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Communication

# Comparison of ASTM saturation techniques for measuring the permeable porosity of concrete

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**Abstract**

The aim of this study is to compare the efficacy of the ASTM saturation techniques for measuring the permeable porosity of concrete. The permeable porosity of two ordinary concretes has been determined by three ASTM saturation techniques, namely cold-water saturation (CWS), boiling-water saturation (BWS) and vacuum saturation (VAS). The concretes were prepared with the water–cement ratios of 0.50 and 0.60, and tested at ages of 7 and 28 days. Based on the test results of permeable porosity, the efficiency of the saturation techniques has been compared. In addition, the compressive strength of concretes was determined to justify the results of permeable porosity. The slump test was also performed to observe the workability. The overall experimental results reveal that vacuum saturation technique is more efficient than cold-water or boiling-water saturation and therefore this technique should be recommended for measuring the permeable porosity of concrete.


*Keywords:* Concrete; Hydration products; Mixture proportioning; Porosity

## 1. Introduction

The permeable porosity affects the transport properties and durability of concrete. It is connected to many deterioration processes driven by the transport properties of concrete. For example, the porous medium of concrete permits the transport of chloride, oxygen, carbon dioxide, and moisture, which are known to cause corrosion in reinforcing bars [1–4]. This is a severe problem in North America owing to the use of deicing salts for winter maintenance. Corrosion-induced deterioration is now plaguing so many concrete structures in this region. There is another deterioration process most commonly occurring in North America. It is the physical deterioration of concrete by freezing and thawing. The deterioration due to freezing and thawing is also related to the permeable porosity of concrete [5]. The permeable pores of concrete accommodate water under saturated condition. This water freezes below freezing temperature, expands and causes hydraulic pressure. Thus, the cracking appears in concrete [6]. Other deterioration processes such as sulfate attack and alkali aggregate reactivity are also linked to the permeable porosity of concrete, as they depend upon the ingress of moisture into the concrete [7]. Furthermore, the permeable porosity of concrete has a major effect on its strength and other mechanical properties [8,9]. Hence, the permeable porosity of concrete should be determined properly in order to predict the durability and serviceability of concrete structures.

ASTM has given three techniques for concrete saturation in various standards. These techniques are used as basis for several material characterization tests. ASTM C 642 [10] presents two saturation techniques: cold-water saturation (CWS) and boiling-water saturation (BWS). Although both techniques measure density and absorption, only the boiling-water saturation technique has been used to measure the permeable pore space or voids (permeable porosity) in hardened concrete. There is another saturation technique, namely vacuum saturation (VAS), as mentioned in ASTM C

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1202 [11]. This technique has been used to saturate the concrete specimens required for measuring chloride ion penetration resistance of concrete.

The present study has investigated the efficacy of the ASTM saturation techniques in determining the permeable porosity of two ordinary concretes. The results of the permeable porosity have been compared and finally the most effective saturation technique has been recommended in this study.

## 2. Research significance

An efficient saturation technique is necessary in order to determine the permeable porosity of concrete. If the saturation of concrete specimens is not complete, the subsequent characterization test for permeable porosity will also be flawed. The present study compares three ASTM saturation techniques and evaluates their effectiveness through the relative differences in permeable porosity. The results are useful to distinguish the most effective saturation technique.

## 3. Experimental details

The constituent materials were selected, tested for some physical properties, and proportioned before starting the key operations of the experimental investigation. The permeable porosity as well as the slump and the compressive strength of two ordinary concretes were determined.

### *3.1. Selection and testing of materials*

Locally available crushed granite stone coarse aggregate, natural river sand fine aggregate, ASTM Type I portland cement, and tap water were used in preparing the concrete mixtures. Tap water was also used in curing the specimens and for various saturation techniques. The materials were tested to determine the physical properties required for mixture proportioning of concrete. The physical properties of materials are shown in Table 1.

