Revista ALCONPAT
www.revistaalconpat.org
eISSN 2007-6835
Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción

Challenges and opportunities for assessing transport properties of high-performance concrete

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DOI: http://dx.doi.org/10.21041/ra.v8i3.301

Reception: 03/03/2018 | Acceptance: 04/07/2018 | Publication: 31/08/2018

ABSTRACT

In this paper, a review of techniques is given so that both, the challenges and opportunities for assessing transport properties of high-performance concrete, are highlighted. A knowledge of performance of structural concrete is required for design and compliance purposes. One driving force for the use of high performance concretes (HPC) is enhanced durability yet it would be wrong to assume that all HPCs can deliver the desired performance level. In situ characterisation of the permeation properties of concrete is the most viable means for assessing durability and has become increasingly important over the past 20 years. A variety of methods exist that provide a range of parameters, e.g. air permeability, water absorption rate, sorptivity and chloride migration coefficient.
Keywords: high-performance concrete; permeation properties; performance-based specification; NDT test methods; reliability.

Cite as: K. Yang, S. Nanukuttan, W. J. McCarter, A. Long, P. A. M. Basheer (2018), *"Challenges and opportunities for assessing transport properties of high-performance concrete"*, Revista ALCONPAT, 8 (3), pp. 246-263, DOI: http://dx.doi.org/10.21041/ra.v8i3.301

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Any dispute, including the replies of the authors, will be published in the second issue of 2019 provided that the information is received before the closing of the first issue of 2019.

Desafios e oportunidades para conhecer as propriedades dependentes dos mecanismos de transporte nos concretos de alto desempenho

RESUMO

Neste artigo, é feita uma revisão dessas técnicas, destacando os desafios e as oportunidades para avaliar as propriedades de transporte do concreto de alto desempenho. O conhecimento do desempenho do concreto estrutural é necessário para propósitos de projeto e conformidade. Uma das fortes vantagens para o uso de concreto de alto desempenho (HPC) é obter uma durabilidade destacada, mas seria errado supor que todos os HPCs podem fornecer, automaticamente, um nível de desempenho desejado. A caracterização in loco das propriedades de permeabilidade do concreto é o meio mais viável para avaliar a durabilidade e tem se tornado cada vez mais importante nos últimos 20 anos. Existe uma variedade de métodos que fornecem uma gama de parâmetros, como, por exemplo, permeabilidade ao ar, absorção de água, absorção capilar, e coeficiente de migração de cloretos.

Palavras-chave: concreto de alto desempenho; permeabilidade; especificação por desempenho; ensaios não destrutivos NDT; confiabilidade.

Retos y oportunidades para evaluar las propiedades de transporte del concreto de alto rendimiento

RESUMEN

En este artículo, se hace una revisión de estas técnicas, destacando los desafíos y las oportunidades para evaluar las propiedades de transporte del concreto de alto desempeño. El conocimiento del desempeño del concreto estructural es necesario para propósitos de diseño y conformidad. Una de las fuertes ventajas para el uso de concreto de alto rendimiento (HPC) es obtener una durabilidad destacada, pero sería erróneo suponer que todos los HPC pueden proporcionar automáticamente un nivel de rendimiento deseado. La caracterización in situ de las propiedades de permeabilidad del concreto es el medio más viable para evaluar la durabilidad y se ha vuelto cada vez más importante en los últimos 20 años. Hay una variedad de métodos que proporcionan una gama de parámetros, como la permeabilidad al aire, la absorción de agua, la absorción capilar, y el coeficiente de migración de los cloruros.

Palabras clave: concreto de alto rendimiento; permeabilidad; especificación por rendimiento; ensayos no destructivos NDT; confiabilidad.

Nomenclature

A	the cross section area subjected to the flow (m^2)
ΔC	the concentration difference (g/m^3)
C	the concentration at the depth x (g/m^3)
C_0	ion concentration at the exposed surface (g/m^3)
D_c	the carbonation diffusion coefficient ($m/s^{0.5}$)
D_g	the gas diffusion coefficient (m^2/s)
D_v	the vapour diffusion coefficient (m^2/s)
D_{is}	the ion diffusion coefficient (m^2/s)
D_{ia}	the diffusion coefficient (m^2/s)
D_{js}	the migration coefficient (m^2/s)

D_{in}	the migration coefficient (m^2/s)
d	depth of penetration (m) at time t (s)
d_c	the carbonation depth (m)
ΔE	the applied potential difference (V)
F	Faraday constant (c/mol)
ΔH	the pressure difference expressed in water head (m)
i	the volume absorbed per unit area (mm)
J_g	gas mass flux ($g/m^2 \bullet s$)
J_v	vapour mass flux ($g/m^2 \bullet s$)
J_s	ion mass flux ($g/m^2 \bullet s$)
J_j	the flux of species ($kg/m^2 \bullet s$)
K_{gs}	the permeability coefficient (m^2)
K_{gn}	the permeability coefficient (m/s)
K_{ws}	the water permeability coefficient (m/s)
K_{wn}	permeability coefficient (m/s)
L	the thickness of the specimen (m)
P_e	the upstream pressure (N/m^2)
P_s	the downstream pressure (N/m^2)
P_i	the pressure at the start of test (N/m^2)
P_t	the pressure at the end of test (N/m^2)
Q_s	the steady-state volume flow rate (m^3/s)
R	universal gas constant ($J/mol \bullet K$)
S_w	the sorptivity of materials ($mm/min^{0.5}$)
S_d	the sorptivity ($mm/min^{0.5}$)
T	the absolute temperature (K)
t	time elapse (s)
t_t-t_i	the test duration (s)
v	porosity of the sample
V_c	the volume of the test chamber (m^3)
erf	the error function
x	ion penetration depth (m)
Z_j	the electrical charge of species
μ	the dynamic viscosity of the gas (Ns/m^2)

