

Repeatability and Reliability of New Air and Water Permeability Tests for Assessing the Durability of High-Performance Concretes

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Abstract: This paper reports on the accuracy of new test methods developed to measure the air and water permeability of high-performance concretes (HPCs). Five representative HPC and one normal concrete (NC) mixtures were tested to estimate both repeatability and reliability of the proposed methods. Repeatability acceptance was adjudged using values of signal-noise ratio (SNR) and discrimination ratio (DR), and reliability was investigated by comparing against standard laboratory-based test methods (i.e., the RILEM gas permeability test and BS EN water penetration test). With SNR and DR values satisfying recommended criteria, it was concluded that test repeatability error has no significant influence on results. In addition, the research confirmed strong positive relationships between the proposed test methods and existing standard permeability assessment techniques. Based on these findings, the proposed test methods show strong potential to become recognized as international methods for determining the permeability of HPCs. DOI: 10.1061/(ASCE)MT.1943-5533.0001262. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <http://creativecommons.org/licenses/by/4.0/>.

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Introduction

The measurement of permeation properties (e.g., permeability, sorptivity, and diffusivity) of the cover concrete is suitable for assessing the durability of concrete, and there are numerous methods to measure them on site [Long et al. 2001; Concrete Society 2008; Tang et al. 2012; ACI228 (ACI 2013)]. However, most test methods currently on the market cannot accurately detect the relative performance of low-permeability concretes; e.g., high-performance concretes (HPCs) (Elahi et al. 2010; Romer 2005). This shortcoming needs to be addressed given the increasing use of HPCs worldwide (Elahi et al. 2010; Neville and Aitcin 1998).

Based on the surface-mounted permeability tests developed at Queen's University Belfast (Basheer et al. 1995), two adaptations potentially enabling accurate differentiation of the permeability of HPCs have been considered (Yang et al. 2010, 2013). One consists of reducing the volume of compressed air exposed to specimens during the air permeability test, and the other uses

high pressure during the water permeability test. Before their widespread application for the characterization of HPCs, a detailed assessment and quantification of repeatability and reliability are necessary. In previous research of this nature, many authors have investigated the reliability of proposed methods by establishing relationships with relevant standard methods (Romer 2005; Andrade et al. 2000; Torrent 1992; RILEM TC 116-PCD 1999), but they did not consider repeatability. In the research reported by Basheer et al. (1995), recommendations by the International Organization for Standardization (ISO) for estimating repeatability of the air and water permeability tests were followed, but no conclusion was provided as to whether this was deemed to be acceptable.

Therefore, the aim of this study was to investigate both the repeatability and reliability of the proposed techniques by following current guidance published by the ISO-5725 (ISO 1994). Although the moisture conditions of concrete must satisfy certain requirements for permeation testing (Elahi et al. 2010; Romer 2005; Andrade et al. 2000; Torrent 1992), specific near-surface moisture requirements for HPCs are not well established. Therefore, test repeatability and reliability were examined under two ideal moisture conditions—namely, fully saturated concrete for the water test and dry concrete (at least, as dry as practically possible) for the air test. The effects of initial moisture conditions are not included in the work reported in this paper.

Experimental Program

Test Methods

Six permeation test methods were investigated. Three different variations of air permeability setups and one high-pressure water permeability adaptation were examined to ensure that permeation properties can be determined under consistently dried and saturated conditions, respectively. These were compared with

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the RILEM gas permeability test (RILEM TC 116-PCD 1999) and water penetration test to BS-EN 12390-8 (BSI 2000c) to assess the reliability of the new test adaptations.

Surface-Mounted Air Permeability Tests

Three air permeability tests were carried out as part of this study. The first test employed a conventional, 50-mm-diameter base ring (designated as AC-A-50), the second test employed a 75-mm-diameter base ring (designated as AC-A-75), while the third test was undertaken using a modified low volume of compressed air (designated as AC-A-LV test) using a 50-mm base ring. Fig. 1 shows the instruments, further details of which are available elsewhere (Yang et al. 2010).

The three air permeability tests have the same working principle; hence, similar testing procedures were applied. A base ring was used to isolate a test area on the surface of the concrete blocks, and the test chamber was pressurized manually. When the pressure reached 0.5 bar (50 kPa), testing commenced automatically, forcing air to escape through the pores in the test specimen. As pressure levels decreased, the pressure was monitored every minute for 15 min. The natural logarithm of air pressure was plotted against time, and the slope of the last 10 data points was reported as an air permeability index (API), measured in $\ln(\text{bar})/\text{min}$ [or could be reported in $\ln(\text{kPa})/\text{s}$].

Surface-Mounted Water Permeability Test

The test setup of the new water permeability test (AC-W-HP) is shown in Fig. 2. The test method was based on the procedure developed by Montgomery and Adams (1985), further details of

which are available elsewhere (Yang et al. 2013). At the beginning of taking measurements, the cylinder supplying water to the test region was filled with water, while a second cylinder was closed by a ball valve. The test head was then clamped onto a given pre-saturated test specimen, and water was admitted by a syringe through the priming valve. The test system was then pressurized using compressed air. Once the pressure in the test system was slightly above 7 bar (700 kPa), initial pressurization was considered to be over and a volume reading was recorded as the initial value ($t = 0$ min). As water passed through the saturated concrete under examination, pressure inside the test head decreased. To maintain the pressure at 7 bar (700 kPa), the pistons were manually advanced and the volume of water recorded every minute. After 120 min, the test was considered to have been completed. The coefficient of water permeability (m/s) was then determined based on the steady rate of flow and a calibration factor (Montgomery and Adams 1985; Yang et al. 2013).

RILEM Gas Permeability Test

The coefficient of gas permeability (K_g) was determined by following the procedure given by RILEM TC-116 PCD (1999) and using three consistently dried 50-mm-diameter cores for each mixture. Each specimen was placed in the permeability cell and nitrogen gas (N_2) was applied under 1.2 bar (120 kPa) of pressure. The test pressure was kept at this value and the rate of gas flow measured. The coefficient of gas permeability was calculated based on Darcy's equation without accounting for any gas slippage effect on the rate of flow (RILEM TC-116 PCD 1999)

$$K_g = (2 \mu L P_o Q_s) / A (P_i^2 - P_o^2) \quad (1)$$

where K_g = coefficient of gas permeability (m^2); μ = dynamic viscosity of N_2 (Ns/m^2) at 20°C ; L = sample thickness (m); A = section area subjected to flow (m^2); Q_s = volume flow rate of gas (m^3/s); and P_i/P_o = inlet/outlet pressure (N/m^2).

