Effectiveness of preconditioning regimes for assessing water permeability of high performance concrete

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Abstract

Saturating high performance concrete (HPC) on site for assessing water permeability is a challenge. This paper reports a testing programme established to assess the reliability and efficiency of two field saturation approaches, viz. vacuum saturation and ponding. The water permeability test results after applying the vacuum saturation and ponding were compared with that after incremental immersion. It is found that ponding was unable to remove the influence of moisture, while vacuum saturation can achieve this for wet concretes. Although the influence of moisture can be removed for different HPCs with high initial moisture contents by using the vacuum saturation method, it is not effective when the initial moisture content is low. The results obtained from numerical simulation model and the electrical resistance measurements after incremental immersion suggested that the water permeability of HPCs can be accurately determined if the surface region (140 mm width and 25 mm depth) is fully saturated.

Key words: *in situ* water permeability test, influence of moisture, high performance concrete, ponding saturation regime, vacuum saturation regime

1 Introduction

Concrete has a reputation as a strong and durable material [1, 2]. The advent of the durability problems along with some catastrophic failures of reinforced concrete structures since 1970's, however, deeply shocked the public and civil engineers [3-6]. In all these cases, one or the other form of mechanism of deterioration was the cause of the loss of structural capacity of the structures, which ultimately resulted in the collapse. Since then numerous approaches have been developed to improve the durability of concrete structures. The use of high performance concrete (HPC) is one amongst such approaches, where concrete is designed to meet a specific durability requirement [7]. Numerous technical papers and reports can be found on HPCs and in all cases one of the key objectives is to modify the pore structure such that the resulting concrete meets the specific durability requirement [8-9]. Therefore, compared to normal concretes (NCs), assessment of the durability of HPCs *in situ* may pose many challenges.

The permeability of cover concrete is a key parameter to assess the durability of concrete structures [10]. Numerous methods for measuring the *in situ* permeation properties of NCs have been proposed, which have played an important role for controlling the quality of structural concrete [10-14]. However, they are not effective for distinguishing the permeation characteristics of very low permeability concretes, such as those typically associated with HPCs, because of their low sensitivity to variations in permeation characteristics. Against this background, new air permeability and water permeability tests were designed to ensure that the differences between HPCs can clearly and reliably be identified [14, 15].

For most field permeability assessments, another technical barrier is that the results are significantly affected by the moisture content of the concrete [10, 16, 17]. Several methods have been proposed to eliminate the effect of moisture on *in situ* gas permeability tests. The Torrent gas permeability test uses the electrical resistivity of the near surface concrete to correct the measured air permeability [18]. In the Autoclam air permeability test [19], it is suggested that the internal relative humidity of the near-surface concrete in the top 10mm depth should be less than 80% to yield reliable permeability coefficients. A similar recommendation is also given by Parrott for the air permeability test that was proposed by the British Cement Association [20, 21]. Nonetheless, these investigations were confined to normal concretes. An investigation by Yang *et al.* has indicated that to remove the influence of moisture on air permeability of HPCs, the relative humidity in the near-surface region (from surface to 20 mm depth) should be less than 60% [14] as opposed to the value of 80% proposed by Basheer and Nolan for NCs [19]. As this capillary moisture free condition is not easy to reach for HPCs [10, 19], it may be advantageous to have an alternative method of measuring their permeation properties.

Instead of the *in situ* air permeability tests, *in situ* water permeability tests may be a possible alternative, as the latter type is usually designed to be carried out under saturation conditions of the concrete. Relatively few publications, however, deal with the influence of moisture on water permeability tests compared with studies on air permeability tests. For the Clam Water pearmability test, the area is saturated for 24 hours by ponding before measurements [22], but this approach is not an effective way to achieve the saturated state for dense concretes (e.g. w/c<0.5) [10]. The results of Meletiou *et al.* indicate that the effect of moisture variations on water permeability tests is nearly removed after applying vacuum saturation [23]. Whiting also attempted to saturate concrete using a similar technique, as a part of the on-site Rapid Chloride Permeability Test [24]. However, it is noted that only normal concretes were examined in their studies. In the case of HPCs, very few investigations on the effect of moisture on *in situ* water permeability tests can be found. Furthermore, both studies do not give any detailed information on the effectiveness of vacuum saturation and, hence, the preconditioning procedures are not fully understood. Therefore, the *in situ* procedures for vacuum saturation need to be developed for HPCs.

In order to establish a site saturation regime for the proposed water permeability test [15], three different saturation regimes were selected, including vacuum saturation, ponding and incremental immersion. The vacuum saturation and ponding are considered as possible approaches for field use, whilst the incremental immersion is considered as the ‘reference’ method, as the previous work [25] has shown that reliable water permeability results can be obtained after incremental immersion of HPCs.

2 Experimental programme

The variables investigated are summarised in **Table 1**, which include the concrete types, saturation approaches and initial moisture conditions before saturation. Ponding and vacuum saturation were chosen to be the potential field approaches to saturate concretes. The results after vacuum saturation and ponding were compared with that after the incremental immersion. To verify whether or not the proposed saturation regime can work under different conditions, the moisture condition before vacuum saturation was also added to the experimental programme.

2.1. Materials and concrete mix proportions

In the context of this research, HPCs refer to concretes with low permeation properties. Mix proportions of the three HPCs were selected based on the previous experimental work [26], details of which are given in **Table 2**. CEM-I cement conforming to BS-EN 197 [27] and two supplementary cementitious materials (SCMs), viz. microsilica (MS) and pulverised fuel ash (PFA), were used in this study. The PFA, conforming to BS-EN 450 [28], was obtained from Kilroot Power station in Northern Ireland, UK and microsilica, conforming to BS-EN 13263-1 [29], was in slurry form from Elkem. A polycarboxylic acid based superplasticiser was used to maintain the required consistence.

The fine aggregate was medium graded natural sand and the coarse aggregate was crushed basalt with 10mm and 20mm size proportioned at equal mass. Before casting, the aggregates were dried in an oven at 105 (± 5)^{o}C for 24 hours followed by cooling to 20 (± 1)^{o}C for one day to control the moisture content.

2.2. Preparation of specimens

The concrete was mixed in accordance with BS 1881: part 125 [30] and the fresh concrete was assessed for slump and air content according to BS-EN 12350-2 [31] and BS-EN 12350-7 [32] respectively. For each concrete mix, 410×100×250 mm blocks were cast for carrying out the water permeability test and 100mm cubes for the compressive strength test at the ages of 28 and 56 days. The slab specimens contained an electrode array for resistance measurements. After casting, the specimens were covered with wet hessian and placed in a constant temperature and relative humidity room at 18 (± 2)^{o}C and 60 (±10)% respectively so that all specimens had similar environmental conditions during their initial period of curing.

All specimens were de-moulded after one day and placed in a temperature controlled water bath at 20 (± 1)^{o}C. The cubes were removed at the age of 28 days and 56 days and tested for the compressive strength [33]. The fresh properties and the compressive strength values for each concrete are reported in **Table 2**.

The blocks were removed from the water bath after three days, wrapped in polythene sheet and relocated at a constant temperature room until the age of 90 days to remove the influence of hydration on subsequent test results. The blocks were then unwrapped, the four sides of which were then painted with an epoxy paint three times to prevent moisture transport through these sides during the experiment.

2.3. Test methods

2.3.1 High pressure water permeability test

Figure 1 shows the high pressure water permeability test setup, details of which and the test procedure are available in Yang *et al.* [14]. To carry out the test, the test head was clamped on the specimen, which was then connected to an air compressor that was used to pressurise the testing system. During measurements, the pressure was maintained at 7 bar by advancing a piston through a cylinder. The volume of water within the cylinder was recorded every minute. Each measurement took 120 mins.