1. INTRODUCTION

In the design of concrete structures, durability and service life prediction have increasingly gained importance in recent years. This is due to inadequate durability performance of many reinforced concrete structures built in the past few decades, which places considerable strain on construction budgets. This is a worldwide problem (Beushausen and Luco, 2016). The use of high-performance concrete (HPC) is an established approach to enhancing the durability of reinforced and pre-stressed concrete structures (Aitcin, 1998). However, with performance levels of HPC typically assessed on laboratory-based testing, the long-term, in-service performance of concrete structures is largely dependent on factors such as construction quality. Set against this background, the ability to undertake accurate, *in situ* quality assessment of HPC is critical.

When discussing testing of concrete durability, it is the permeation and mass transport properties which are of significance and terms such as adsorption[1], diffusion, migration, absorption and permeability are used in this respect. Tests are normally undertaken on 150×300 mm cylinders using standard test methods, generally at the age of 28 days. It should be remembered that transport properties can be determined by laboratory techniques and/or *in situ* techniques (Basheer et al., 2008; McCarter et al., 2017). Laboratory techniques are easy to perform and most have been standardised to determine the compliance of structures with their design (Dhir et al., 1989; Zhang et al., 2017).

In situ permeation tests can be used to obtain much information; however, this does not suggest stopping laboratory measurements completely as noted in the Concrete Society Technical Report-31 (2008). There is clearly a demonstrable need for *in situ* testing to provide an owner with documentation (and reassurance) of the acceptability of the finished structure comparable to the documentation required for other aspects of concrete quality control/assurance (Bentur and Mitchell, 2008).

Numerous techniques have been applied to assess the permeation properties of normal concrete (NC), but few of them are suitable for distinguishing HPCs. There are two technical challenges for current testing techniques: firstly, the characteristics of HPC due to its dense pore structure, and secondly, the difficulty in controlling the test conditions before and during the measurements. This paper reviews the current permeation testing techniques with the aim of identifying a reliable method for HPCs. The scope of the test methods reviewed is confined to direct permeation methods.

2. TECHNIQUES FOR TESTING AND MONITORING PERFORMANCE OF CONCRETE STRUCTURES

2.1 Laboratory methods for assessing permeation properties

2.1.1 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 (Basheer, 2001). 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 (Torrent, 1992; Basheer, 2001; Yang et al., 2013).

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 (Basheer, 1993; Yang et al. 2013). 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 (Hearn and Morley, 1997; El-Dieb and Hooton, 1995), 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 (1995) 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 of HPC determined by Nokken and Hooton (2007) varied from 10^{-13} to 10^{-15} m/s, which is in agreement with the results reported by others using similar test arrangements (Galle et al., 2004; Reinhardt and Jooss, 2003). As the steady state tests require long test duration to achieve the steady state, the depth of water

[1] Adsorption is not discussed here, as this parameter is not commonly used as a durability indicator.

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 (2009). Chia and Zhang (2002) and Pocock and Corrans (2007) 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_{gs} (m^2)	$>10^{-13}$	10^{-14}-10^{-15}	$<10^{-16}$	15%-30%
K_{ws} (m/s)	$>10^{-11}$	10^{-11}-10^{-13}	$<10^{-14}$	20%-40%
K_{wn} (m/s)	$>10^{-10}$	10^{-10}-10^{-12}	$<10^{-13}$	40%-100%

2.1.2 Ion diffusion

The transport of chloride ions can be assessed by means of an ionic diffusion test (Basheer, 2001; Tang et al., 2011). Such tests can be grouped into two categories; diffusion based and migration based methods. Diffusion tests simulate the movement of chloride ions under the influence of a concentration gradient and the traditional set-up includes either diffusion cells (steady-state and non-steady state), or immersion/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 the error function solution of 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.

Since the 1980's, many techniques have been proposed which apply an external electrical field to accelerate the ingress of chloride ions. Some of the tests have utilised a high concentration of chloride source solution to further expedite ionic movement (Tang et al., 2011). 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 (2015) and ASTM C1202 (2017). In this test, the resistance of concrete against chloride is categorised by the total charge passing through the specimen during the first 6 hours. As charge is carried by all ions and not just chlorides, this test has been criticised by some researchers in 1990s (Andrade, 1993; Tang and Nilsson, 1992). The most recent test is the steady-state migration test. The test arrangement is similar to RCPT, however, in this instance, the chloride concentration of the anolyte is measured instead of the charge passed. The migration coefficient is calculated using a modified Nernst-Planck equation (Tang et al., 2011). Tang and Nilsson (1992) proposed a rapid test based on the non-steady state chloride migration theory, known as the rapid chloride migration (RCM) test. 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 NT-Build 492 (1999). 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 (Andrade, 1993; Basheer et al., 2005). 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 other two methods are based on the well-established theory and widely accepted by researchers to assess HPCs. 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_{is} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-12}$	15%-25%
D_{ia} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-13}$	20%-35%
D_{js} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-13}$	20%-35%
D_{in} (m^2/s)	$>10^{-11}$	10^{-11}-10^{-12}	$<10^{-13}$	20%-35%