Table 1
Properties of materials

| Material | Property |
|---|---|
| Portland cement | Specific gravity: 3.15 |
| Natural river sand fine aggregate | Fineness modulus: 2.0<br>Saturated surface-dry basis specific gravity: 2.60<br>Absorption: 1.6%<br>Moisture content: 0.5% |
| Crushed granite stone coarse aggregate | Maximum size: 20 mm<br>Oven-dry basis unit weight: 1674 kg/m$^3$<br>Saturated surface-dry basis specific gravity: 2.70<br>Absorption: 0.5%<br>Moisture content: 0% |
| Tap water | Density: 998~1000 kg/m$^3$ |

Table 2
Saturated surface-dry basis concrete mixture proportions

| NPCC50 (Water–cement ratio=0.50) | | NPCC60 (Water–cement ratio=0.60) | |
|---|---|---|---|
| Cement (kg/m$^3$) | 410 | Cement (kg/m$^3$) | 342 |
| Fine aggregate (kg/m$^3$) | 594.5 | Fine aggregate (kg/m$^3$) | 650.6 |
| Coarse aggregate (kg/m$^3$) | 1177.7 | Coarse aggregate (kg/m$^3$) | 1177.7 |
| Water (kg/m$^3$) | 205 | Water (kg/m$^3$) | 205 |

### *3.2. Concrete mixture proportioning*

Two ordinary concrete mixtures were designed using the method recommended by ACI Committee 211 [12]. The water–cement ratios of 0.50 and 0.60 were selected for designing the concrete mixtures designated as NPCC50 and NPCC60, respectively. The concrete mixtures were designed for the same workability. The specified slump for both concretes was in the range of 75–100 mm. The fineness modulus of sand was found at 2.0, which is below the typical range of fineness moduli. Nevertheless, the obtained fineness modulus was used in mixture proportioning. The mixtures were designed based on the absolute volumes of the constituent materials in saturated surface-dry condition, but the proportions of materials were obtained on weight basis. The details of saturated surface-dry basis concrete mixture proportions are shown in Table 2. In order to facilitate the batching process, the aggregates were used in air-dry condition and, therefore, extra water was required to account for absorption during mixing. Consequently, the proportions of coarse aggregate, fine aggregate and water were adjusted. The details of adjusted mixture proportions are shown in Table 3.

### *3.3. Preparation of fresh concrete*

Fresh concretes were prepared based on the adjusted mixture proportions. The constituent materials were batched by weight and mixed in a pan-type mixer. The batch volume was calculated taking the quantity of fresh concrete at least 15% more than the required in order to compensate the loss during mixing, sampling, testing of slump, and molding of

Table 3
Adjusted concrete mixture proportions

| NPCC50 (Water–cement ratio=0.50) | | NPCC60 (Water–cement ratio=0.60) | |
|---|---|---|---|
| Cement (kg/m$^3$) | 410 | Cement (kg/m$^3$) | 342 |
| Fine aggregate (kg/m$^3$) | 588 | Fine aggregate (kg/m$^3$) | 643.5 |
| Coarse aggregate (kg/m$^3$) | 1171.8 | Coarse aggregate (kg/m$^3$) | 1171.8 |
| Water (kg/m$^3$) | 217.4 | Water (kg/m$^3$) | 218 |

test specimens. Coarse and fine aggregates were charged first into the mixer and mixed with some mixing water. Then the cement and the rest of the mixing water were added, and the mixing was continued. The overall mixing time was about 6 min.

### 3.4. Testing of fresh concrete

Fresh concrete mixtures were sampled for the slump test in order to examine the workability. The slump test was carried out according to ASTM C 143/C 143M [13]. The workability of both concretes was tested before molding the cylinder specimens.

### 3.5. Preparation of test specimens

Fresh concrete mixtures were used to cast twenty-four 100 (diameter)×200 (height) mm cylinder specimens. The specimens were molded in single-use plastic molds. The molds were sealed immediately using the lids and left undisturbed. The cylinder specimens were removed from their molds after 24 h. Then, the specimens were marked and transferred to the curing tank. Water curing by submerging was used to cure the specimens until testing at 7 and 28 days. The curing temperature was 23±2 °C. ASTM standard practice [14] was followed in preparing and curing the specimens.

In total, twelve 100×200 mm cylinders were used for the compression test. The remaining 12 cylinders were cut to prepare the specimens needed for testing permeable porosity. The cutting was done at the very first day of testing. While cutting operation, thin sections from both ends were discarded to minimize the end effects. Three 100 (diameter)×50 (height) mm small cylinders were prepared from each 100×200 mm cylinder. Under each saturation technique, six 100×50 mm cylinder specimens were tested for each concrete. Three cylinders were used at 7 days whereas the other three were used at 28 days to determine the permeable porosity.