BS-EN Water Penetration Test

The coefficient of water permeability (K_w) was determined by carrying out the water penetration test according to BS-EN: 12390-8 (BSI 2000c). Three presaturated 100-mm-diameter cores extracted from the slab specimens were tested for each concrete mixture. A constant test pressure of 7.3 bar (730 kPa) was applied for three days at one end of the test specimen. It should be remembered that irregular waterfronts are unavoidable for all water penetration tests. Therefore, a test head with a guard ring (GR) arrangement, the details of which are as in Yang et al. (2013), was used in this study to ensure a unidirectional water penetration. At the end of the test, the specimens were split open, the depth of water penetration at the central region measured, and the permeability coefficient calculated using the following equation (Bamforth 1987):

$$K_w = d^2 / 2tH \quad (2)$$

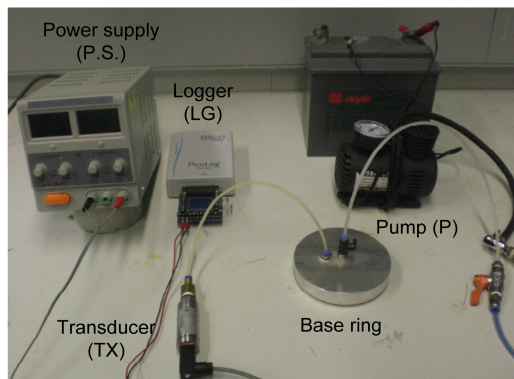
where d = depth of penetration (m) at time t (s); K_w = water permeability coefficient (m/s); and H = pressure head (m).

Concrete Mixtures and Materials Used

Based on experience gained from previous experimental work (Elahi et al. 2010; Basheer et al. 1995), five HPCs and one normal concrete (NC) were tested. Mixture proportions are reported in Table 1. Portland cement (CEM-I) conforming to BS-EN



(a)



(b)

Fig. 1. Test setup for the three air permeability tests: (a) established air permeability test (AC-A-50 and AC-A-75); (b) proposed low-volume air permeability test (AC-A-LV)

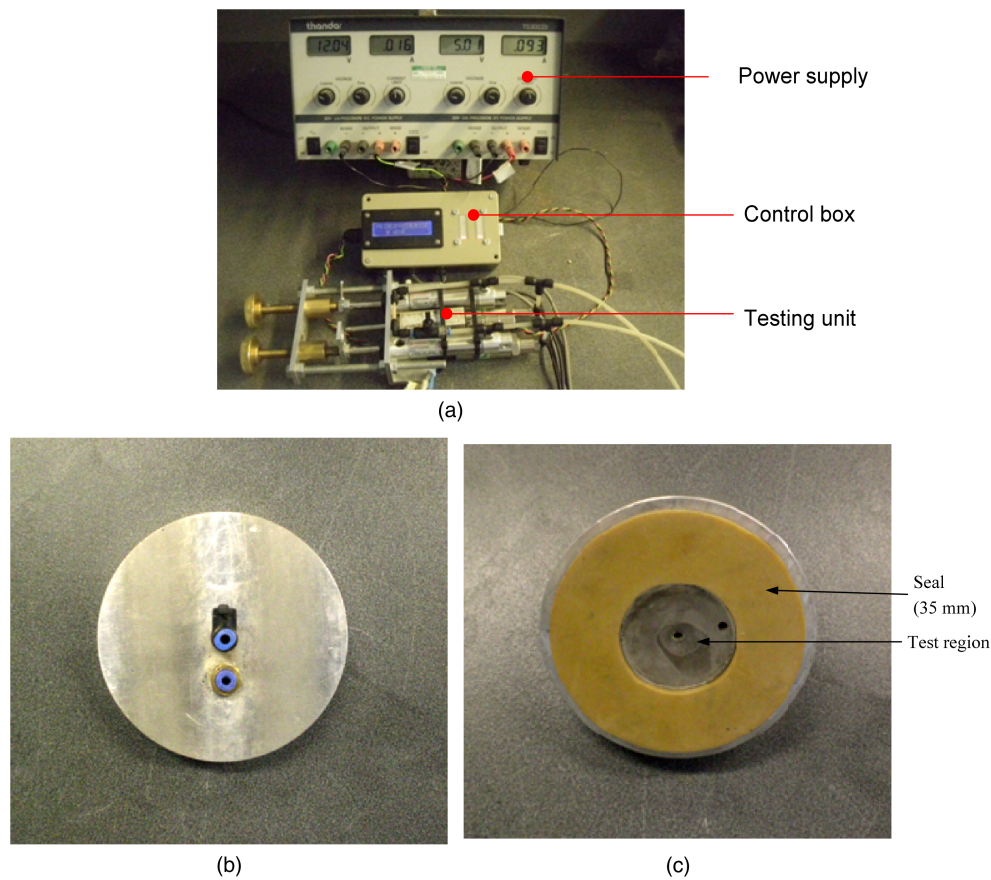


Fig. 2. Test setup for the new water permeability test (AC-W-HP): (a) main body of water permeability test; (b) top view of test head; (c) bottom view of test head

197-1 (BSI 2000d) and fly ash conforming to BS-EN 450 (BSI 2005a) were used. The ground granulated blast-furnace slag (GGBS) and silica fume used in this research conformed to BS-EN 15167 (BSI 2006) and BS-EN 13263-1 (BSI 2009b), respectively. The superplasticizer was a polycarboxylic acid-based polymer, specifications of which complied with BS-EN 934-2 (BSI 2009a).

The fine aggregate was medium-grade natural sand, and the coarse aggregate was crushed basalt with 10 and 20 mm sizes proportioned in equal mass. The moisture condition of the aggregates was controlled by predrying in an oven at $105(\pm 5)^{\circ}\text{C}$ for 1 day, followed by cooling to $20(\pm 1)^{\circ}\text{C}$ for 24 h before using them to manufacture the concrete.

Preparation of Specimens and Testing

Concrete was manufactured in accordance with BS 1881, part 125 (BSI 2005b), which was followed immediately by slump and air content testing in accordance with BS-EN 12350-2 (BSI 2000a) and BS-EN 12350-7 (BSI 2000b), respectively. Three $230 \times 230 \times 100$ -mm slabs and six 100-mm cubes were manufactured for each mixture. The molds were filled with concrete in two layers, with each layer compacted using a vibrating table until air bubbles stopped appearing on the surface. All test specimens were covered with wet hessian and placed in a constant temperature room at $18(\pm 2)^{\circ}\text{C}$. After 1 day, the specimens were removed from their mold and cured in a water bath at a constant temperature of

Table 1. Concrete Mixture Proportions

Concrete designation	Binder proportions PC:MS:GGBS:FA (% by mass)	Material quantities (kg/m^3)								SP (% by mass)
		PC	MS	GGBS	FA	Water	Sand	Coarse aggregate	W/B	
Control concrete										
NC	100:0:0:0	375	0	0	0	256	625	1,136	0.68	0
HPC										
SF	73:7:0:20	352	36	0	97	145	652	1,150	0.3	1.5
PC	100:0:0:0	485	0	0	0	145	689	1,150	0.3	1.3
FA	80:0:0:20	388	0	0	97	145	668	1,150	0.3	1.4
GGBS	50:0:50:0	243	0	243	0	145	676	1,150	0.3	1.4
GF	30:0:50:20	145	0	243	97	145	655	1,150	0.3	1.3

Note: FA = HPC with FA; GF = HPC with both GGBS and FA; GGBS = HPC with GGBS; NC = normal concrete; PC = HPC with pure PC; SF = HPC with both MS and FA; SP = superplasticizer dosage as a percentage by mass of the total binder content.