2.1.3 Sorptivity methods

Sorptivity is the parameter to estimate the ability of liquid penetration due to capillary potential (Basheer, 2001; McCarter et al., 2009). Two kinds of tests are used to measure sorptivity: (1) weight gain method; and (2) water penetration depth. The weight gain method has been accepted as a European standard method: EN-13057 (2002). Basheer (2001) has reviewed the results for NC, which vary from 0.05 and 0.15 $mm/min^{0.5}$. The depth of water penetration – estimated using a sample splitting technique - caused by capillary suction can also be used to evaluate the sorptivity (McCarter et al., 1995). However, the need for multiple samples is the main drawback for this method. It is also difficult to observe a clear water-front for concrete containing fly ash and microsilica. Ganjian and Pouya (2009) studied the effects of supplementary cementitious materials (SCMs) on sorptivity of HPCs and found no significant difference among different HPCs. Similar results have also been reported by other researchers (Elahi et al., 2010) hence sorptivity is not a sufficiently sensitive parameter in assessing the performance of HPCs.

2.1.4 Considerations of assessing permeation properties of HPCs by laboratory techniques

To assess the permeation properties of HPCs using laboratory test techniques, steady-state water permeability and ion diffusion tests offer a simple analysis procedure. However, they have a common limitation, the long test duration, which may lead to coupled chemical and physical interactions. Non-steady state tests perform better in this aspect and could be used to evaluate HPC. Another point that should be highlighted is the initial condition of a specimen, including moisture content and distribution, which has a predominant effect on results and has to be assessed prior to measurements. Table 3 summarises laboratory test techniques and their governing equations along with recommendations to assess HPC.

Table 3. Summary of laboratory permeation test techniques and governing equations

Transport mechanism	Testing medium	Moisture condition	Theory	Governing equation	Suitable to test HPCs
Permeability	Gas	Dry	Steady-state	$K_{gs} = {2\mu L P_s Q_s}\big/{A(P_e^2 - P_s^2)}$	Yes
			Non-steady state	$K_{gn} = {V_c L}/{RTA} \times ln \frac{P_i}{P_t}\big/(t_t - t_i)$	Yes
	Water	Saturated	Steady-state	$K_{ws} = {Q_s}/{A} \times {L}/{\Delta H}$	No
			Non-steady state	$K_{wn} = {d^2 v}/{t\Delta H}$	Yes
Diffusivity and Migration	Gas	Dry	Steady-state	$D_g = J_g\, {L}/{\Delta C}$	No
			Non-steady state	$D_c = {d_c}/{t^{0.5}}$	Yes
	Vapour	Dry	Steady-state	$D_v = J_v\, {L}/{\Delta C}$	No
		Saturated	Steady-state		
	Ion diffusivity	Saturated	Steady-state	$D_{is} = J_s\, {L}/{\Delta C}$	No
			Non-steady state	$C = C_0[1 - \text{erf}({x}/{2\sqrt{D_{ia}t}})]$	Yes
	Ion migration	Saturated	Non-steady state	Classification of chloride resistance according to the total charge passing through a specimen	No
			Steady-state	$D_{js} = {J_j}\big/{C_j} \times {RT}/{Z_j F} \times {L}/{\Delta E}$	Yes
			Non-steady state	$D_{in} = {RT}/{Z_j F \Delta E} \times (x_d - 1.061 x_d^{0.589})/{t}$	Yes
Sorption	Water	Dry	Non-steady state	$S_w = {i}/{t^{0.5}}$	No
			Non-steady state	$S_d = {d}/{t^{0.5}}$	No

2.2 Field methods

2.2.1 In situ air 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 (1987) 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. One modification that needs to be highlighted is Torrent's method (1992) which introduced a guard ring to develop a double-chamber apparatus. By assuming a unidirectional flow of air through the concrete in the inner chamber, the air permeability coefficient is calculated from the pressure change in the inner chamber. Similarly, Guth and Zia (2001) used flow patterns through a two-concentric-chamber cell to determine air permeability of concrete. The application of a guard ring was proposed for the *in situ* water absorption test. In the strictest sense, the guard ring cannot guarantee unidirectional air flow across the whole section, as the flow simulation carried out by Yang et al. (2015) has indicated that the guard ring can confine the flow at the near surface and a uni-directional flow is not achievable for the whole depth of the test specimen. However, Torrent's method may serve as a conservative approximation of air permeability with the simplifying assumptions. The other type of surface-mounted air permeability test is the constant head test. Whiting and Cady (1992) applied the vacuum technique to measure the air permeability on site, named as surface air flow test (SAF). The steady-state air flow rate under a constant vacuum level is regarded as an indicator of air permeability.