2.3.2 Electrical resistance measurement

Electrical resistance measurements were carried out in order to monitor the degree of saturation within the cover region. **Figure 2** shows the electrode array installed in the concrete block. The stainless steel rods were placed at depths of 10, 15, 20, 25, 30mm from the surface, which is the same as that used by McCarter [34]. The changes in electrical resistance with time across each electrode pair were measured by an LCR meter and recorded by a data logging system.

2.4. <u>*Design of the set-up for vacuum saturation*</u>

2.4.1 Description of the test arrangement for vacuum saturation

Figure 3 illustrates the whole vacuum saturation setup. The design concept of the vacuum saturation set-up used in this study was based on Whiting's work [35] and that used in a number of surface permeability tests [36-37]. Three saturation heads were connected in parallel and clamped on the concrete surface allowing vacuum saturation to be carried out at different locations simultaneously. The vacuum pressure was controlled by a regulator, and a vacuum pressure gauge was used to monitor the change in vacuum level in the chamber.

2.4.2 The procedure for vacuum saturation

After setting up the vacuum saturation system, the vacuum pump was switched on and the vacuum pressure was adjusted to the desired level of 40mm Hg and 240mm Hg for the two duration of vacuum application using a regulator. The pressure level was monitored by the gauge and adjustments were made, if necessary. By the end of the specified period of vacuum application of 3 hour and 6 hour, water was admitted into the chamber. After filling the saturation head, vacuum was released and the specimen was left to admit water for another 40 hours. The water permeability tests were performed subsequently on these specimens.

3 Results and discussion

3.1. Investigation of the effectiveness of vacuum saturation and ponding

The two vacuum levels and the duration of application of each are given in **Table 3**. The water permeability measurement was carried out after the vacuum saturation and five replicate tests were performed for each combination of the saturation regime. For this part of the experimental programme, only one HPC was tested (MF mix containing microsilica and PFA – see Table 1) and the diameter of the saturation area was 75 mm.

3.1.1 *The possibility to achieve 'steady-state' after vacuum saturation*

Figure 4 shows the water flow into the concrete blocks after the four different vacuum saturation regimes. The behaviour of the water flow was examined before attempting further interpretation because the new water permeability test is based on the steady-state flow theory. The duration to reach a 'steady-state' as well as the rate of flow were determined, the procedures of which are similar to that reported in the previous publication [15]. It is evident that the relationship between the volume of flow and time is non-linear in all cases, especially during the initial period. Further examination of the flow behaviour was done by plotting the rate of flow against time (Figure 5).

The flowrates at different test duration in Figure 5 were estimated using the regression analysis of the volume of water versus time. In this figure, the error bar refers to the standard deviation of the flowrates in the five replicate tests. The results indicate that the flowrates decrease as time increases and the magnitude of the standard deviations reduces as the flowrate decreases. This would mean the flowrates seem to stabilise after 45 mins and the variations in the flowrates expressed as standard deviation are comparatively small.

The duration to reach the 'steady-state' was further confirmed by analysis of variance (ANOVA). It should be noted that the results of flowrate were transformed by the log-function to obtain the homogenous variance. The duration was plotted in a bar chart, as shown in **Figure 6**. It generally took around 45 mins for flow to stabilise, except for the tests under 240 mm Hg vacuum saturation for 6 hour, which needed 60 mins to obtain the constant flowrate. Therefore, the flowrates for all tests were estimated based on the regression analysis of the data after 60 mins.

3.1.2 *The effect of vacuum pressure and duration of vacuum application*

The effect of vacuum pressure and duration of vacuum on the steady-state flowrate was analysed through a 2^2 factorial experiment. **Table 4** summarises the results of the statistical analysis and **Figure 7** shows the main effects of the factors and the interaction between vacuum pressure and vacuum duration. As can be seen from the table, only the effect of vacuum duration is significant, whilst the others do not remarkably affect the flowrate. In **Figure 7**, it can be seen that the vacuum duration had a negative contribution on the response, meaning that a higher level leads to a lower flowrate. This can be expected because longer duration can remove the air effectively and more pores can become saturated, hence giving a lower flowrate. Furthermore, the increase of the vacuum pressure can be seen to cause an increase in the flowrates

Although **Figure 7** demonstrates the existence of interaction between the vacuum pressure and the duration of vacuum application, **Table 4** shows that this is not significant. Therefore, the vacuum level and its duration can be decided based on their main effects. In other words, a lower vacuum pressure and longer vacuum duration are preferable for field applications to achieve the steady state of flow.

3.1.3 *The effect of ponding*

Ponding the test area with water was another approach that was investigated to saturate concrete on site and, hence, its influence on water permeability results was assessed. The test head that was described in section 3.1.1 was clamped on the concrete surface and water was filled in the head (termed as ponding with water). After 48-hours of ponding, the new water permeability test was carried out at the conditioned region and the volume of water transported into the concrete at different durations determined. From these data the flowrate was obtained, as was done for the vacuum saturation method. The flowrate corresponding to the steady state is presented in **Figure 8**, along with those from the vacuum saturation and incremental immersion test conditions. It can be seen from this figure that the flowrate after ponding is roughly three times of what was obtained after the vacuum saturation. This is because ponding is known to be effective only to saturate the near surface region, typically up to 1 to 2 mm [38], which is lower than the effective depth in the water permeability tests (typically 25 mm). Therefore, it can be concluded that ponding is not an effective saturation method for the steady state water permeability tests on HPCs.

3.1.4 Comparison of the flowrates for vacuum saturation and incremental immersion

The effectiveness of vacuum saturation and ponding were examined to identify if the effect of moisture has been eliminated. The flowrates after the two preconditioning regimes were compared with that after two incremental immersion periods, viz. 6 days and 10 days, were applied to study if the duration of immersion has any significant effect. The incremental immersion, principally reported by researchers from Queen's University Belfast [7, 18, 26], was a method to saturate concrete samples in the laboratory. The incremental immersion method is able to remove air in specimens by leaving one surface exposed to the ambient whilst water is absorbed through other surfaces, which enables 100% degree of saturation. According to results obtained previously [39, 40], this method could give similar results as the vacuum saturation.

Figure 8 summaries the flowrates after incremental immersion, ponding and vacuum saturation. The mean values in **Figure 8** are cross-compared using the least significant difference (LSD) [41] and the results are summarised in **Table 5**. The reason for comparing the mean flowrates of both the ponding and the vacuum saturation conditions (V-240-3, V240-6, V40-3 and V40-6) with that for the incremental immersion for 6 days (IM-6) in this table is given below.

In **Figure 8**, three features can be identified. Firstly, the flowrates after incremental immersion are the lowest (IM-6 and IM-10 in Figure 8) and no obvious difference existed between 6 days and 10 days of immersion. The data in **Table 5** show that the difference between the means for these two test conditions is not significant. Therefore, the effectiveness of other saturation methods can be assessed by comparing with the flowrate for either of these two; hence hereafter the comparison is made with data from incremental immersion for 6 days (IM-6).

Secondly, there is noticeable difference in flowrate between incremental immersion and ponding (Figure 8). The data in Table 5 highlights that this difference is highly significant.

Thirdly, the effect of vacuum level and duration on flowrate reported in **Figure 7** is confirmed in **Figure 8** as well; that is, as the vacuum level was decreased from 240 mmHg to 40 mmHg and the duration of vacuum application was increased from 3 hours to 6 hours, the flowrate decreased. Further, the 40 mmHg-6 hour vacuum saturation regime gave similar flowrate to that of the incremental immersion (Figure 8) and the data in Table 5 confirms that the difference between the mean flowrates for these two test conditions was not significant. However, this is not the case for other treatment combinations.