Table 2. Slump, Air Content, and Compressive Strength of Concrete

Mixture	Slump (mm)	Air content (% by volume)	Compressive strength (MPa)	
			28 days	56 days
NC	145	1.2	36.8	43.2
SF	240	1.6	84.2	94.6
PC	225	1.0	81.8	87.3
FA	220	0.6	81.3	90.7
GGBS	235	1.5	74.7	79.9
GF	195	1.7	62.8	69.7

20(±1)°C. The cubes were removed after 28 and 56 days and tested for compressive strength according to BS-EN 12390-3 (BSI 2009c). The fresh properties (slump and air content) and compressive strength for all concretes are given in Table 2.

The slab specimens were removed from the water bath after 3 days, wrapped in polythene sheets, and stored at a constant temperature (20 ± 2°C) for 90 days. After this, the sides of the slabs were painted with three coats of an epoxy paint to prevent any moisture from passing through these sides. The slab specimens were then saturated in water in layers by an incremental immersion method (Yang et al. 2013; Russell et al. 2001). When the specimens were saturated, the AC-W-HP test was carried out.

Following this, the slabs were placed in a drying cabinet (40 ± 1°C and 35%RH) for 35 days to remove free moisture from the near-surface region. The specimens were then removed from the oven and cooled in a constant temperature (20 ± 1°C) environment for 1 day before carrying out the three air permeability tests.

Once these tests were completed, six cores (three 50-mm-diameter and three 100-mm-diameter) were cut from the slab specimens. The 50-mm-diameter cores were dried in an oven at 40°C until they reached a constant weight and then left in a constant temperature room (20 ± 2°C, 50%RH) to cool for 1 day. The RILEM gas permeability test was then carried out. The 100-mm-diameter cores were used for the BS-EN water penetration test. The curved surface of the cores was coated with an epoxy resin paint to ensure unidirectional water penetration during testing. The samples were then saturated by the incremental immersion as described previously (Yang et al. 2013; Russell et al. 2001) and then tested for water penetration in accordance with BS-EN 12390-8 (BSI 2000c). It should be noted that the saturation regime is mainly used to remove the influence of capillary suction on results, and it was found that this method of saturation was not sufficient to fully saturate HPCs.

Repeatability and Reliability Analysis

Repeatability

The repeatability of the proposed air and water permeability test methods was assessed using values of signal-noise ratio (SNR) and discrimination ratio (DR). SNR represents the number of distinct categories that can be reliably distinguished by the measurement system and was determined using the following equation (Montgomery 2009; AIAG 2002):

$$\text{SNR} = \sqrt{\frac{2\rho_C}{1-\rho_C}} \quad (3)$$

where ρ_C denotes the ratio of concrete variability to total variability that is caused by samples and the test method applied, where

$\rho_C = \sigma_C^2 / \sigma_T^2$; σ_C^2 denotes the variance due to concrete; and σ_T^2 denotes the total variance of results.

Another parameter widely used in statistical process control, DR, was employed. DR also represents the number of distinct categories differentiable by a measuring system and was calculated using the following equation (Montgomery 2009):

$$\text{DR} = \frac{1 + \rho_C}{1 - \rho_C} \quad (4)$$

where ρ_C = ratio of concrete variability to total variability as defined previously. The measurement variance and the total variance were determined first, from which the concrete variance (ρ_C) was computed by subtracting the measurement variance from the total variance (Montgomery 2009; AIAG 2002).

Reliability

The reliability of the new test methods was assessed by comparing the results of the new tests with reference values determined using the RILEM gas permeability test (RILEM TC 116-PCD 1999) and the BS-EN water penetration test [BS-EN 12390 (BSI 2000c)]. Linear regression analysis (Graybill and Iyer 1994; Chatterjee and Hadi 2006) was performed to investigate the relative strength of the relationships. As data obtained from the different tests could not easily be compared directly due to their nonhomogeneous variance and different units for expressing results, values were transformed by log-function and normalized as follows:

$$Z = (x_i - x_{av}) / SD \quad (5)$$

where Z = normalized data; x_i = log-transformed data; x_{av} = average value of the specific method; and SD = standard deviation of the specific method. With no physical meaning, values obtained in this way were used only to reflect relative differences in concrete permeability properties.

Results and Discussion

Investigation of the Level of Precision of the Proposed Water Permeability Test

Repeatability of the Proposed Water Permeability Test

Before evaluating repeatability, instrument error of the proposed water permeability test (AC-W-HP) was determined. This was achieved by calculating its bias, defined as the difference between measured values and corresponding true values [ISO-5725 (ISO 1994)]. True values, however, are not easily obtained and are often replaced by reference values. As the AC-W-HP test measures the volume of water flowing into concrete, the equivalent reference parameter must also be the volume of water penetrating the concrete. In this study, a 250- μL capillary tube was connected directly to the test apparatus to allow reference values to be established. Test bias was then estimated by comparing instrument readings with corresponding readings on the capillary tube. Clearly, this form of comparative analysis was not possible for the proposed air permeability tests.

Shewhart charts were then employed to investigate the behavior of bias and moving range (MR) (Montgomery 2009; AIAG 2002). MR values are calculated as the difference between two consecutive data (bias) points (Montgomery 2009). Note that the hypothesis of normal distribution of bias was confirmed by the Ryan-Joiner test (Montgomery 2009; AIAG 2002) before the construction of control charts. Fig. 3 shows the control charts for bias