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. The Torrent method, Guth-Zia's device and Autoclam have been used to attempt to measure the permeability of HPCs. Romer (2005) reported that misleading results were obtained using the Torrent test when moist concrete specimens were tested. A similar finding was also reported by Guth and Zia (2001) and Elahi et al. (2010). The modified Autoclam (Low volume test method) was designed to measure *in situ* air permeability of HPCs (Yang et al., 2015) and Figure 1 highlights the development progress of AutoClam test and typical results to measure air permeability of 1 NCs and 5 HPCs. The research confirmed strong positive relationships between the proposed test method and existing standard permeability assessment technique and strong potential to become recognized as international methods for determining the permeability of HPCs.

Figg (1973) developed the drill hole suction test during his work at the Building Research Establishment. A hypodermic needle is pushed into the cavity and connected to a mercury filled manometer and hand vacuum pump. After applying vacuum in the cavity, the time taken for the air pressure increase from 15 to 20 kN/m^2 is regarded as a measure of the air permeability of concrete. Two similar test methods are also found in the literature: one developed by Parrott and Hong (1991) at the British Cement Association, and the other developed by Dinku and Reinhardt (1997) at the University of Stuttgart. One issue noted by Figg (1973) is that microcracks are induced by application of the hammer-action drill and may affect the results significantly. For HPCs, the situation may become even more severe due to the high brittleness and difficulty of drilling very high strength concrete (Aitcin, 1998). It is evident from the literature that there is a paucity of data on air permeability measurements for HPCs.

