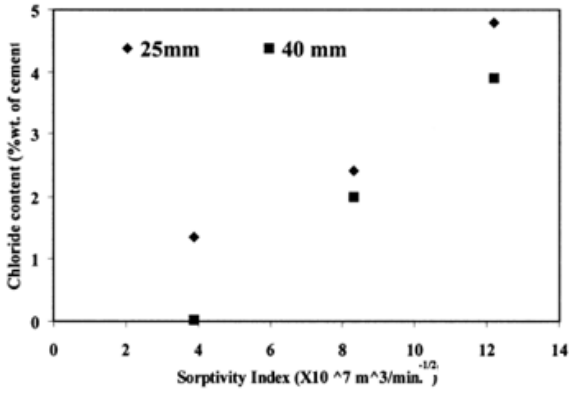


Figure 7: Relationship between sorptivity index and chloride content at two different depths [39]

The relationship between sorptivity and corrosion initiation time is shown in Figure 8 [39]. Although there exists a good trend between sorptivity and the corrosion initiation time, of the interaction between sorptivity, cover depth and corrosion initiation time can also be seen in this figure. That is, the effect of sorptivity is dominant at the lower cover of 25mm for the concrete studied. In other words, in addition to providing good quality concrete a minimum cover depth also is needed to ensure greater protection against chloride induced corrosion.

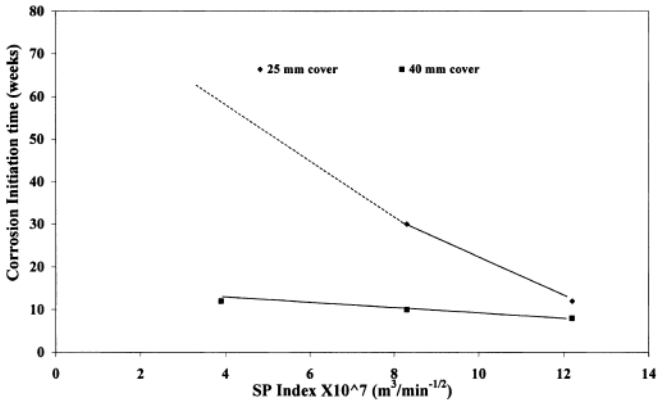


Figure 8: Relationship between sorptivity index and corrosion initiation time [39]

INFLUENCE OF THE EFFECT OF SERVICE LOADING AND THE RESULTING MICRO-CRACKS ON RESISTANCE TO CHLORIDE INGRESS (AS EXPRESSED BY CHLORIDE MIGRATION COEFFICIENT)

It has been recognised that structural cracks do influence the chloride transport and chloride induced corrosion in reinforced concrete structures, but there is little published work on the influence of micro-cracks due to service loads on these properties. Thus, the effect of micro-cracks caused by loading on chloride transport into concrete was studied by Wang *et al.* (40). Four different stress levels (0%, 25%, 50% and 75% of the stress at ultimate load – f_u) were applied to 100 mm diameter concrete cores and chloride migration coefficient was determined using a bespoke test setup based on the NT BUILD 492 test. The effects of replacing Portland cement CEMI by ground granulated blast furnace slag (GGBS), pulverised fuel ash (PFA) and silica fume (SF) on chloride transport in concrete under sustained loading were studied. The results are shown in Figure 9, which indicate that chloride migration coefficients changed little when the stress level was below 50% of the $f_{u,,}$ suggesting that it is desirable to keep concrete stress less than 50% f_u if this is practical. The effect of removing the load on the change of chloride migration coefficient was also studied. An increase of loading up to 50% did not cause any significant non-recoverable damage to concrete as far as the migration coefficients are concerned. However, the increase of loading above 50% of f_u resulted in a significant change in migration coefficient between unloaded condition and no load condition.