Therefore, it has been concluded that vacuum saturation with the application of the lower vacuum pressure (40 mmHg) and the longer duration (6 hours) is adequate to remove the influence of variations in moisture on the steady state water permeability test and ponding for 48 hours is not sufficient to achieve this.

3.2. Confirmation of the effectiveness of the proposed vacuum saturation regime

Despite the similarities in flowrates between vacuum saturation and incremental immersion, there is a potential risk to draw an improper conclusion. To see if the effect of mixes on water flowrates determined by using the vacuum saturation method is similar to that from the incremental immersion method, the flowrates for the two methods of saturating three concrete mixes were obtained and compared in **Figure 9**. It can be seen that the flowrates after vacuum saturation are similar to those after incremental immersion, albeit the vacuum saturation offering slightly higher value for all the mixes. However, the t-test [42] for comparing the flowrates (**Table 6**) shows that the difference between the flowrates for the two precondition regimes is not statistically significant. That is, the proposed vacuum saturation regime is sufficient to achieve steady state permeability values similar to that for the incremental immersion.

Although the objective of the research reported in this paper was not to compare the water permeability of different HPCs, but to evaluate the preconditioning regimes for carrying out the steady state water permeability tests on HPCs, it is important to highlight here that the PC mix had the lowest flowrate in comparison with the PFA and MF mixes. Most classical concrete technology books state that the use of SCMs can give a lower permeability, provided samples are cured under a suitable condition [2, 6, 43]. This apparent anomaly might have been caused by the effect of different degrees of compaction of the three HPCs on their pore structure characteristics and transport properties, as highlighted by Banthia *et al.* [44]. However, the results in **Figure 9** would suggest that, even though SCMs could be used to produce a potentially lower permeability concrete, this cannot be guaranteed for all manufacturing and exposure conditions. Therefore, direct on site measurements of concrete permeability are strongly recommended. The results also highlight that the proposed test method is able to identify the differences caused by these factors.

3.3. *Effectiveness of the vacuum saturation regime for different test conditions*

3.3.1 *Influence of initial moisture condition of test specimens*

In the previous sections, the flowrate measurements were carried out under a specific initial moisture condition. More specifically, the moisture content of concrete specimens was comparatively high, as the samples were not exposed to any drying conditions. However, this is not the case for most concrete structures in service, hence, a further experiment was carried out using test specimens which were under a 'dry' condition. The samples were dried in an oven at 40 (±1)^{o}C for 7 days and cooled in a constant temperature room (20±1^{o}C) for 1 day. It should be noted that the objective for oven drying samples was to achieve a different initial moisture condition before vacuum saturation rather than completely drying the specimens. For this reason, as well as to minimise any pore structure changes, including microcracking, due to drying [19, 21, 45, 46], the low temperature was chosen.

The steady state water permeability test was carried out on these samples after applying the vacuum saturation, the flowrates of which are reported in **Figure 10**. Evidently, the flowrates are greater for all of the oven dried samples in comparison to those after wet curing. This implies that there was either microstructural changes due to drying or improved hydration for the wet cured samples, both of which were not investigated further in this research. Another possible explanation is that when the concrete has relatively low moisture content, the proposed saturation regime may not be suitable, i.e. adjustments are required to either the degree of vacuum applied or its duration or both during the vacuum saturation regime. This aspect is investigated further below.

The water flow was simulated using numerical analysis as detailed in the previous work [15]. **Figure 11** shows the relative flowrates at different depths and all flowrates were normalised to the central point on the test surface. It reveals that the flowrate on the surface increases with increasing distance to the line of symmetry and reaches maximum value at 25 mm, around 2.6 times higher than that at the centre point. At the deeper levels, the relative flowrates are comparatively constant and at 30 mm and 40 mm the flowrates are less than 0.5. The direct measurement of flowrates at different depths was carried out by Whiting and Cady [37] and the results have shown that the flowrate is negligible beyond 1 inch (25.4 mm). Similar findings were also reported by Guth and Zia [47].

Another notable feature of **Figure 11** is that the flowrates at different levels beyond 70 mm (distance to the axis of symmetry) are close to zero. The diameter of saturation area was 75 mm, which means only 37.5 mm around the axis of symmetry was saturated. In the unsaturated region, water could flow faster due to the compressibility of air and filling the unsaturated pores with water. Therefore, the proposed vacuum saturation regime (vacuum pressure: 40 mm Hg, vacuum duration: 6 hours, vacuum application area: 4415.63 mm^2 corresponding to Φ75 mm) is not effective to remove the influence of moisture on water permeability test results if concrete is oven dried.

3.3.2 *Influence of vacuum saturation area*

The results in **Figure 11** suggest one possible solution to improve the effectiveness of vacuum saturation for drier concretes, which is to increase the saturation area. It should be noted that pores can be saturated by the inflow of water eventually, but as Scherer [48] has highlighted, this process would last for a very long period, meaning that a longer test duration is required to saturate the test area in this manner, which is not suitable, especially for field application. Considering the features of the model in Figure 11, a larger saturation area (a diameter of 180 mm and 20 mm seal) was investigated. The vacuum saturation was applied by using a new saturation head for this area, while the intensity of vacuum (40 mm Hg) and the duration (6 hours) were not changed.

Figure 12 shows the results of the steady state water permeability test after vacuum saturation. Generally, the flowrates decreased with increasing the saturation area, which indicate that the flowrates can be controlled for drier concretes by increasing the saturation area. A comparison of the data for 180mm dia vacuum saturation area in Figure 12 with the corresponding data in Figure 10 for wet cured specimens would indicate that the effect of drying of concrete before applying the vacuum saturation was not substantially seen for both MF and PFA concretes. However, there was still some noticeable variation for the PC concrete. This aspect needs to be investigated further. One possibility is that this must have been caused by the variability of the concrete specimens tested in different test conditions.

3.3.3 *Overall comparison of different test conditions*

An overall comparison for different test conditions was made and results are displayed in **Figure 13**. The notation 'VS' means vacuum saturation, while 'AC' and 'OD' refer to the initial condition of specimens: after wet curing (AC) and after oven dried (OD). Two notable features can be found. One is that the influence of moisture cannot entirely be removed, as the flowrates for all vacuum saturation regimes are higher than these obtained after incremental immersion. More importantly, different trends were found for the three concretes. The highest difference in flowrates in the case of OD sample was found for PC, while the flowrates of PFA under VS-OD (180 mm dia.) were very close to the line of equality. This means that the concrete with the lowest permeability (i.e. PC in this study) is insensitive to the saturation regime. Another influencing factor is the initial condition before saturation, which directly determines the effect of vacuum saturation. Only under certain conditions (in this case after sealed curing), the vacuum saturation method used in this study can reach similar trend to what was obtained after incremental immersion. After oven drying, an opposite trend was seen. It suggests that the proposed preconditioning regime should be used with caution.

3.4. Requirements to obtain reliable water permeability results

As stated above, the proposed saturation regime is not totally effective to remove the moisture influence under the dry conditions and it is necessary to specify the requirements to yield a reliable measurement. Provided the results after incremental immersion are considered as the 'reference' data, the moisture condition after other saturation techniques should be identical for achieving similar results. The saturation degree is the ideal parameter to describe this feature and the method proposed by Archie [49] was used to estimate the degree of saturation in this study:

$$S = \left(\frac{R_O}{R_t}\right)^{\frac{1}{m}} \times 100\% \qquad \text{Eq (1)}$$

where S denotes the saturation degree of the pore system (%), R_o denotes the resistance at the saturation condition (Ω), R_t denotes the resistance at the time of measurement (Ω), m denotes the cementation factor reflecting the tortuous nature of the capillary pores.