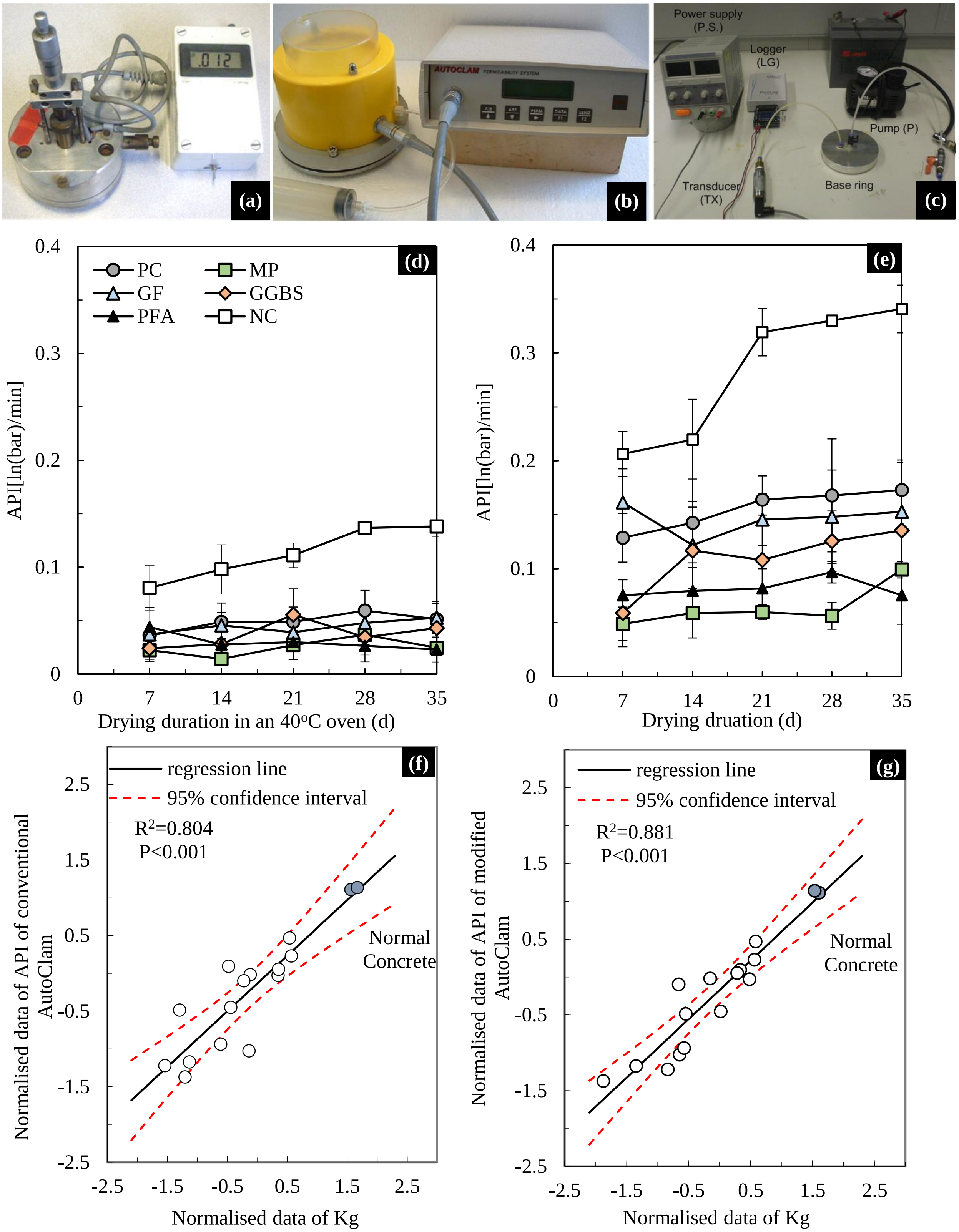


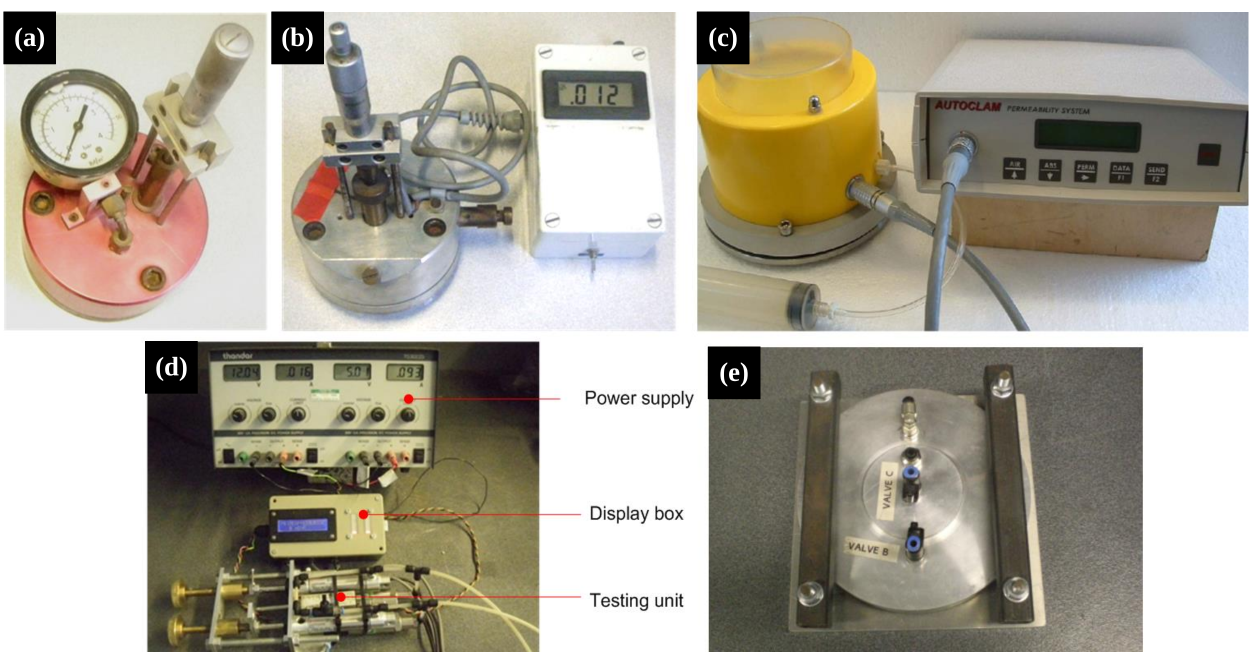
Figure 1. Development of Autoclam air permeability test (a) Universal CLAM air test (1985), (b) Autoclam air test (1992), (c) modified Autoclam air test (2011), (d) conventional Autoclam air test results, (e) modified Autoclam air test results, (f) conventional Autoclam Vs RILEM air test, (g) modified Autoclam Vs RILEM air test

2.2.2 In situ water permeability tests

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°C (Yang et al., 2013). This can be ensured by achieving a relative humidity of less than 60% in the near-surface region of approximately 40mm thickness (Basheer, 2001; Yang et al., 2013). This 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 and annual precipitation varies from 600 to nearly 2000 mm (Perry and Hollis, 2003). Therefore, it is logical that concrete in structures should be tested when it is in a saturated condition rather than in a dry state and, in this respect, *in situ* water permeability tests are preferable to air permeability tests for assessing the quality of concrete in these regions.

The first standardised test aimed at measuring the field absorption property of concrete was the initial surface absorption test (ISAT) in BS:1881-208 (1996): Testing concrete - Recommendations for the determination of the initial surface absorption of concrete. Initial surface absorption is defined as the rate of water flow into concrete per unit area under a constant pressure head. The Autoclam uses the same test procedure and can measure both the water absorption and sorptivity of concrete (Basheer et al., 1994). Figg (1973) and Dhir et al. (1989) developed drill-hole methods that are able to perform water absorption measurements, but it is not appropriate to estimate the sorptivity using the intrusive methods, as the water absorption process is initiated from the drilled hole, not from the surface. The ISAT can be used to study the sorptivity of concrete, while the Autoclam is a direct, easy and fast way to determine this property. As discussed in section 1, however, sorptivity is not a sensitive parameter to test HPCs.

The Clam test, first reported by Montgomery and Adams (1985), for measuring the water permeability of *in situ* concrete was modified by Basheer et al. (1994), which is currently available as the Autoclam Permeability System (Figure 2). 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 can be selected to assess HPCs and improve the repeatability and accuracy of the measurements (Yang et al., 2015), results of which are given in Figure 2.