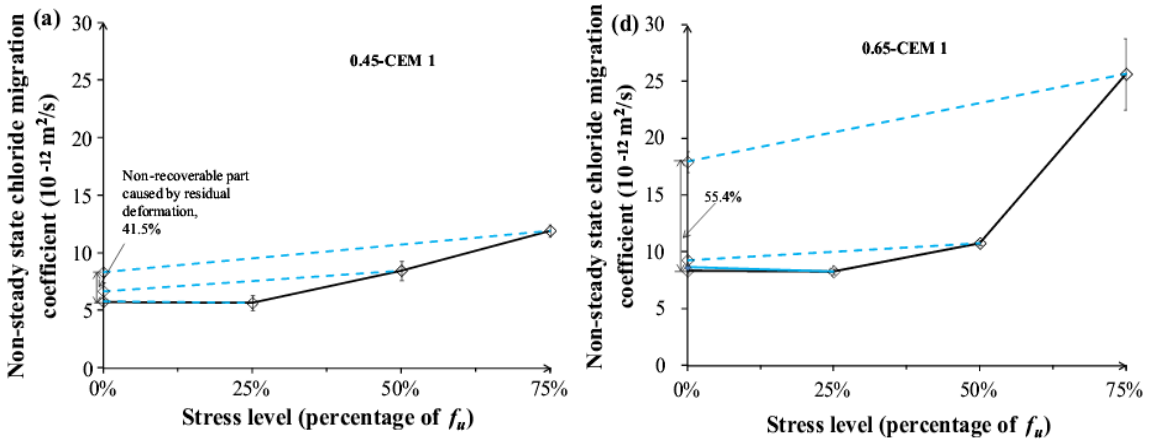


Figure 9: Relationship between applied stress level and chloride migration coefficient [40]

EFFECT OF COMBINED CARBONATION AND CHLORIDE INGRESS IN CONCRETES (AS QUANTIFIED BY AIR PERMEABILITY AND CHLORIDE MIGRATION COEFFICIENTS)

In many exposure environments for concrete structures, there is a high probability of the cyclic effect of both the chloride ingress and carbonation. Wang *et al.* (41) reported a detailed investigation on the influence of carbonation on both the ingress and distribution of chlorides in three different types of concretes, by comparing results from exposure to chlorides, chlorides before carbonation and chlorides after carbonation. Concretes studied were of 0.55 water-binder ratio with 100% Portland Cement (PC), 70% PC + 30% pulverized fuel ash (PFA) and 85% PC + 10% PFA + 5% microsilica (MS) as binders. Chloride profiles were compared to assess the effects of all variables studied in this research. The effect of carbonation was quantified by measuring air permeability and its influence on chloride transport was measured in terms of chloride migration coefficient. The results, shown in Figure 10, indicate that carbonation of concrete increases chloride transport, but the precise nature of this is dependent on the combined regime as well as the type of binder. In general, it was found that carbonation of chloride contaminated concretes results in a decrease of their chloride binding capacity, that is it releases the bound Cl^- in concretes and pushes chlorides inwards, as has been established previously by other researchers. It has also been established that the combined regimes detrimentally affect the service life of concrete structures, particularly when chloride induced corrosion is a concern.

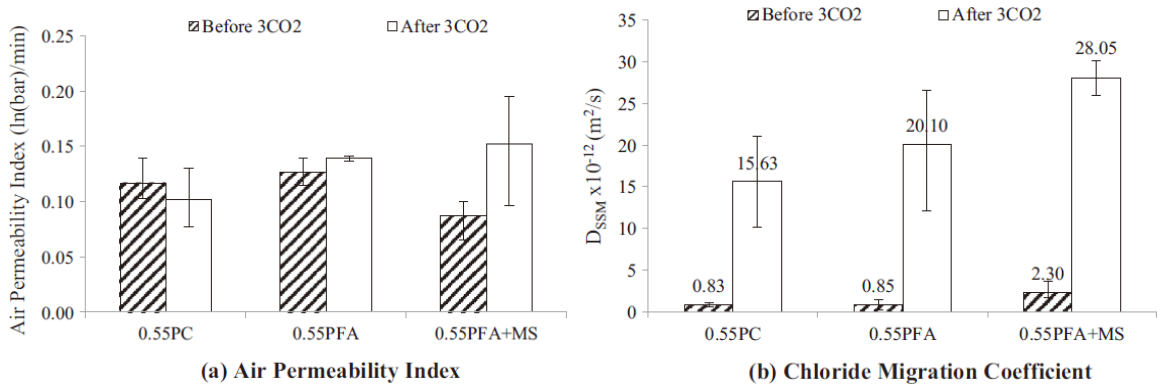


Figure 10: Influence of carbonation on air permeability and chloride migration coefficient of different types of concrete [41]