To evaluate the value of saturation degree, R_o and m in Equation (1) need to be determined. A fully saturated condition is difficult to reach and, hence, the samples were immersed for 50 days (leaving one surface exposed to surface) and the resistance measurements were carried out to obtain R_o. For the value of '*m*', it is generally in the range from 1.5 to 3 [38] and a middle value, 2, was used in this case.

Figure 14 shows the saturation degree for the different conditions, viz. after drying before immersion (AD), incremental immersion (IM, 6 days and 10 days respectively) and vacuum saturation (VS). As expected, the saturation degree after VS is generally higher than that of AD, especially at the surface region (around 20 mm). Meanwhile, the saturation degree after VS was lower than those after the two IMs. These results show why the proposed vacuum saturation procedure was not as effective as the incremental immersion. Furthermore, the surface region, approximately 20 to 25 mm, achieved a higher degree of saturation (higher than 95%) after incremental immersion. This moisture condition can be considered as the requirement for the proposed steady state water permeability test, as there is a concentration of flow paths located within this region (confirmed by experiments [37, 47] and water flow simulation in **Figure 11**).

4 Conclusions

In this study, the effectiveness of ponding and vacuum saturation on the water permeability test was assessed and based on the results obtained, the following conclusions have been drawn:

1) The vacuum saturation gives statistically similar results compared with results after incremental immersion when the moisture content inside the concrete is high. To remove the influence of moisture on permeability tests, only the low level of vacuum (40 mm Hg) and the long duration (6 hours) is effective. Furthermore, significant interactions among vacuum level, vacuum duration, saturation area, concrete type and moisture condition inside concrete have been found. Before this

vacuum saturation method can be recommended for general use it should be tested for a variety of initial conditions.

2) Ponding for 48 hours before carrying out the new water permeability test is insufficient to remove the influence of moisture, as the flowrates of the new water permeability test after ponding are approximately 4 times greater than after incremental immersion, which is mainly attributed to the fact that only the surface region (typically 1-2 mm) was saturated.
3) The studies of the flow model and the resistance profile after incremental immersion showed that most of the flow occurred in the top surface region of a sample and the results indicate that a region of 140 mm width and 25 mm depth should be saturated for performing reliable site water permeability tests.
4) The permeability of HPCs is a complicated function of many factors, especially sensitive to the construction practice, curing regime and mix proportion. Therefore, direct measurements of permeability on site are highly recommended and the new test method could be a potential technique for this purpose.

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Tables and Figures

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Table 1 Variables studied

Variables	Level
Mixes*	PC; PFA; MF
Moisture condition before saturation	After sealed curing (Reference 1) After drying for 1 week in an oven at 40 °C (Reference 2)
Saturation methods	Incremental immersion (Laboratory) Ponding (Field technique) Vacuum saturation: vacuum pressure and duration (Field technique)

*Note: PC, PFA and MF refer to three high performance concretes tested; PC denotes high performance concrete made from plain Portland cement; PFA denotes high performance concrete containing PFA; MF denotes high performance concrete manufactured with microsilica and PFA; the mix proportions are given in Table 2.

Table 2 Concrete mix proportions and both fresh properties and compressive strength

Concrete	PFA	PC	MF
Water (kg/m³)	145	145	145
Portland cement (kg/m³)	388	485	449
Microsilica (kg/m³)	0	0	36
PFA (kg/m³)	97	0	97
Sand (kg/m³)	668	689	652
Coarse aggregate (kg/m³)	1150	1150	1150
Superplasticiser (% of binder content)	1.4	1.3	1.5
Air content (%)	0.6	1.0	1.6
Slump (mm)	220	225	240
28 day compressive strength (MPa)	81.3	81.8	84.2
56 day compressive strength (MPa)	90.7	87.3	94.6

Table 3 The levels of the intensity of vacuum pressure and duration

Factor	Level	
	+	-
Vacuum pressure	1 (240mm Hg)	-1 (40mm Hg)
Duration	1 (6 hour)	-1 (3 hour)

Note: A pressure of 40 mm Hg is advised by NT Build 492, which also suggests a vacuum duration of 3 hours. ASTM C1202 recommends applying vacuum for 6 hours. The 'high (+)' level was selected as 240 mmHg to avoid damages caused by a high vacuum pressure.

Table 4 The analysis of the 2^2 experiment variance

Factor	Sum of square	Degree of freedom	Mean square	Fo-value	p-value*
Vacuum pressure	0.0062	1	0.0062	0.234	0.637
Duration	0.147	1	0.147	5.573	0.036
Vacuum pressure×Duration	0.0258	1	0.0258	0.981	0.342
Error	0.316	12	0.0263		
Total	0.522	15			

*Note: p-value < 0.01 means highly significant, 0.05 < p-value < 0.01 means significant, p-value > 0.05 means non-significant.

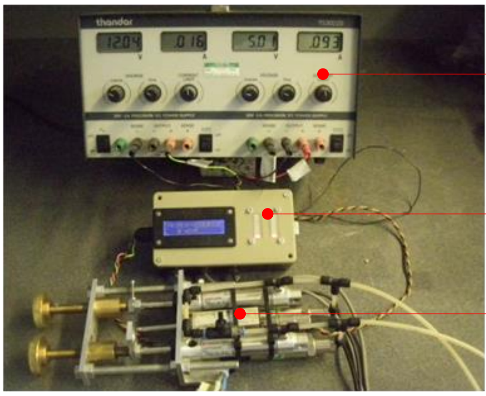
Table 5 Summary of cross-comparison of the flowrates determined from the new water permeability tests after different preconditioning regimes

Saturation method	Comparison	Mean difference	Degree of Freedom	Error	t-statistic	P-value*
Ponding	Ponding vs IM-6	0.802	1	0.096	8.369	< 0.0001
V240-3	V240-3 vs IM-6	0.327	1	0.102	3.212	0.0036
V240-6	V240-6 vs IM-6	0.227	1	0.102	2.233	0.0347
V40-3	V40-3 vs IM-6	0.368	1	0.102	3.622	0.0013
V40-6	V40-6 vs IM-6	0.092	1	0.096	0.964	0.3441
IM-6	IM-6 vs IM-10	0.025	1	0.096	0.261	0.7961

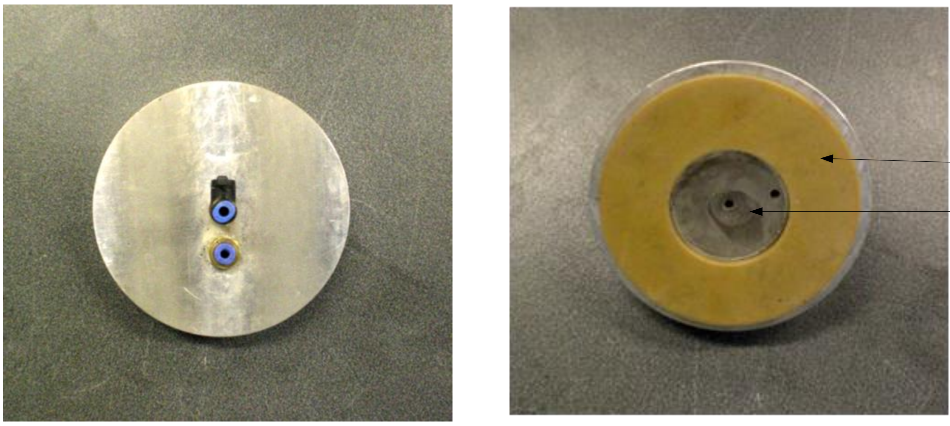
*Note: p-value < 0.01 means highly significant, 0.05 < p-value < 0.01 means significant, p-value > 0.05 means non-significant.

