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Development of a new *in situ* test method to measure the air permeability of high performance concretes

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ABSTRACT

Although several *in situ* techniques, including the Autoclam Permeability System, are available to examine normal concretes (NCs) for this purpose, none are sufficiently sensitive to quantify and distinguish relative high performance concrete (HPC) performance. Therefore, to assess the HPC performance characteristics using the Autoclam air permeability test methodology, two key modifications were investigated and a new test protocol developed. The first modification considered a reduced volume of compressed air applied to the test area (named LV test), and the second an increased test area (named A-75). The reliability of the proposed modifications was investigated by comparing against a laboratory-based gas permeability test method (RILEM air permeability test). Surface resistivity and relative humidity were assessed to evaluate the influence of moisture conditions on *in situ* air permeability test results. A strong correlation between LV test and RILEM air permeability test results was found when the free moisture near concrete surface regions (up to 20 mm) was removed. It was concluded that the LV test exhibits strong potential to become an established method for assessing *in situ* HPC permeability.

1. Introduction

High performance concretes (HPCs) are typically designed with superior performance characteristics relative to normal concretes (NCs) [1–3]. Resulting enhanced durability of concrete structures containing HPCs is a key driving force behind their application [2,3]. This is particularly relevant given the large sums of money spent annually on repairing and maintaining structures worldwide [4,5]. Various grades of HPCs can be designed, manufactured and tested in laboratory conditions to satisfy design specifications for different service conditions [2,6,7]. However, it is not safe to assume at all times that pre-specified durability levels are achieved on site, as ultimate engineering concrete properties are not solely related to materials, mix proportions and service environments, but also factors which are difficult to control on site, such as manufacturing and delivery processes, as well as construction practices employed from initial placement to final curing [4,8,9]. As a result, a correlation between performance assumptions and *in situ* construction quality should ideally be considered.

To ensure the ultimate delivery of high performance in practice, on site evaluation is essential and so were many field techniques proposed [10–14]. Amongst these, assessment of concrete's near-surface permeation characteristics is recognised as a reliable tool to qualify durability [4,10,14,15], because deterioration of reinforced concrete usually involves ingress of aggressive substances from the surrounding environment [3,5,7,11]. Air permeability tests have gained popularity in recent years due to their short test duration and the fact that concrete pore structure is unaffected during testing [5,13,16]. While a variety of field methods are available for the assessment of NC air permeability and some have become standards [4,10,11,17], no suitable *in situ* method exists for the assessment of HPCs. Previous research attempting to utilise currently available *in situ* methods has found that due to low test sensitivity, most are ineffective at quantifying permeation characteristics of concrete with very low porosity and permeability [18–20]. This is unfortunate given that air permeability is an excellent parameter for *in situ* quality control [3,5,8]. Using the established Autoclam air permeability method, a preliminary study by Yang et al. [21] identified two potential approaches for improving test sensitivity sufficiently to assess relative HPC permeability. This included using a reduced volume of compressed air exposed to the test area (designated as low volume, or LV, Autoclam air permeability test) and using a larger test area (75 mm internal diameter base ring instead of 50 mm). While positive results were obtained using these modifications, further assessment and quantification of basic instrument performance

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characteristics and measurement processes is required before widespread *in situ* use. In addition, reliability needs to be established by testing a wider range of HPCs as well as any preconditioning requirements for the proposed methods.

2. Aims and scope of the research

Against this background, the aim of the current study was to assess the performance characteristics of these modified test approaches that enable more sensitive and reliable determination of air permeability of HPCs. This requires:

1. Establishment of the preconditioning regime for air permeability measurement, targeting at selecting a suitable indicator to reflect concrete moisture conditions.
2. Assessment of the effect of moisture on air permeability tests with the aim of identifying an initial condition for *in situ* measurement.
3. Validation of the proposed technique by comparing against results obtained from a standard laboratory-based RILEM gas permeability test method.
4. Comparison of two modified air permeability tests in order to select the better test for future research investigations.