USE OF ELECTRICAL RESISTIVITY MEASUREMENTS TO ASSIST THE PERFORMANCE TESTING APPROACH FOR CONCRETE STRUCTURES

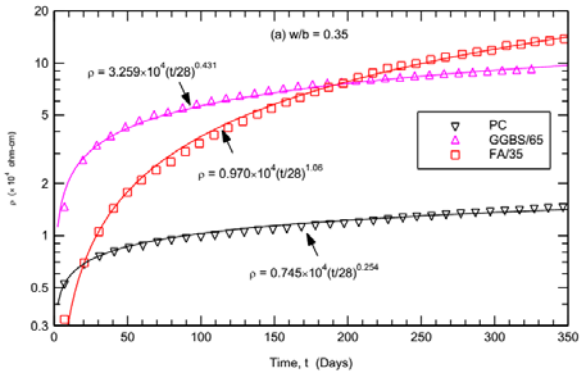
The challenges posed by a performance-based testing and specification approach to ensure the service life of concrete structures have been acknowledged. Amongst the different types of sensors available, the resistivity sensors, such as the Covercrete Array by McCarter *et al.* [37] have been found to be promising for performance monitoring and compliance testing. To investigate its applicability, the electrical response of concrete under long-term hardening and cyclic ponding was monitored up to 350 days. Figures 11 (a) and (b) display the resistivity at 75mm from the surface from 7-days up to approximately 350 days for both 0.35 and 0.65 w/b ratio. The influence of supplementary cementitious materials on the resistivity is clearly evident from these two figures; at the end of the test period, the

resistivity of the FA/35 and GGBS/65 mixes are almost an order of magnitude higher than the PC mix, at both w/b ratios. The increase in resistivity for both the GGBS and FA concretes reflects the on-going reactivity of the SCMs and pore structure refinement during the post-curing period. The temporal increase in resistivity for the concretes can be represented by the equation of the form:

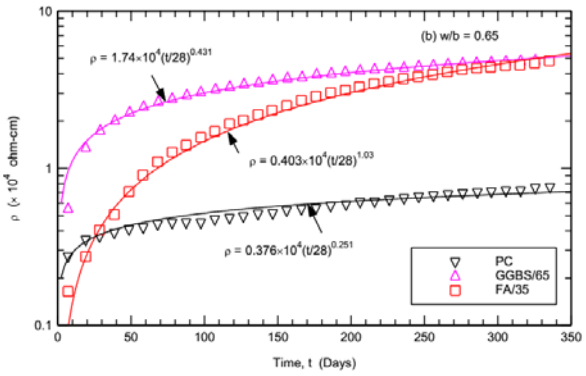
$$\rho_t = \rho_{ref}\left(\frac{t}{t_{ref}}\right)^n$$

where, ρ_t is the resistivity (ohm.cm) at time, t (days); ρ_{ref} is the resistivity at a reference time, t_{ref}, and n could be regarded as an aging exponent which will be related to hydration and pozzolanic reaction. The reference time could be taken as 28-days, hence t_{ref} = 28-days and the respective resistivity at 28-days is ρ_{ref}. Best-fit curves to the data are plotted in Figures 11-(a) and (b) (solid lines) through the measurement points with the fitting equations presented on these figures.