Table 6 Summary of the results of the paired t-test between incremental immersion and vacuum saturation for PFA and PC

t-test	PFA incremental immersion Vs Vacuum saturation	PC incremental immersion Vs Vacuum saturation
	0.087	0.053
σ^*_d	0.338	0.274
$t_{0.05}/(n-1)^{0.5}$	0.953	0.953
$t_{0.01}/(n-1)^{0.5}$	1.676	1.676
$A_{0.05}$	0.322	0.261
$A_{0.01}$	0.566	0.459
Conclusion	Non-significant	Non-significant



a) The main body of the new water permeability test



b) The top view of the test head c) The bottom view of the test head

Figure 1 The test set-up of the new water permeability test

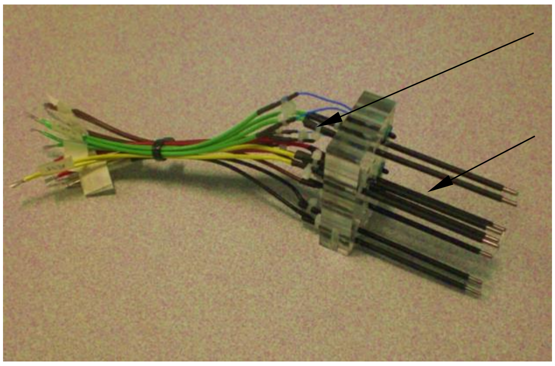


Figure 2 The electrode array used to measure the electrical resistance

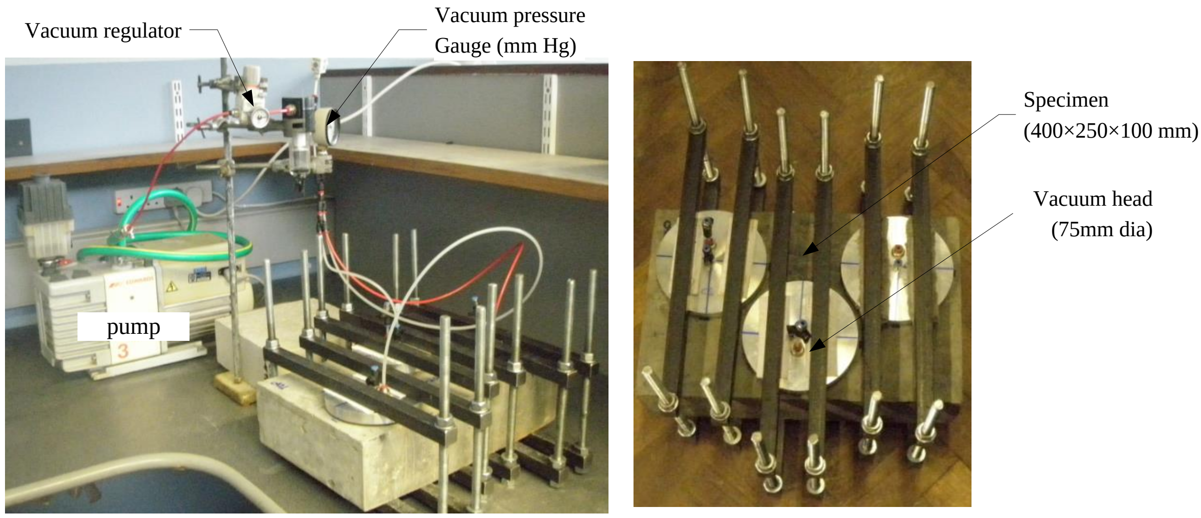
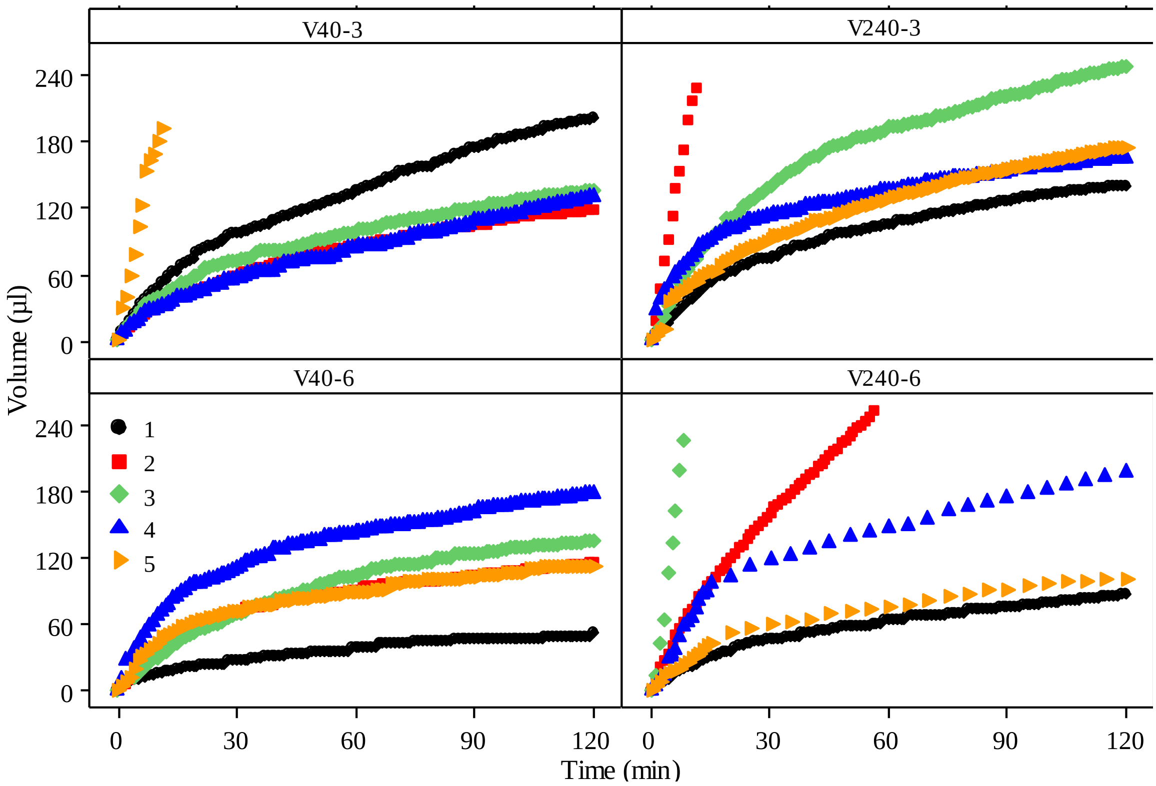


Figure 3 Overall view of the vacuum saturation set-up



Note: V240-3 refers to vacuum saturation at 240 mm Hg for 3 hours; V240-6 refers to vacuum saturation 240 mm Hg for 6 hours; V40-3 refers to vacuum saturation 40 mm Hg for 3 hours; V40-6 refers to vacuum saturation at 40 mm Hg for 6 hours; IM-6 refers to incremental immersion for 6 days; 7 refers to incremental immersion for 10 days.