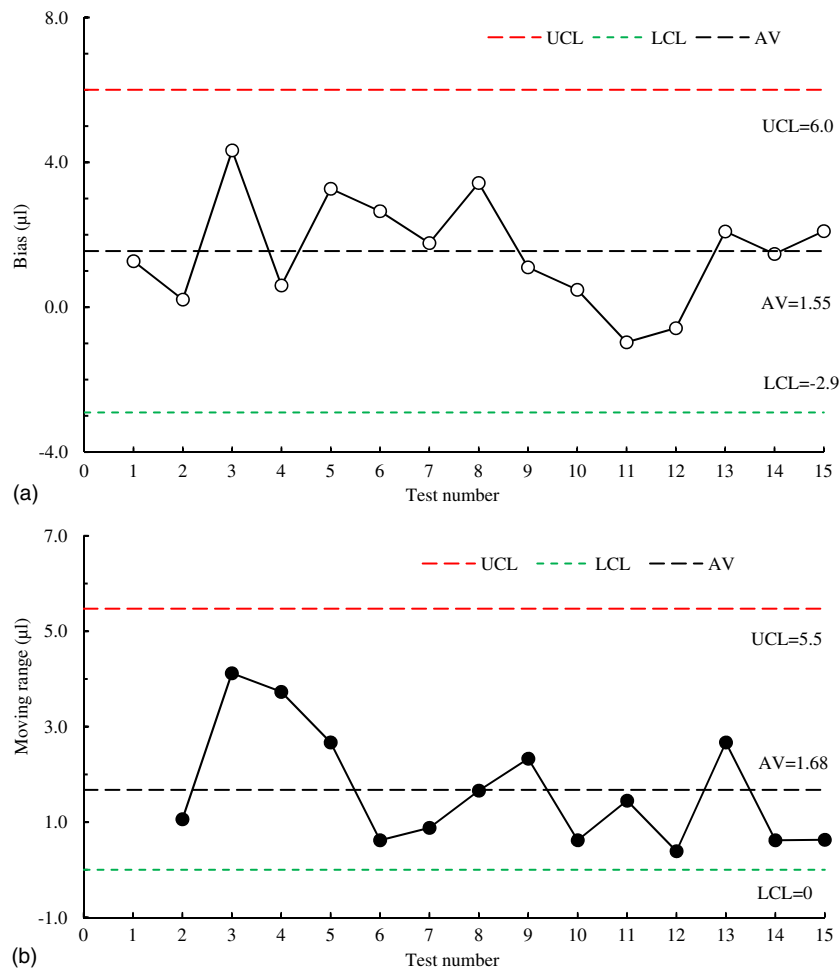


Fig. 3. Statistical control charts for the new water permeability test (AC-W-HP): (a) control chart for bias; (b) control chart for moving range; upper control limit (UCL): a value that gives the highest acceptable level of quality; average (AV): average value of quality; lower control limit (LCL): a value that gives the lowest acceptable level of quality

and MR. By observing the MR plot, it was clear that no data point strayed beyond the upper and lower control limits and no abnormal behavior existed. With respect to the bias chart, values of bias varied from -1.0 to $4.3 \mu\text{L}$, with all but two being positive. This indicated that readings originating from the test device were marginally higher than those from the capillary tube. Further, all points again fell within upper and lower limits and a nonsystematic behavior was confirmed. Consequently, it was concluded that no out-of-control conditions existed and the bias of the instrument should be considered as $1.6 \mu\text{L}$, falling in the range of $-3 \mu\text{L}$ (lower control limit) to $6 \mu\text{L}$ (upper control limit).

As water permeability coefficients determined by the AC-W-HP test rely on flow rates gained from regression analysis performed on values of water volume flowing into concrete against time (Yang et al. 2013; Montgomery and Adam 1985), the variation of the slope under the repeatability condition was assessed. Two factors contributed to variance during this investigation: the instrumentation and procedures used.

To assess variance caused by the test device itself, the testing setup was kept constant until all measurements were completed. Under the repeatability condition, the testing setup was disassembled after each test and the calibration procedure repeated. Measurements were repeated five times for each test condition. Relationships were then established based on regression analysis undertaken between readings recorded from both the instrument and attached capillary tube.

Fig. 4 gives test results under these two conditions. It is evident that the AC-W-HP gives similar volume readings to the capillary tube, as all data under two conditions are located along the line of equivalence. This indicates that the readings generated by the test device are almost equal to those obtained from the capillary tube. Fig. 4 also illustrates that the range of graph slope under the repeatability condition caused mainly due to procedural error was higher (0.98 – 1.01) than that due to instrument error (0.99 – 1.00). As such, it can be concluded that the standard deviation of instrument error is insignificant.

Acceptability of the Repeatability of the Proposed Water Permeability Test

The next objective of the work was to assess whether the identified levels of repeatability were acceptable. Two parameters, SNR and DR, were used for this purpose. In order to determine the values of SNR and DR, ratios of concrete variability to total variability (ρ_C) were estimated initially. With variability of measurement (repeatability) estimated in the previous section, variability due to concrete can be determined, provided that total variability is known. To evaluate total variability, the average variance of six concrete mixtures (five HPCs and one NC) was evaluated, with three replicates for each concrete mixture considered. As explained previously, a log transformation was applied before assessing the variance of concrete because the variance of permeability depends on its magnitude (Basheer et al. 1995; Yang et al. 2010).

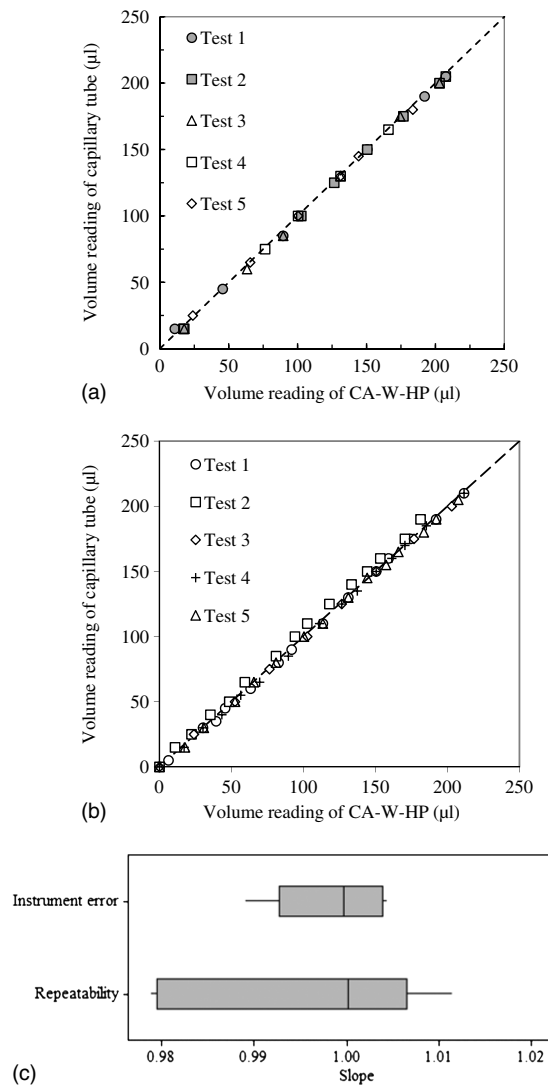


Fig. 4. Investigation of the instrument error and repeatability of the AC-W-HP test: (a) estimation of instrument error for the proposed water permeability test from five repeated measurements at the same test location and test assembly; (b) estimation of the repeatability for the proposed water permeability test from repeated tests at the same location with five repeated assemblies of the apparatus; (c) box and whisker plot of slopes from plots of capillary tube versus test instrument (AC-W-HP) under these two test conditions

Calculated values of SNR and DR are given in Table 3. Guidance published by the Automotive Industry Action Group (AIAG 2002) recommends that values of SNR higher than 5 indicate reliable results. Furthermore, Montgomery (2009) suggests that for acceptable repeatability, DR values must exceed 4. From Table 3, it can be seen that calculated values of SNR and DR were 14 and 198, respectively. Consequently, the conclusion drawn from this analysis was that the test method was capable of distinguishing performance levels between different materials.