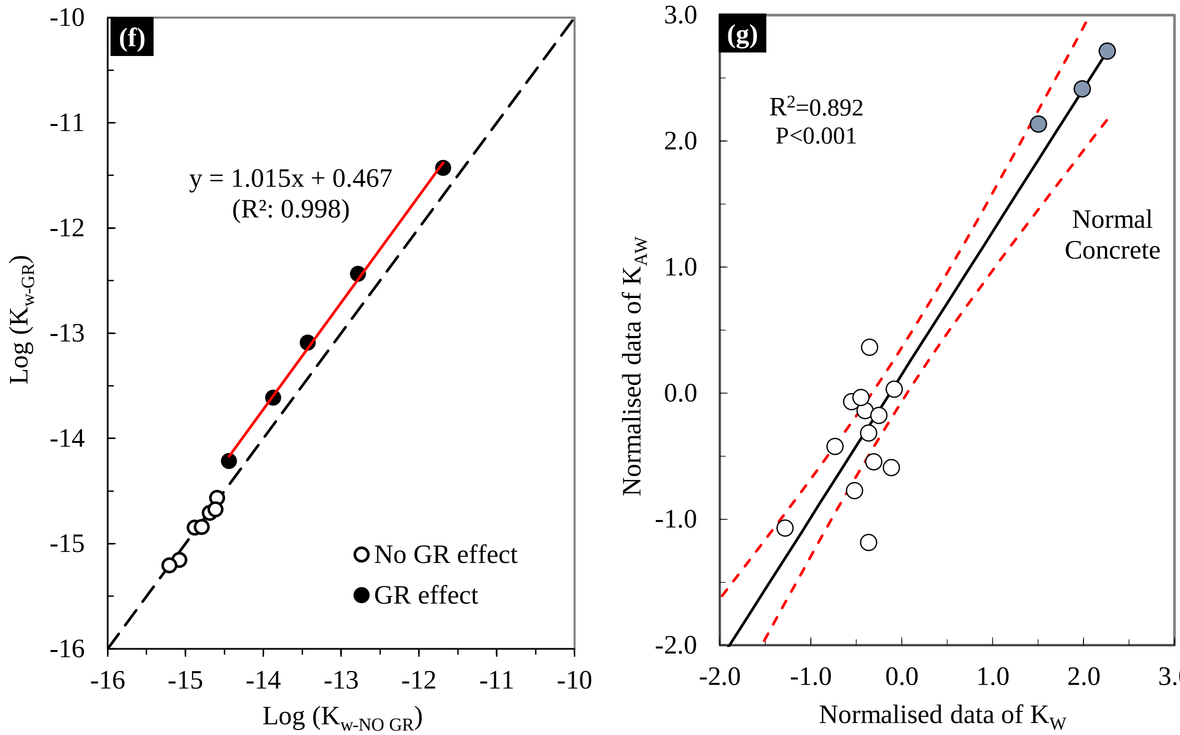


Figure 2. Development of CLAM water permeability tests (a) CLAM test (1985), (b) Universal CLAM test (1989), (c) Autoclam Test (1992), (d) High pressure CLAM water test (2012), (e) test head with the guard ring, (f) relationship between permeability coefficient from tests with and without the guard ring, (g) high pressure CLAM water test (K_{AW}) Vs BS-EN water penetration test (K_W)

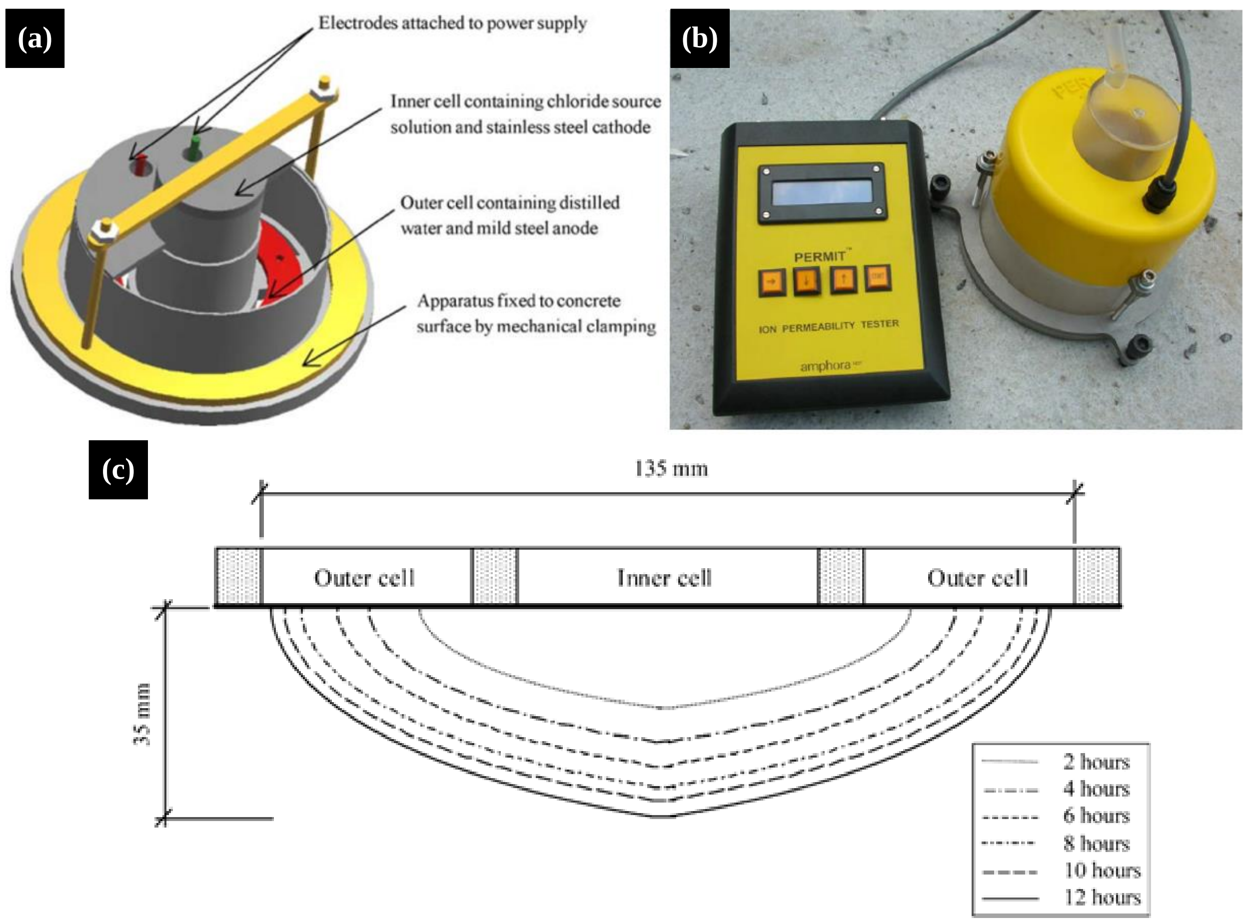
A field permeability test (FPT) developed by Meletiou et al. (1992) uses a steady-state, drill-hole water permeability procedure and to remove the influence of moisture on test results, vacuum saturation is applied before measurements. The water flow is monitored by the water level in the manometer tube. Flow is assumed to stabilise after 2 hours and the steady-state flow rate is used to calculate the coefficient of permeability. The results indicate that the effect of moisture variations is nearly removed after applying vacuum saturation, although the additional potential influence of microcracks induced by drilling is not fully addressed.