Figure 4 Water permeability test data after vacuum saturation of the MF concrete

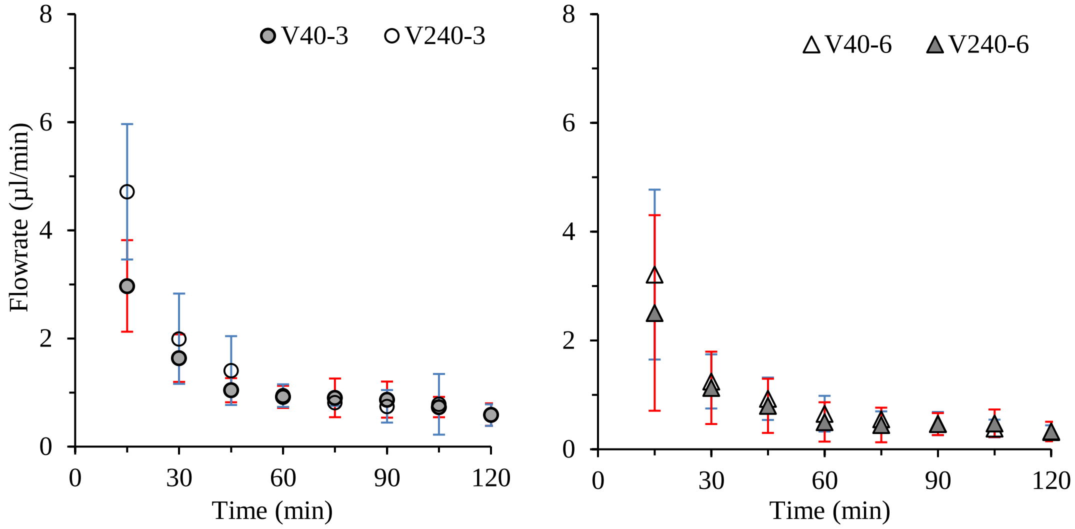


Figure 5 The relationship between flowrates and the test duration

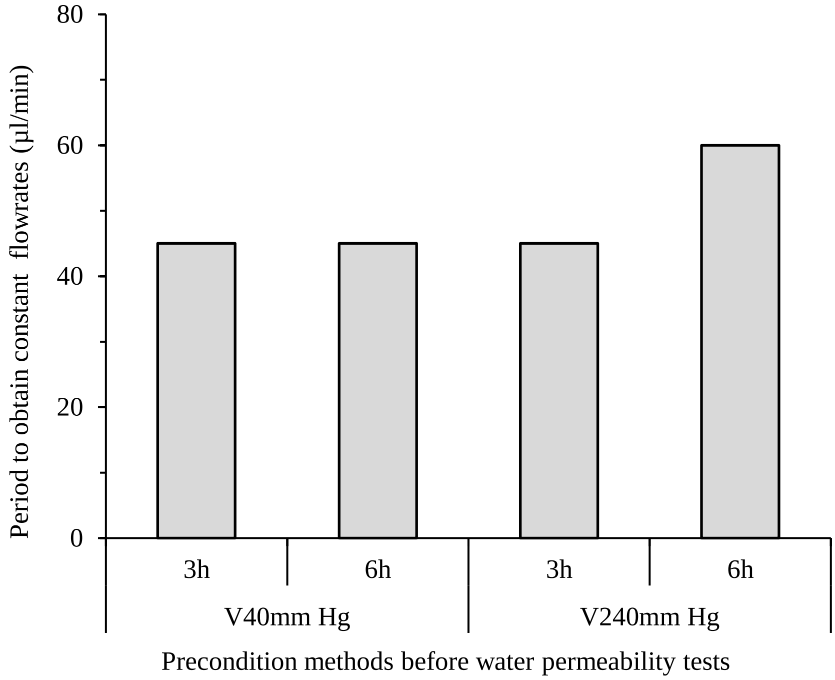
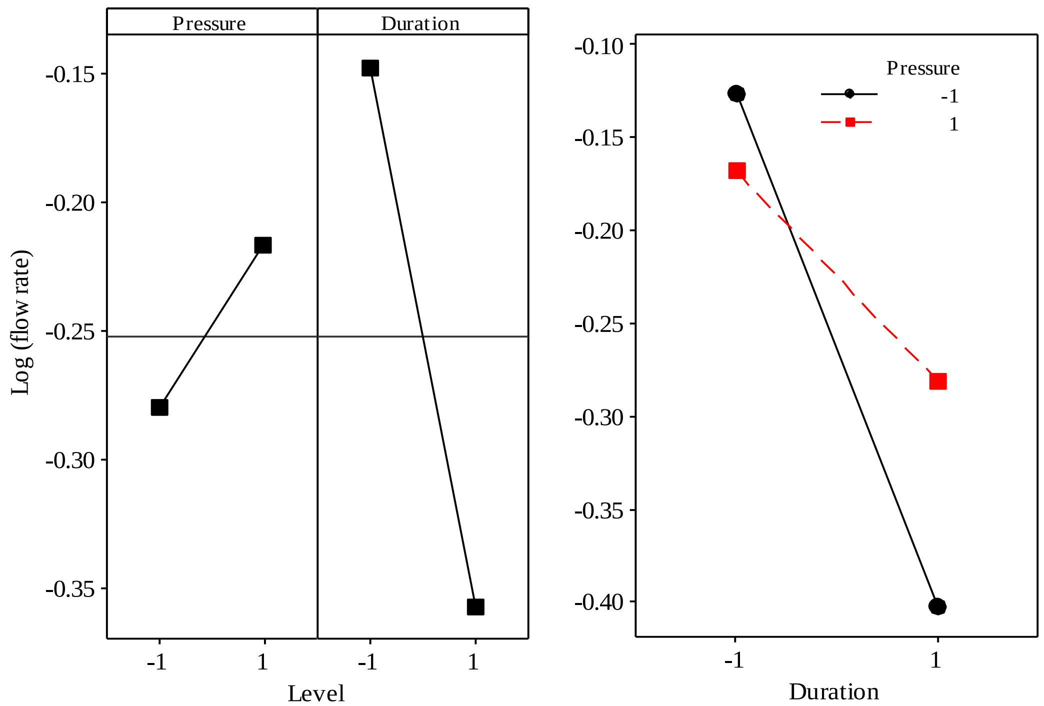
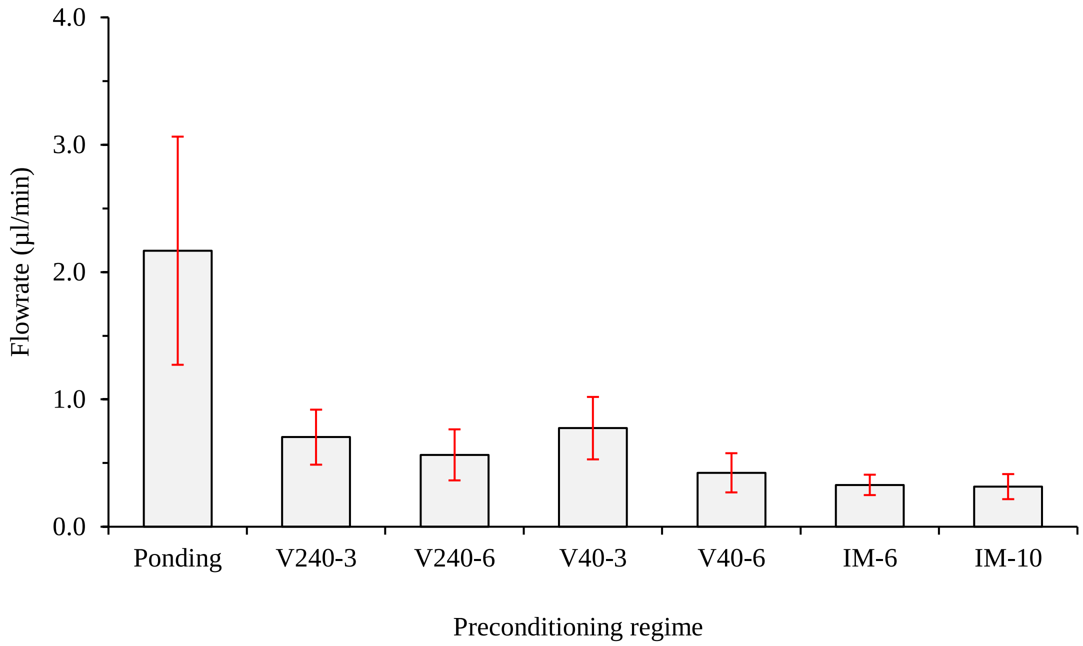