Investigation of the Reliability of the Proposed Water Permeability Test

Reliability of the proposed water permeability test was investigated by establishing relationships between normalized results obtained (K_{AW}) and normalized values of permeability (K_W) obtained from the BS-EN water penetration test. As evaluation of K_{AW} is based on

Table 3. Summary of SNR and DR Determinations for the Proposed Tests

Parameter	New water permeability test	New air permeability tests		
	AC-W-HP	AC-A-50	AC-A-75	AC-A-LV
Total variance	0.0205	0.0189	0.0233	0.0104
Variance of concrete	0.0020	0.0167	0.0216	0.0102
ρ_C (%)	99	88.6	92.7	97.6
SNR	14	3.95	5.02	9.07
DR	198	16.6	26.2	83.2

Note: DR = discrimination ratio; SNR = signal-noise ratio; ρ_C = ratio of concrete variability to total variability.

flow-net theory, requiring a value of steady-state flow (Yang et al. 2013; Montgomery and Adam 1985), the as-recorded water permeability data for the six concretes are provided in Fig. 5. It can be observed that while the relationships between the volume of water flowing into concrete and time are not linear, the curvature of the plot was comparatively small after 60 min. After this point, all correlation coefficients were close to a value of 1, meaning that volume flow was proportional to time. Against this background, flow rates used to estimate permeability coefficients (K_{AW}) were determined using data obtained between 60 and 120 min (Yang et al. 2013).

Table 4 summarizes the subsequent permeability coefficients determined. Average water permeability coefficients (K_{AW}) obtained from the AC-W-HP test for all concretes were relatively low, ranging from 3.4 to 61.2×10^{-16} m/s. As expected, the control NC mixture achieved the highest average value (61.2×10^{-16} m/s). While results from the BS-EN water penetration testing generally provided a similar trend regarding relative performance of the NC and HPC mixtures, a high degree of variance between results was immediately noticeable. Fig. 6 shows representative results obtained for the FA concrete after carrying out the BS-EN water penetration test. Clearly, the wet fronts for the three samples were irregular and corresponding values of coefficients of variance (CoV) exceeded 50%. Similar observations for this test have been reported elsewhere in the literature (Collins et al. 1986; Zhang and Gjtrv 1991; Pocock and Corrans 2007), attributable predominantly to the measuring method. Explanations include the fact that the BS-EN method uses a single value, based on visual interpretation and measurement, to compute permeability coefficients. Comparative CoV values for the AC-W-HP test, which is based on a regression analysis of the data obtained, is around 30%.

Against this background, individual, rather than average, data points for each mixture from the BS-EN test were used in subsequent reliability analysis to ensure that regression analysis was not affected by the different variances of results obtained by the two methods. Normalized K_W is plotted against normalized K_{AW} in Fig. 7, with 95% confidence interval (CI) limits attached. In general, the existence of a strong correlation between the two tests is evident in Fig. 7. This observation is supported by the p-values (shown in Fig. 7), which if less than 0.001 indicate statistical significance (AIAG 2002; Chatterjee and Hadi 2006). It should be noted, however, that this strong relationship deteriorates markedly if the three data points corresponding to the NC mixture are removed. This suggests that the link between the two water-based tests is strongly dependent on the type of concrete assessed.

To confirm the conclusions drawn from the regression analysis, all the hypotheses were subsequently verified by graphic analysis as advised in the literature (e.g., Graybill and Iyer 1994; Chatterjee and Hadi 2006). From the resulting diagnostic plots in Fig. 8, it can

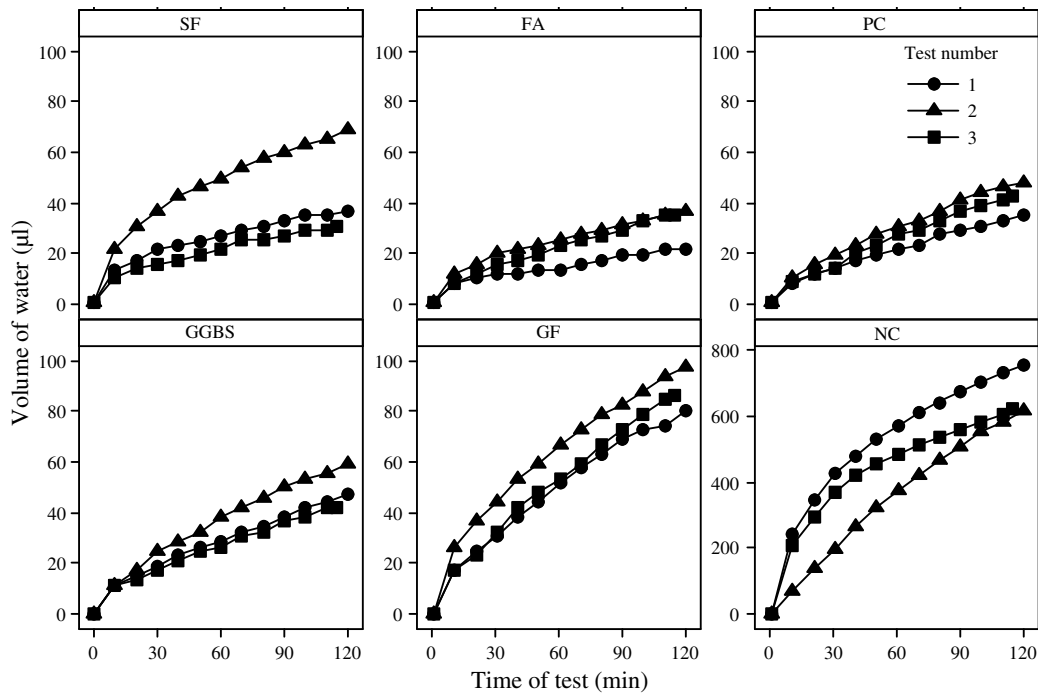


Fig. 5. Volume of water transported during the new water permeability test

Table 4. Summary of As-Received Results Determined by Different Permeability Test Methods

Mixture	Proposed permeability test methods				Standard permeability test method	
	Air permeability index [ln(bar)/min]			Water permeability coefficient K_{AW} (m/s)	RILEM method	BSEN method
	AC-A-50	AC-A-75	AC-A-LV		Gas permeability coefficient K_g (m^2)	Water permeability coefficient K_W (m/s)
SF	0.025	0.033	0.099	3.72×10^{-16}	3.05×10^{-17}	0.68×10^{-11}
FA	0.023	0.053	0.075	3.40×10^{-16}	2.53×10^{-17}	1.29×10^{-11}
PC	0.051	0.067	0.173	4.95×10^{-16}	5.37×10^{-17}	1.07×10^{-11}
GGBS	0.036	0.080	0.150	6.88×10^{-16}	5.74×10^{-17}	1.63×10^{-11}
GF	0.053	0.083	0.153	6.87×10^{-16}	6.24×10^{-17}	2.60×10^{-11}
NC	0.133	0.163	0.328	61.2×10^{-16}	12.1×10^{-17}	367×10^{-11}