The research scope is to assess the HPC performance characteristics using the Autoclam air permeability test methodology, after incorporating two key modifications investigated and a new test protocol developed. The first modification considered a reduced volume of compressed air applied to the test area (named LV test), and the second an increased test area (named A-75). The reliability of the proposed modifications was investigated by comparing against a laboratory-based gas permeability test method (RILEM air permeability test). Surface resistivity and relative humidity (RH) were assessed to evaluate the influence of moisture conditions on *in situ* air permeability test results. The results obtained from this investigation led to the development of a new protocol for measuring the *in situ* air permeability of HPCs and a proposal for eliminating the effect of moisture content on measured air permeability values. Furthermore, the suitability of RH and resistivity measurements for quantifying the influence of moisture content of the HPCs on air permeability was established.

3. Experiment programme

3.1. Variables investigated

As shown in Table 1, the two key variables studied in this work included concrete mix type and test methodology using the Autoclam air permeability apparatus. In terms of mix type, one normal concrete (control) and five HPCs were investigated. The intention was to assess a sufficiently wide range of performance levels to allow accuracy to be established adequately [22]. In terms of test methodology, three approaches were considered; namely the conventional Autoclam air permeability test with both a 50 and 75 mm base ring (designated as A-50 and A-75 respectively) and the low volume Autoclam air permeability test (designated as LV-test). To investigate the effect of moisture condition on results obtained, all three test methods were carried out on concretes exposed to five different drying durations. Moisture conditions of test specimens were subsequently quantified using relative humidity and surface resistivity measurements.

3.2. Materials and concrete mixes

Based on previous studies carried out at Queen's University Belfast [18,23], mix compositions of the NC and five HPCs were decided (reported in Tables 1 and 2). Typical of HPCs [1–3,8], four of the HPC mixes contained SCMs, including microsilica (MS), pulversised fuel ash (PFA) and ground granulated blast-furnace slag (GGBS).

CEM-I cement confirming to BS-EN 197 [24] was used where applicable. PFA was obtained from Kilroot Power Station in Northern Ireland, UK, with its properties conforming to BS-EN 450 [25]. Microsilica used was in the form of slurry from Elkem, manufactured to BS-EN 13263-1 [26]. GGBS was from Civil Marine Slag Cement Ltd, manufactured according to BS-EN 15167 [27]. The superplasticiser was a polycarboxylic acid based polymer. The fine aggregate was medium graded natural sand and the coarse aggregate was crushed basalt with 10 and 20 mm size proportions in equal mass. The moisture condition of the aggregates was controlled by pre-drying in an oven at 105($\pm$ 5) °C for 24 h, followed by cooling to 20($\pm$ 1) °C for one day before casting.

3.3. Preparation of specimens and testing

Concrete mixing was undertaken in accordance with BS 1881, Part 125: 2005 [28] and followed immediately by slump and air content testing in accordance with BS-EN 12350-2 [29] BS-EN 12350-7 [30] respectively. Three $230 \times 230 \times 100$ mm slabs and six 100 mm cubes were manufactured for each mix. Moulds were filled with concrete in two equal layers, with each being 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) °C. After 24 h, specimens were removed from their moulds and cured in a water bath at constant temperature of 20($\pm$ 1) °C. Cube specimens were removed after 28 and 56 days and tested for compressive strength according to BS-EN 12390-3 [31].

Fresh properties and compressive strength values for each concrete are shown in Table 3. Disparity between the normal concrete (NC) and HPC is evidenced by the variation in 28-day compressive strength, which was 37 N/mm^2 for mix NC and, on average, 70 N/mm^2 for the five HPC mixes.

Table 1
Experimental variables.

Mix proportions[a]		Test variables[c]	
Control	One normal concrete: NC[b]	A-50 A-75 LV	Oven drying at 40 °C for 7, 14, 21, 28, 35 days
HPC	Five HPCs: MF, PC, PFA, GGBS, GF	A-50 A-75 LV	Oven drying at 40 °C for 7, 14, 21, 28, 35 days

[a] Proportion details of six concrete mixes are given in Table 2.
[b] A-50 refers to conventional Autoclam testing with a 50 mm base ring; A-75 refers to Autoclam testing with a modified 75 mm base ring; LV refers to low volume Autoclam testing with a 50 mm base ring.
[c] NC – normal concrete. MF – HPC with both MS and PFA. PC – HPC with only PC. PFA – HPC with PFA. GGBS – HPC with GGBS. GF – HPC with both GGBS and PFA.