### 3.6. Testing of hardened concrete specimens

#### 3.6.1. Compression test

The compression test was conducted for each concrete at ages of 7 and 28 days. Triplicate 100×200 mm cylinder specimens were used at each testing age to determine the compressive strength. The compression test was carried out according to ASTM C 39/C 39M [15]. Prior to compression test, the cylinders were dried in room temperature (20–25 °C) for about 3 h and then capped by sulfur mortar.

#### 3.6.2. Porosity test

Three ASTM saturation techniques were used to determine the permeable porosity of concrete. ASTM standard procedures were employed in cold-water and boiling-water saturation techniques using 100×50 mm cylinder specimens. The specimens were dried in the oven at 105±5 °C for more than 48 h to determine the oven-dry mass. In order to determine the saturated surface-dry mass in cold-water saturation technique, the specimens were simply immersed in cool water at approximately 21 °C for more than 48 h. During boiling-water saturation, the specimens were boiled in a receptacle for 5 h and then allowed to cool for 19 h to a final temperature of 20–25 °C. In vacuum saturation, the oven-drying process was same as that in cold-water and boiling-water saturation techniques. The specimens were

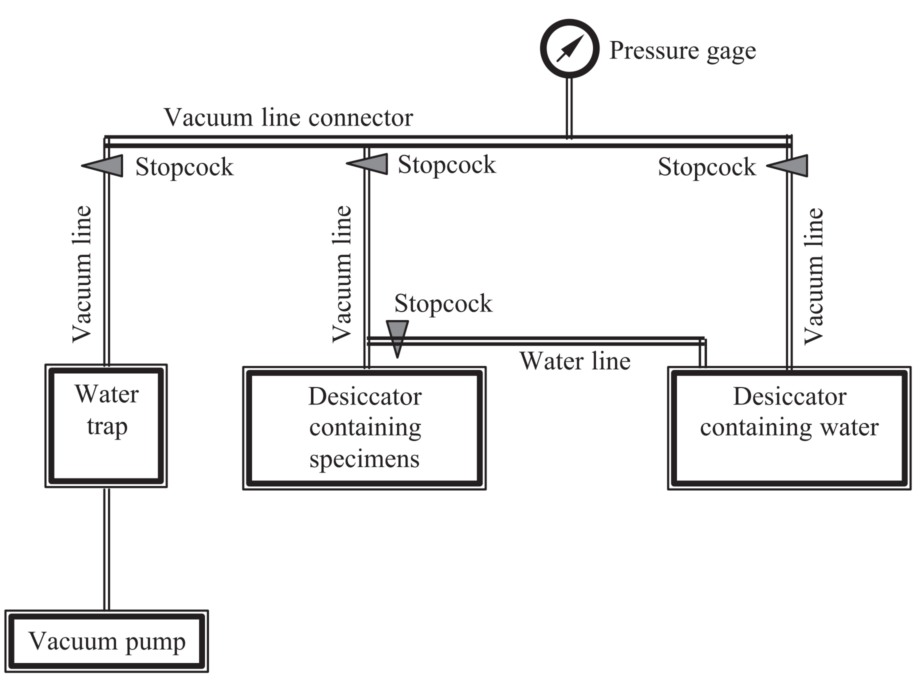


Fig. 1. Schematic of vacuum saturation technique.

removed from the oven, cooled in dry air to a room temperature of 20–25 °C, and then weighed to obtain the oven-dry mass. Therefore the specimens were vacuum saturated. The schematic of the experimental set-up for vacuum saturation is presented in Fig. 1. Triplicate 100×50 mm small cylinder specimens were placed in a vacuum desiccator with both end faces being exposed. The desiccator was covered by the lid and sealed using vacuum grease. Cool tap water was poured in another desiccator. Both the desiccators were then connected to a vacuum pump through a water trap by means of a vacuum line connector. A pressure gage was attached to the vacuum line connector. The vacuum pump was started and run for 3 h at a pressure of −90 kPa (−26.5 in. Hg). With vacuum pump still running, the stopcock for the desiccator containing water was closed and the vacuum was released. Immediately, the vacuum line of the desiccator holding the test specimens was closed, the water line was opened, and the sufficient amount of deaired water was drained from the other desiccator to entirely cover the specimens. Then the water line was closed, the vacuum line was opened, and the specimens covered with water were further allowed to be under vacuum for an additional hour. After 4 h of vacuum operation in total, the vacuum line stopcock for the desiccator containing the specimens was closed again, the pump was turned off, and the air was allowed to enter the desiccator. The specimens were soaked under water keeping them in desiccator for 20 h and then the saturated surface-dry mass and the buoyant mass were determined. Finally, for all saturation techniques, the permeable porosity of concrete was calculated based on the concept of weight gain due to water absorption and weight loss because of buoyancy. The following equation [Eq. (1)] has been used to calculate the permeable porosity of concrete:

$$\text{Permeable porosity} = \frac{W_s - W_d}{W_s - W_b} \times 100\% \quad (1)$$

where, $W_b$=Buoyant mass of the saturated specimen in water, $W_d$=Oven-dry mass of the specimen in air, $W_s$= Saturated surface-dry mass of the specimen in air.

## 4. Results and discussion

The average observed slump was in the specified range for the two concrete mixtures. The workability was quite good to ease the placing and consolidation of concrete. The average results of the compression test are given in Table 4. The average results of the porosity test are presented in Figs. 2 and 3. It is revealed from the test results that the water–cement ratio and curing age significantly influenced the strength and permeable porosity of concrete. The permeable porosity of NPCC50 at water–cement ratio of 0.50 was much lower than that of NPCC60 with the water–cement ratio of 0.60. The average permeable porosity decreased by 18% to 22% when water–cement ratio was reduced from 0.60 to 0.50. This is consistent with the increase in compressive strength. It indicates that relatively a large amount of hydration products was produced in NPCC50 due to higher cement content. These hydration products filled greater spaces in pores, and thus enhanced obstruction to the flow path and reduced the continuity of pores. Hence, the permeable porosity of NPCC50 diminished and the compressive strength was increased. Besides, 28 days water curing provided much lower permeable porosity and greater compressive strength than 7 days curing in both concretes.

Table 4
Test results for compressive strength of concrete

| Concrete designation | Water–cement ratio | Test age (day) | Compressive strength (MPa) |
|---|---|---|---|
| NPCC50 | 0.50 | 7 | 27.6 |
| | | 28 | 35.4 |
| NPCC60 | 0.60 | 7 | 20.6 |
| | | 28 | 23.6 |

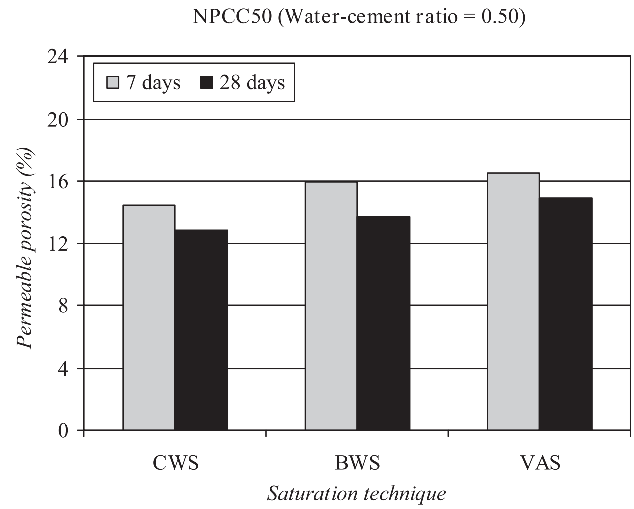


Fig. 2. Permeable porosity of NPCC50 measured by different ASTM saturation techniques.

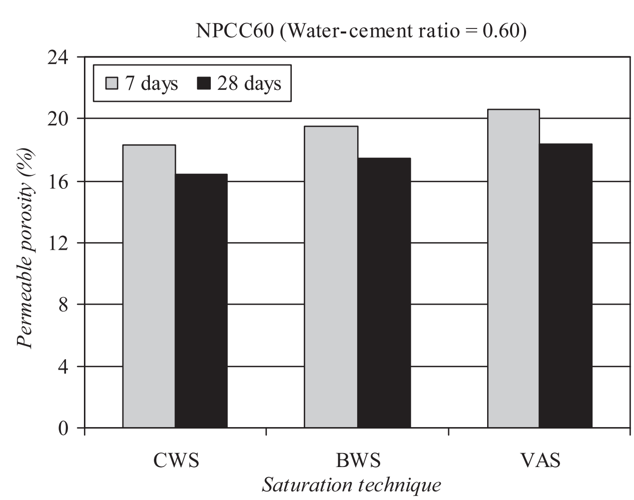


Fig. 3. Permeable porosity of NPCC60 measured by different ASTM saturation techniques.