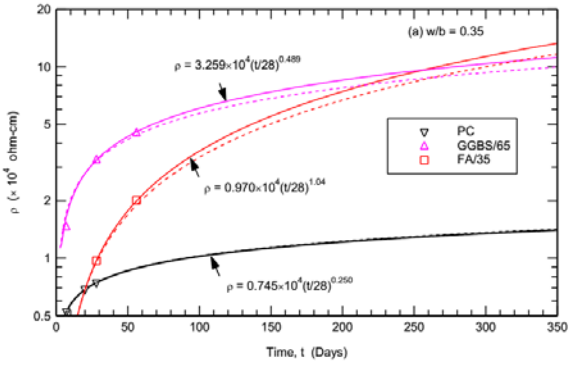
Although the equations on these figures were developed on the best-fit line to all the data points for a particular w/b ratio, a curve could be evaluated from fewer measurements, which has obvious practical implications. Figures 11 (c) and (d) present the best-fit curves (solid lines) based on resistivity measurements at 3 measurement points (7, 28 and 56 days) using the same reference time of 28-days. For comparative purposes, the best-fit curves based on all the measurement points on Figure 11 (a) and (b) are also presented, from which a fairly strong agreement can be found.

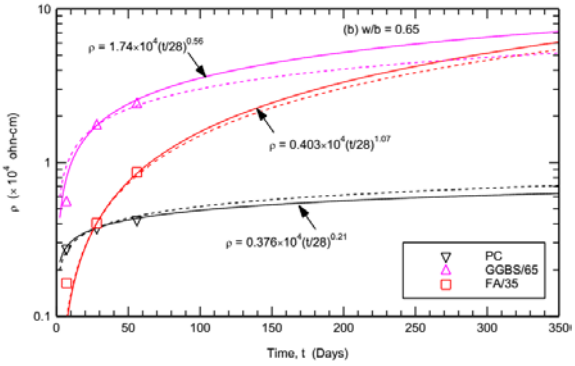


(a) Measured data for w/b = 0.35



(b) Measured data for w/b = 0.65 f





(c) Prediction based on early results for w/b = 0.35 (d) Prediction based on early results for w/b = 0.65 (solid lines in both graphs, Dash lines are curves fitted based on all measurement points)

Figure 11: Increase in resistivity of different types of concrete (FA/35: 35% FA + 65% PC; GGBS/65: 65%GGBS + 35% PC) over the period 7-350 days after casting [42]

Once the resistivity is predicted using early data as indicated in Figures 11(c) and (d), it is possible to estimate the change in resistivity over the life time of the structure. This would give information on pore structure (more specifically pore connectivity) and the instantaneous chloride diffusion coefficient. Once this methodology is validated in on-going research projects, the performance indicator of concrete can be assessed by monitoring electrical responses, which could be considered as a step in the right direction for developing performance specifications and service life prediction models for structures in service.

CONCLUSIONS

Both *in situ* testing and monitoring methods have been found to be useful for assessing the resistance of the covercrete against carbonation, chloride ingress and chloride induced corrosion of steel in concrete. A range of methods exists for determining the air permeability, water permeability and ionic transport resistance of concrete. Air permeability measurements are likely to be influenced by the moisture distribution in the cover region of the concrete. However, they are easy to carry out and have short test duration. Non-steady state water penetration tests are also influenced by the moisture gradient of the cover concrete. Therefore, saturated water permeability tests are preferable. Although cores extracted from structures in service could be tested in the laboratory under controlled temperature and moisture conditions, reliable *in situ* permeability tests have the advantage of carrying out numerous tests at the same test location, without damaging the structure. To determine the chloride transport resistance, there exist both steady state and non-steady state diffusion tests as well as steady state and non-steady state migration tests. They all have their own specific benefits as well as drawbacks. Diffusion tests normally have long test duration. Therefore, migration tests have become very popular and they can be completed within an acceptable test duration.

It has been found that there exists good correlation between permeation measurements and durability indicators. The effects of service loading and combinations of exposure on these durability indicators could be quantified using the various permeation test methods. Therefore, these test methods could form the basis of developing a performance based specification strategy for concrete structures.

Further, it has been established that the measurement of electrical resistivity at early stages of cement hydration could form the basis of predicting its longer-term behaviour. Therefore, further research relating the electrical resistivity to durability parameters could form the basis of an approach to specify durability and test for its compliance for structures in service.

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