Figure 6 The test duration to reach 'steady-state' under different test conditions



(a) The main effects (b) Interaction

Figure 7 The plots of main effects and interaction



Note: See Table 5 for details of the notations

Figure 8 Flowrates of the new water permeability tests after incremental immersion, ponding and vacuum saturation

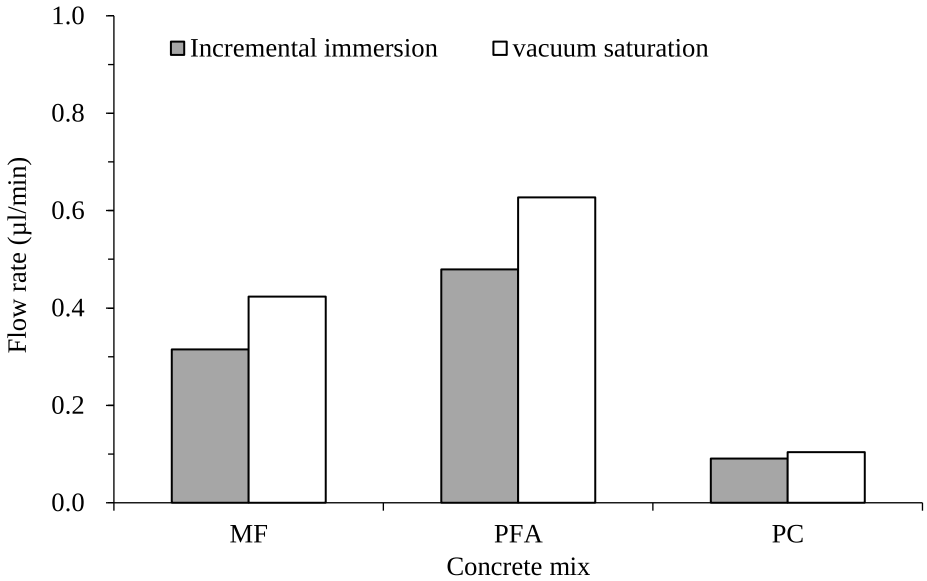


Figure 9 Comparison of flowrates after saturating by incremental immersion and vacuum saturation for three different concrete mixes

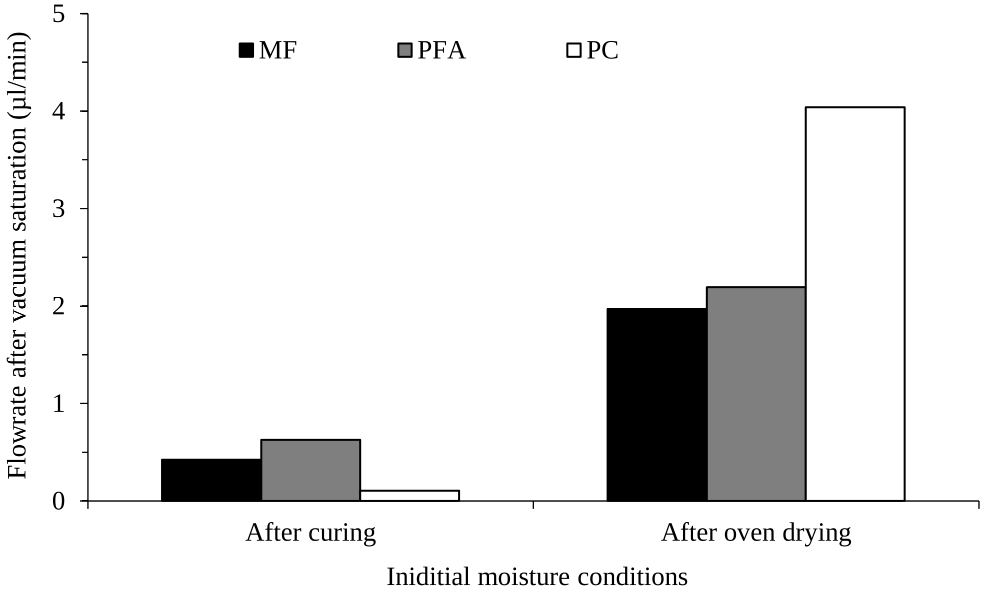


Figure 10 Flowrates after vacuum saturation under two different initial moisture conditions

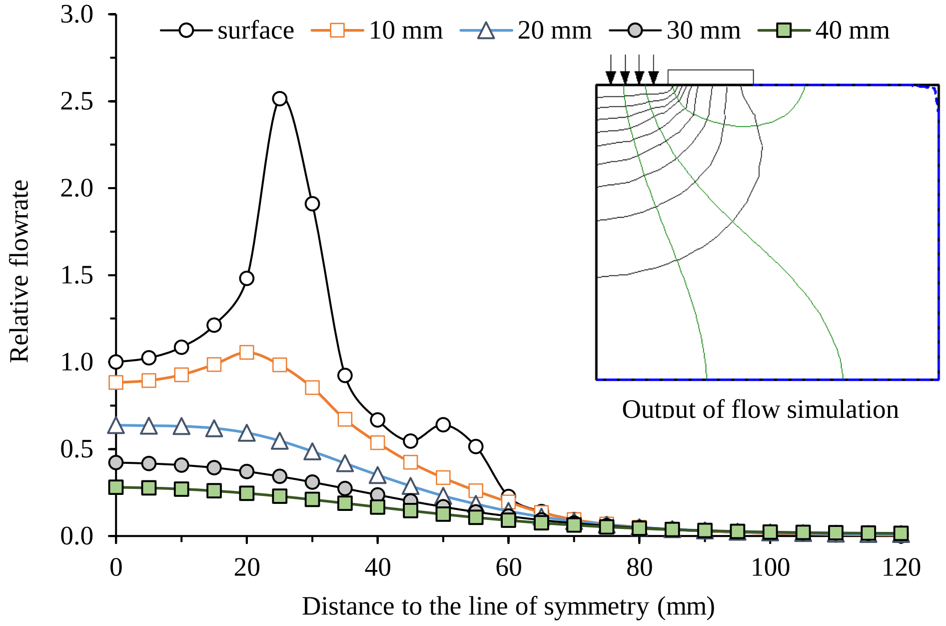


Figure 11 The relative flowrates at different locations determined for the saturated model

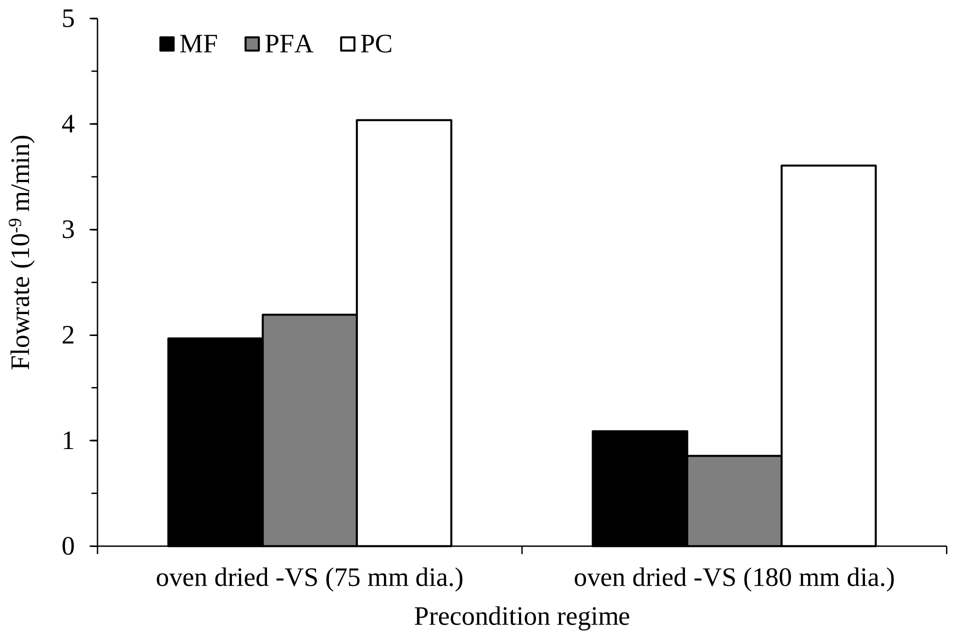


Figure 12 The effect of vacuum saturation area on water flowrates of the three concretes after oven drying