In addition, the size, distribution and tortuosity of pores, the type and distribution of aggregates, and the nature and thickness of interfacial transition zone also have considerable effects on the permeable porosity of concrete [3]. However, these issues are beyond the scope of this paper. In general, the permeable porosity of concrete is reduced with the decrease in water–cement ratio.

The efficacy of the adopted saturation techniques can be observed in Figs. 2 and 3. It is revealed from these figures that the vacuum saturation is more efficient than the cold-water and boiling-water saturation techniques for measuring the permeable porosity of concrete. Cold-water saturation technique has provided the lowest permeable porosity. Conversely, vacuum saturation technique has measured the highest permeable porosity. It has accounted for 5% to 10% more permeable porosity than boiling-water saturation. Besides, vacuum saturation technique has measured 10% to 20% more permeable porosity than cold-water saturation. It indicates that water cannot completely fill the dead-end pores and replace all residual air bubbles under atmospheric pressure in cold-water and boiling-water saturation techniques. Although boiling-water saturation technique tends to expand the air bubbles and push them to get out of the pore structure at higher temperature, it may not remove all residual air bubbles. On the contrary, most of the residual air bubbles could come out during vacuum saturation under the applied negative pressure or vacuum and allow the water to fill up the corresponding pore spaces. It reveals that vacuum saturation technique is able to take into account the air porosity. Thus, vacuum saturation technique can measure the permeable porosity of concrete to a greater extent.

The efficiency of different saturation techniques can be judged from another standpoint. When water enters the pore system of concrete, some water molecules are likely to be adsorbed to the hydrophilic hydration products. This may narrow the pore channels and impede the further movement of water and air bubbles. The adsorption of water molecules could occur quite comfortably in cold-water saturation technique. In boiling-water saturation technique, the adsorption of water molecules could be reduced by agitation due to heating, and thus may enhance the release of air bubbles and the ingress of water into pore structure. Perhaps, the narrowing of pore channels by adsorbed water molecules is minimized in vacuum saturation technique because of the negative pressure applied to the system. Consequently, vacuum saturation technique results in greater efficiency for measuring the permeable porosity of concrete.

The details of the specimen drying prior to saturation could also affect the results of porosity test. In the present study, the test specimens were oven-dried at 105±5 °C before applying each saturation technique. Unfortunately, the fine pore structure of concrete is very sensitive to drying procedures. Hence, the 105 °C drying method might result in microstructural damage in concrete [8,16]. The microcracking due to drying may also add an apparent increase in the permeable porosity of concrete. These adverse effects could be eliminated by drying the specimens at relatively a low temperature of 50 °C or in air and dessicator containing a desiccant until achieving a constant mass [17,18]. However, these procedures will take a longer period for drying. Nokken and Hooton [19] also have mentioned that the 50 °C drying method may not be good for all concretes. This is because the concretes with low water–cement ratio dry at a much slower rate than those with high water–cement ratio. Hence, the method of specimen drying is still a controversial issue. This controversy can be eradicated in porosity test if the drying is conducted at the final stage of testing. The oven-dry mass could be found after getting the saturated surface-dry mass and the buoyant mass of the saturated specimens. This procedure will improve the porosity results in cold-water and vacuum saturation techniques by avoiding the additional permeable porosity due to microstructural damage and microcracking. In contrast, it may not be effective in boiling-water saturation, as the microcracking could also occur when the specimens are boiled in a receptacle. However, for comparison purpose, the cylinder specimens were dried initially in the oven at 105±5 °C in case of all saturation techniques employed in the present study.

## 5. Conclusions

The following conclusions can be drawn based on the test results and discussion of the present study for measuring the permeable porosity of concrete:

(1) The permeable porosity of concrete diminishes with increased curing age and decreased water–cement ratio resulting in a greater amount of hydration products.
(2) The ability of water in filling the concrete pores is lower in cold-water and boiling-water saturation than in vacuum saturation technique.
(3) Cold-water saturation technique is not effective to account for the dead-end pores and the air voids of concrete.
(4) Vacuum saturation technique is more efficient than boiling-water saturation in measuring the dead-end pores as well as the air voids of concrete.
(5) Vacuum saturation is the most efficient technique to measure the permeable porosity of concrete and therefore it should be recommended.
(6) The specimens drying should be conducted at the final stage of testing in order to avoid the additional permeable porosity due to microstructural damage and microcracking.

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