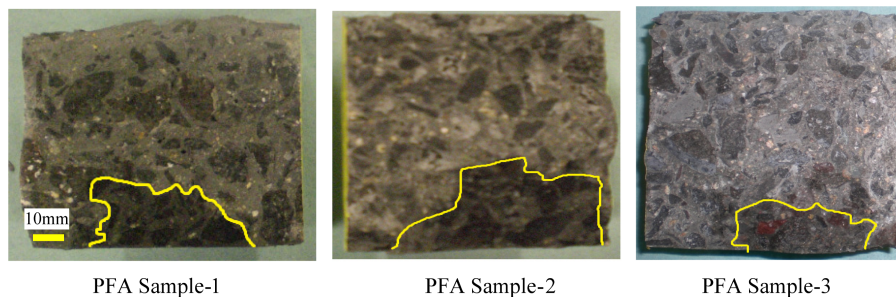


Fig. 6. Typical water ingress profile for BS-EN water penetration test (FA mixture)

be observed that the probability plot reassembles a straight line, meaning that errors are normally distributed. The plot of residuals versus fitted values shows that the residuals are randomly scattered around zero and that no indication of inconsistent variability exists over the data range. Furthermore, there is no evidence to show dependence between residuals and fitted values. As such, the

assumptions were considered to be proven and the regression analysis justified.

The strong relationship between the proposed water permeability test and the BS-EN water permeability test is perhaps unexpected, given trends previously published by the U.K. Concrete Society. In its Technical Report 31 (Concrete Society 2008), while

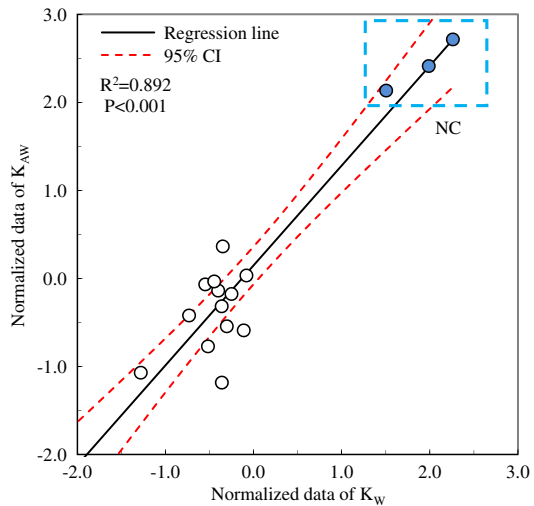


Fig. 7. Relationship between the new water permeability test (K_{AW}) and the BS-EN water penetration test (K_W)

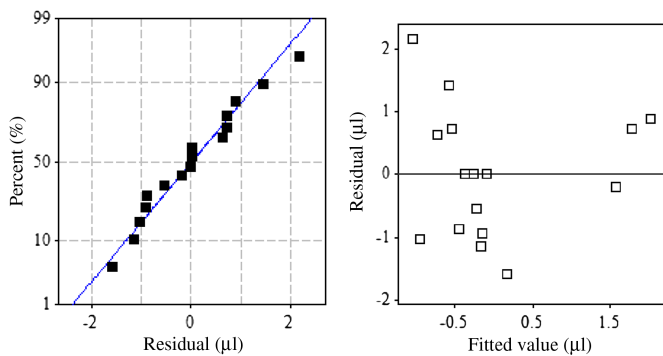


Fig. 8. Diagnostic plots of regression analysis between the new water permeability test (K_{AW}) and the BS-EN water penetration test (K_W)

only a general trend is shown, a weak correlation is reported between permeability coefficients determined by steady-state water permeability tests and non-steady state tests. No detailed information on the concretes or test conditions is given in the report, but a possible reason for this reported trend may be that considerable variability existed between concrete batches and specimen preconditioning history. Previous test data reported by Montgomery and Adams (1985) have shown coefficients of variation for

permeability coefficients to be 30 and 50% for the same concrete batch and different batches of the same concrete, respectively. Equally, in terms of sample moisture conditioning, Hall and Hoff (2002) suggested that this is crucial for the reliability of any transport-related test technique. In contrast, the fact that samples in this investigation were taken from the same concrete batch and exposed to a predetermined saturation regime is proposed as the explanation for the strong correlation between tests observed. This observation indicates that while most permeability tests are based on sound theory, difficulty associated with cross-comparing results exists because of differences in specimens and test conditions.

Investigation of the Level of Precision of the Proposed Air Permeability Test

Repeatability of the Proposed Air Permeability Test

Following the completion of water permeability testing, all specimens were preconditioned by drying at 40°C for 35 days; this regime was adopted to ensure the elimination of sample variation prior to repeated API measurement using the three test protocols (i.e., AC-A-50, AC-A-75, and AC-A-LV) (Yang et al. 2010).

For each test protocol, the instrument remained on the PC specimen under investigation and the air permeability tests were repeated five times after allowing pressure buildup caused by the previous test to dissipate. As recommended by Basheer et al. (1995), the interval between consecutive measurements was limited to between 1 and 1.5 h to eliminate material effects, attributing any variability of measured air permeability values to instrument inaccuracy.

Shown in Figs. 9(a and b) are API values recorded from the three air permeability test methods and the confidence intervals for the corresponding standard deviations. Reflecting its increased sensitivity, the AC-A-LV test provided significantly higher API values [on average 0.15 ln(bar)/min] than the AC-A-50 and AC-A-75 tests [on average 0.04 ln(bar)/min]. In addition, consecutive results for all three tests were very similar, indicating low variance. From Fig. 9(b), it can be observed that the variability of the AC-A-50 and AC-A-75 is close to zero. This finding is perhaps not surprising given the known low sensitivity of these tests when assessing HPC performance. In addition, the two tests are fully automated, with any error (typically very low once the equipment is set up) mainly dependent on its components.

In contrast, measured standard deviation for the AC-A-LV test was five times higher than the other two tests. This most likely reflects the fact that the AC-A-LV test is not fully automated. Besides, the range of sensor pressure measurement differed for the different tests. For the AC-A-50 and AC-A-75 tests, the full sensor

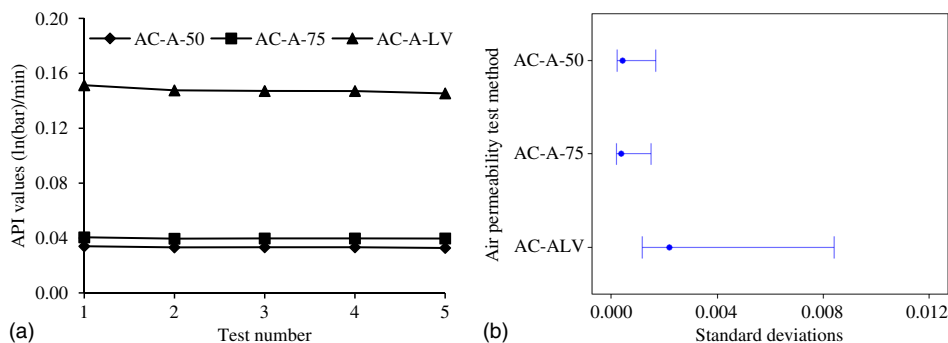


Fig. 9. Investigation of equipment error for the three air permeability test results: (a) air permeability index versus test number; (b) 95% CIs for standard deviations