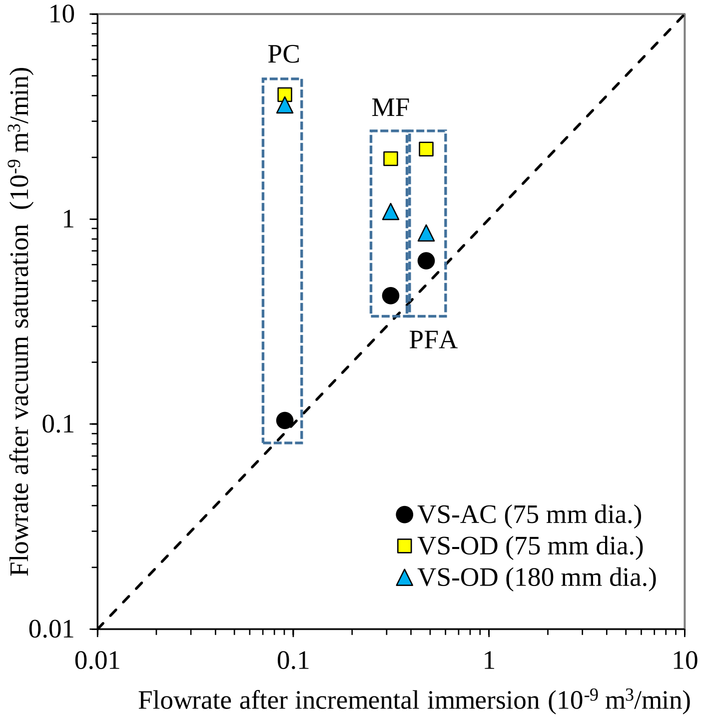
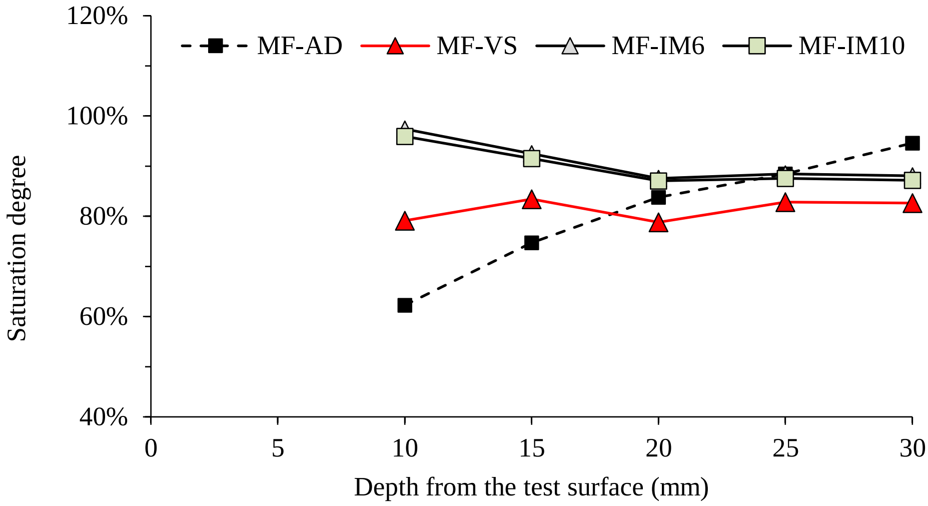
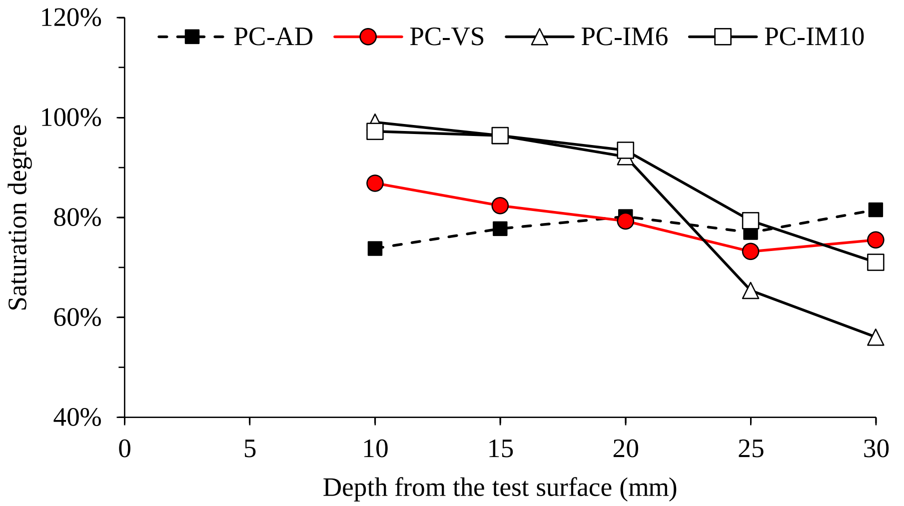


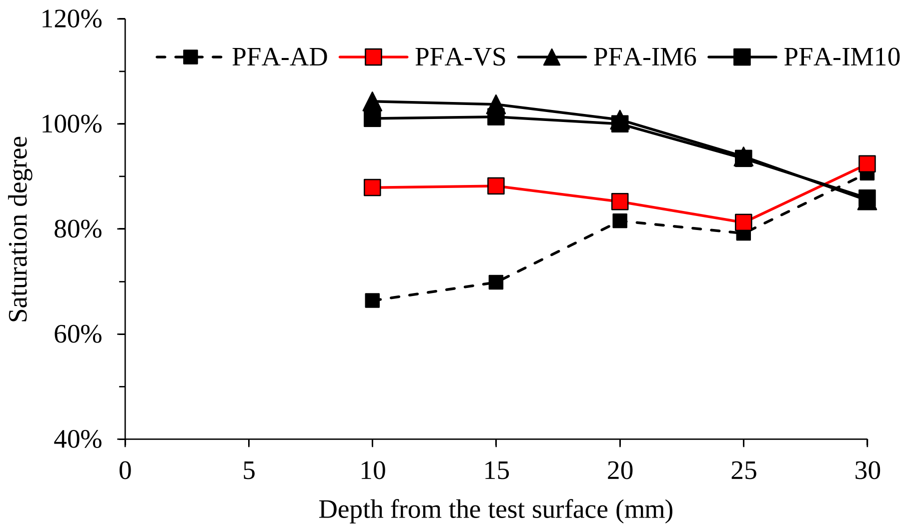
Figure 13 Overall comparison of flowrates after incremental immersion and vacuum saturation



(a) MF



(b) PC



(c) PFA

Figure 14 Comparison of the saturation degree between vacuum saturation and incremental immersion