2.2.3 In situ migration tests

Steady state diffusion tests are not suitable for *in situ* application due to their long test duration. An external electric field can accelerate ionic transport and, as a consequence, some migration tests have been designed as field-test techniques. Such test methods include the Coulomb test developed by Whiting (1981), the *in situ* rapid chloride migration test (RCM test) (Tang et al., 2011) and the PERMIT ion migration test (Nanukuttan et al., 2015).

Whiting (1981) 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, 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 (Tang et al., 2011) and based on the rapid chloride migration (RCM) test. An external potential 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. As cores are required for interpretation of the *in situ* RCM method there is no obvious advantage compared with laboratory methods.

The PERMIT ion migration test (Figure 3) was developed by Nanukuttan et al. (2009). 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 influenced by the potential difference created by the external electric field. The change in conductivity of the anolyte is used as a means to monitor the chloride movement. The *in situ* migration coefficient is evaluated by using 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 (Basheer et al., 2005; Nanukuttan et.al. 2015). 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 3. Note that the performance of the PERMIT is confirmed in the laboratory and for site application, as test area is saturated by ponding for 24 hours, it is not possible to achieve full saturation from the surface to 30mm, especially for HPCs. Therefore, PERMIT needs to be validated for its ability to assess HPCs on site.



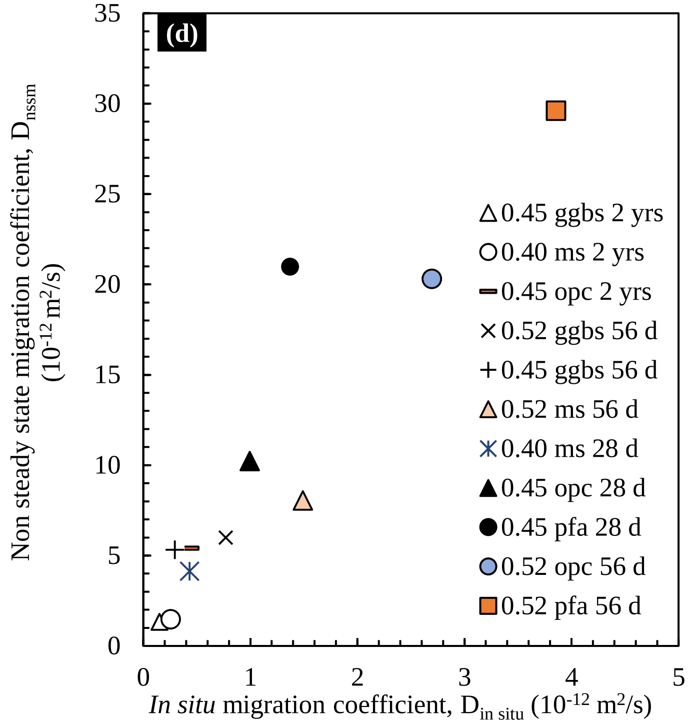


Figure 3. Development of PERMIT (a) schematic of PERMIT test, (b) the PERMIT ion migration test apparatus (2005), (c) flow area of chloride at different test duration, (d) PERMIT Vs non-steady migration test

The commercially available techniques are grouped into permeability tests, diffusion tests and sorptivity (water absorption) tests, similar to the laboratory methods, main features of which are summarised in Table 4.