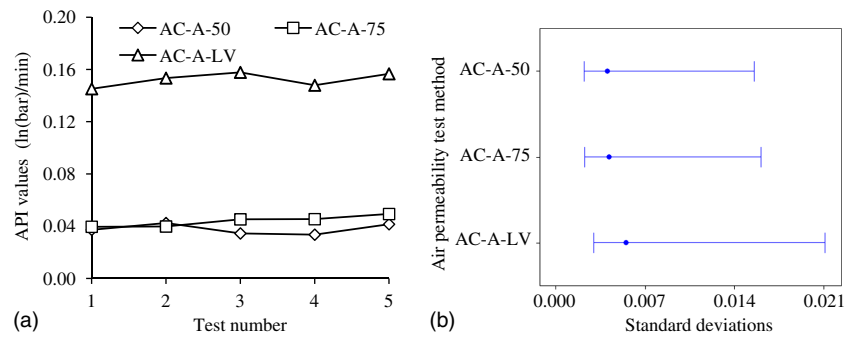


Fig. 10. Investigation of the repeatability of the air permeability test methods: (a) air permeability index versus test number; (b) 95% CIs for standard deviations

test range was 1 bar (100 kPa), compared to 10 bar (1,000 kPa) for the AC-A-LV test. Assuming similar accuracy levels for both sensors (around 0.5% of the full range), this implies that the sensitivity of the AC-A-LV pressure sensor may be lower. With this said, the standard deviation of the AC-A-LV test data was still acceptably low (less than 0.003).

To evaluate repeatability of the three air test methods, measurements for each method were also conducted five times in succession at the same test area, but with removal and reattachment of the instrument each time. After completion of each test, the apparatus base ring was released and the sample was left for 1 h to allow pressure in concrete pores to dissipate (Basheer et al. 1995).

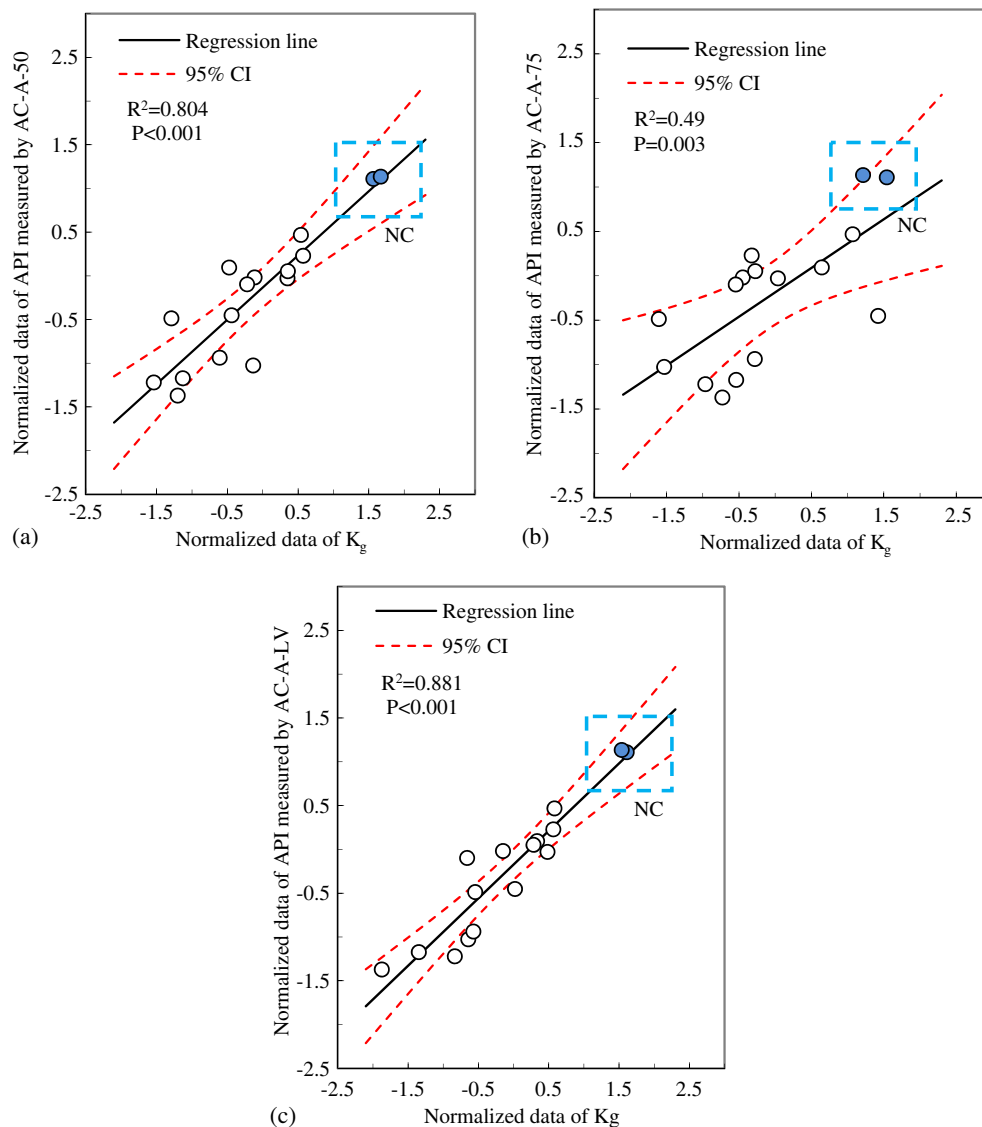


Fig. 11. Relationships between the three air permeability values and the RILEM gas permeability coefficient: (a) AC-A-50 versus RILEM gas test; (b) AC-A-75 versus RILEM gas test; (c) AC-A-LV versus RILEM gas test

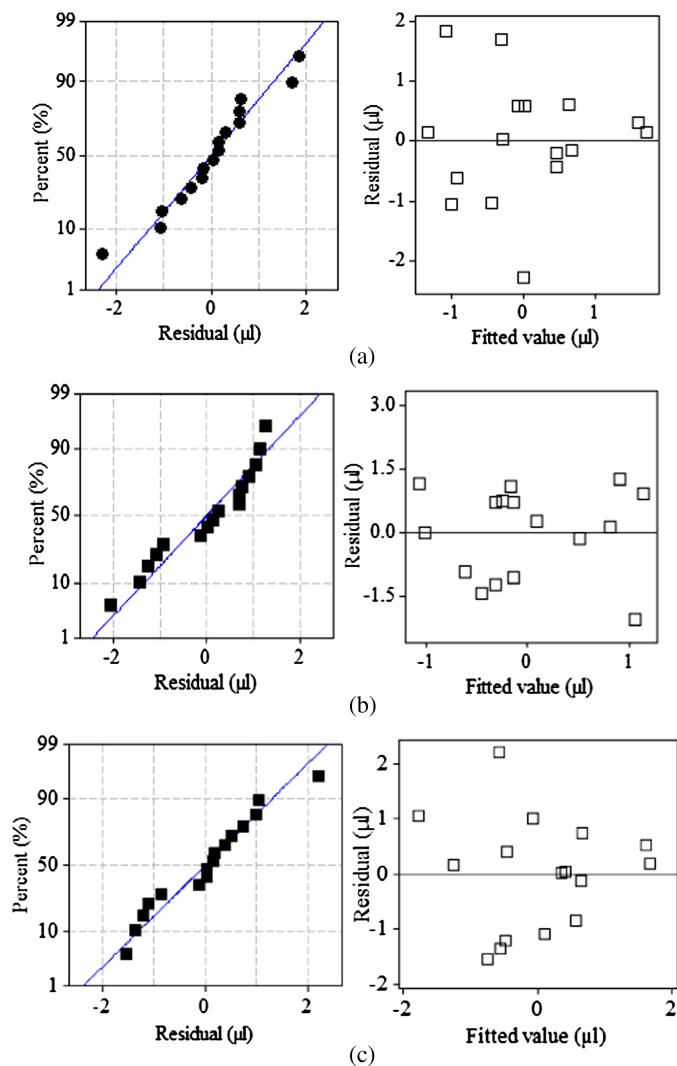


Fig. 12. Diagnostic plots of regression analysis for the three air permeability tests: (a) AC-A-50 versus RILEM gas permeability test; (b) AC-A-75 versus RILEM gas permeability test; (c) AC-A-LV versus RILEM gas permeability test

The same PC mixture specimen was examined each time to avoid potential variability caused by testing different materials.

Fig. 10 displays the results obtained for all three air permeability tests under these conditions. It is clear that API values fluctuated to a higher degree as a result of repeated apparatus removal and re-attachment despite the results being similar to those reported in Fig. 9. This increased variance is clearly reflected in the standard deviation plots shown in Fig. 10(b), where the value was 0.0055, 0.0040, and 0.0042 for the AC-A-50, AC-A-75, and AC-A-LV tests, respectively. When measurements were performed under repeatability conditions, variance of results was not solely due to instrument error, but also on the procedures applied. In spite of this, Fig. 10(b) indicates no significant difference in the standard deviation values calculated for each of the three test methods.

Acceptability of Repeatability of the Proposed Air Permeability Test

In order to investigate the repeatability of the proposed air permeability test method, SNR and DR values were also compared against the recommended limiting values discussed previously. As with the water permeability test, this analysis was undertaken using six concrete mixtures (5 HPCs and 1 NC) tested after drying

at 40°C for 35 days, with three replicates for each concrete considered. The results of SNR and DR are given in Table 3, and it can be seen that, while the AC-A-50 and AC-A-75 tests yielded satisfactory DR values (16.6 and 26.2, respectively), values of SNR were marginal in terms of acceptability (3.95 and 5.02, respectively). This finding most likely reflects the low sensitivity of these tests when assessing HPC and is in agreement with previous results (Elahi et al. 2010; Yang et al. 2010). More encouragingly for the AC-A-LV test, the recommended minimums were met comfortably, with SNR and DR values of 9.07 and 83.2, respectively. While the aforementioned minimum requirements of SNR and DR are somewhat arbitrary, both play important roles in the analysis of any measurement system (Montgomery 2009; AIAG 2002). As such, from this work, the repeatability of both the AC-A-75 and the AC-A-LV tests was considered to be acceptable.

Investigation of the Reliability of the Proposed Air Permeability Test

The next phase of the research focused on assessing the reliability of the proposed test methods by establishing relationships with the RILEM gas permeability test. As shown in Table 4, average gas permeability coefficients obtained from the latter test for all concretes were relatively low, with the control NC mixture returning the highest average value. In comparison, the HPC mixtures achieved values that were on average around three times lower. Results of the three Autoclam air permeability tests showed a very similar trend in terms of relative performance between NC and HPC mixtures.

Reliability of the three air permeability tests was established using relationships between normalized data obtained and corresponding normalized values of permeability (K_g) from the RILEM gas permeability test. The results of this analysis are given in Fig. 11, with 95% confidence interval attached. For all three air tests, general positive relationships between normalized API and K_g values are seen, which are further verified by the p -values shown in Fig. 11. All of these are significantly lower than 0.05, indicating that the relationship between the independent (K_g) and dependent variable (API) may be considered as statistically significant. Apparent from this analysis, however, was a weaker correlation for the AC-A-75 test than for the other two tests, with data points clearly distributing remotely from the regression line. As concrete is a nonhomogeneous material, this trend most likely reflects the larger concrete surface area employed as part of the AC-A-75 test. The conclusion from this finding is that, unless necessary, the test diameter should not be increased beyond 50 mm.

To confirm the conclusion of the regression analysis, the three hypotheses were subsequently verified by graphic analysis, as previously described. Diagnostic plots of the regression analysis for the three air tests are provided in Fig. 12, which highlights no abnormal behavior in the probability plots and the plot of residuals versus fitted values. On this basis, the conclusions drawn from regression analysis appear valid.

Conclusions

In this study, an experimental investigation was carried out to assess the characteristics of three air permeability tests and one water permeability test. On the basis of the data presented and discussed, the following conclusions have been drawn:

1. For the proposed steady-state water permeability test (AC-W-HP), instrument error data showed no out-of-control conditions and were acceptable in the range of $-3 \mu\text{L}$ (LCL) to $6 \mu\text{L}$ (UCL). The analysis of SNR and DR indicated that

AC-W-HP test was capable of distinguishing the performance variance of HPCs and that there were no significant issues with repeatability. With respect to validation of the reliability, permeability coefficients of different HPCs determined by the standard BS-EN water penetration test had a strong positive relationship with values obtained with the proposed AC-W-HP test.

2. Of the two enhanced air permeability tests (AC-A-75 and AC-A-LV), AC-A-LV had a slightly higher instrument error, but no statistically significant difference existed in repeatability between these two methods. Furthermore, examination of repeatability by SNR and DR suggested that both methods can differentiate HPC permeability. In reliability validation, a strong correlation existed between the AC-A-LV test and the RILEM gas permeability test. The relationship was weaker for the AC-A-75 test, meaning that it had a lower reliability. Combining the findings of the repeatability and reliability analysis, it is concluded that AC-A-LV test performed better than the other two air permeability tests investigated in this research.
3. In terms of the immediate impact of this research, the findings indicate that the proposed water (AC-W-HP) and air (AC-A-LV) permeability tests show strong potential for widespread industry adoption. By providing engineers and infrastructure clients with enhanced ability to accurately assess and benchmark HPCs, this represents significant progress toward the delivery of durable, resilient, next-generation built infrastructure.

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