Table 4 Summary of *in situ* test method to assess permeation properties of concrete

Name	Penetrating Medium	Approach to control moisture effect	Parameters determined	Accuracy	Cost per test	Surface mounted or Intrusive methods
Schonlin and Hilsdorf	Air	Use of a heat gun to remove moisture	Pressure decay	Good	Low	Surface mounted
Torrent	Air	Resistivity measurement	Pressure decay	Good	Relative low	Surface mounted
Guth and Zia	Air	No requirement	Pressure decay	Fair	Low	Surface mounted
SAF	Air	No requirement	Flow rate	Good	High	Surface mounted
Autoclam	Water , Air	RH requirement	Pressure decay or water volume	Good	Relative low	Surface mounted
LV Autoclam	Air	RH Measurement	Pressure decay	Good	Low	Surface mounted

Figg	Water, Air	No requirement	Pressure decay	Good	Low	Intrusive methods
Parrot	Air	RH measurement	Pressure decay	Good	Relative low	Intrusive methods
Dinku and Reinhardt	Air	Use of high pressure	Pressure decay	Good	Relative low	Intrusive methods
Dhir	Air	Use of vacuum to remove moistures	Pressure decay	Good	Low	Surface mounted
CLAM	Water	Ponding for 24 hours	Water volume	Good	Relative low	Surface mounted
High pressure CLAM	Water	Vacuum saturation	Water volume	Good	Relative low	Surface mounted
GWT	Water	RH measurement	Flow rate	Fair	Relative low	Surface mounted
ISAT	Water	Protect tested surface from water for at least 48h	Water volume	Fair	Low	Surface mounted
FPT	Water	Vacuum saturation	Flow rate	Good	High	Intrusive methods
CAT	Water	No requirement	Water volume	Fair	Relative low	Intrusive methods
PERMIT	Ion	Ponding for 24 hours	Conductivity	Good	Relative low	Surface mounted
In situ RCM	Ion	No requirement	Penetration depth	Fair	High	Surface mounted
Coulomb test	Ion	Vacuum saturation	Coulomb	Fair	Relative low	Surface mounted

Note: Some *in situ* test methods are not included in this table because there is no enough information to support their products.

2.2.4 Recommendation of in situ permeation methods in the context of assessing HPCs

Two questions always arise for *in situ* testing. One is whether it can provide the information that is actually needed, as an obvious objection is that most techniques measure something related to the transport properties other than intrinsic permeation characteristics. The other concerns the capability of these techniques for testing new cementitious materials. Due to the difference in the microstructure between NC and HPCs, the performance characteristics of the test apparatus need to be carefully examined and validated. With respect to the permeation methods discussed above, some points are briefly highlighted below:

1) The drill-hole method is a partially destructive method as repairs are unavoidable after carrying out measurements. More importantly, the percussion action of the hammer-drill used to drill the hole may create a detrimental and uncontrollable damage of concrete in the vicinity of the hole. This can cause discrepancies of test results. As such, this type of method is not recommended. The surface-mounted method can overcome the above disadvantages. The flow of most surface based methods is axi-symmetric, not unidirectional. This means multi-dimensional flow analysis is needed to examine test results.

2) The differences in permeability of HPCs are much smaller and this challenges most *in situ* test apparatus to differentiate between them. Both the falling-pressure and the constant-pressure air tests are possible for characterising HPCs. The former requires the pressurised reservoir geometry to be known and recording of the decrease in pressure within the reservoir, while the latter needs a knowledge of the testing geometry, flow rate and pressure. The high-pressure water test and modified air test are designed based on these concepts to measure permeability of HPCs.
3) The success of field assessments is greatly influenced by the water-content and moisture gradients in the concrete. The importance of the initial condition before the measurements has to be highlighted. Either 'dry' or 'saturated' samples are preferred for measuring the transport properties. Moreover, the presence of cracking and heterogeneity in concrete can also greatly affect flow rates.
4) Most work focusses on *in situ* permeability tests, while only three ion migration tests have been trialled for field application. More effort should be given on the laboratory investigation to fully improve the effectiveness of these methods for field application, as site ion migration tests are able to assess the quality of covercrete from the surface to 30 mm.

3. CONCLUSIONS

If testing has been undertaken earlier in the contruction process, then potential problems could have been identified and approriate measures taken early in the life of structures. Both *in situ* and laboratory permeation testing methods show potential for assessing the durability performance of HPCs. Although cores extracted from structures in-service could be tested in the laboratory under controlled temperature and moisture conditions, reliable *in situ* permeation tests have the advantage of carrying out numerous tests at the same test location, without damaging the structure. These test methods could form the basis of developing a performance-based specification strategy for concrete structures, but they all have their own specific benefits as well as drawbacks. Furthermore, several interesting aspects have not fully been addressed in previous studies, e.g. the coupled influence of deterioration and loading, influence of cracking, relationship between microstructure and permeation properties, suitability of conventional permeation test methods to assess new multi-functional cementitious materials. Therefore, further research is required to clarify these factors. The established knowledge and techniques for assessing permeation properties of normal Portland cement concretes is an area which requires development, if they are to be used in evaluating the performance of HPCs.

4. ACKNOWLEDGEMENTS

This paper has been prepared based on research carried out by the authors along with their colleagues and students. It has not been possible to list all contributors as authors, but their input in discussions and contributions to the content of this paper is gratefully acknowledged. Funding for the work was received from a range of sources, including Engineering and Physical Sciences Research Council, Technology Strategy Board and National Science Foundation of China.

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