

Development of Concrete Water Absorption Testing for Quality Control

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ABSTRACT

Development of Concrete Water Absorption Testing for Quality Control

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Concrete durability can be evaluated by a number of properties - such as water absorption and chloride diffusion. Each of these properties can be measured using Standardized methods. Water absorption can be linked to porosity and therefore to eventual deterioration. Tests based on absorption have the potential to be simple and rapid tests for placed concrete. However, it is impossible to provide the Standard conditions for in-situ measurements. Water absorption is strongly affected by environmental temperature and concrete moisture content. These different conditions may cause incorrect evaluation of concrete performance.

In this thesis, several samples were taken from three different construction projects in the Montréal region. These samples were taken to the laboratory, conditioned in different relative humidity and temperature environments and later water absorption tests were performed on them to investigate the effect of these two factors. In addition, three samples of each concrete mixture were placed outdoors and were tested in different environmental situations. Lastly, in-situ water absorption tests were performed on real concrete elements for one of the projects in actual field conditions.

It was found that the concrete water absorption rate increases linearly with increasing temperature and decreasing moisture content. In addition, surface relative humidity was found as an accurate and practical indicator of concrete moisture content. These relationships were verified by additional exposed and in-situ measurements. It is suggested to perform several water absorption tests along with temperature and concrete surface relative humidity measurements to arrive at a Standardized value for quality control purposes.

TO THE GREATESTS IN MY WORLD;

MY FAMILY;

ALIASHRAF,

SHOKOUH, and

SEPIDEH.

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1 INTRODUCTION

1.1 GENERAL

Long service life is an important issue for sustainability of construction materials. Concrete is the most widely used construction material, and its durability has importance as high as its mechanical properties. In order to obtain a low life-cycle cost structure, it is necessary to minimize repair expenses with the use of durable construction materials. In prescriptive specifications, durability is intended to be achieved by requiring particular ingredients, proportions, or construction operations. Each of these requirements is actually a means to an end, and durable concrete is likely to be the result of following these means. The focus of Civil Engineering research community on the durability failures of concrete structures has increased in the last decades. Now, most national concrete codes include some recognition that concrete structures must be designed for durability as well as mechanical strength. In many instances, this desire to achieve the required durability has led to performance-based specifications. These specifications often require properties measured through a variety of test methods. In recent years, there has been an interest in development of new methods that are both rapid and capable of field measurements.

Concrete durability is known by a group of features which denote the concrete performance against a wide variety of exposures. The main reason for concrete degradation is penetration of deleterious substances through the cover zone named as “covercrete”. As most of these substances are dissolved in water, one of the most promising evaluation methods regarding concrete durability is water penetration based tests.

The rate at which water is absorbed into concrete by capillary suction can provide useful information related to the pore structure, permeation characteristics and durability of the concrete surface zone that is penetrated (Parrott, 1992). It has been found that in-situ permeability tests give much more reliable evaluation than an in-situ strength tests in order to evaluate durability properties of concrete (Long, 1983). There are some Standard methods for concrete water absorption, like ASTM C1585 and ASTM C642. According to these Standards, concrete samples should be acclimatised in certain environmental conditions to obtain a specified internal relative humidity prior to the test process and that the test should be performed at Standard laboratory temperature.

The need for non-destructive durability evaluation of existing concrete structures has motivated engineers to produce different commercial apparatuses for in-situ water absorption. These instruments, which all follow the same principles, measure the in-situ concrete water absorption rate in order to measure the sorptivity index for field concrete elements. However, the limitation of these devices is that environmental conditions seriously affect concrete sorptivity. Two of the most important factors which affect water absorption results in field measurements are the concrete moisture content and temperature. Changes in these parameters may cause different results for a same concrete element. To fully utilize these commercial devices, it is necessary to develop a method to normalize field results to those of a Standard lab condition.

1.2 OBJECTIVES AND SCOPE OF WORK

The main objective of this research is to define and propose a practical method for engineers to avoid misleading evaluations in the use of in-situ water absorption results.

This method should be applicable in field situations on real concrete elements and be reliable based on further laboratory and in-situ tests done in this research.

In order to achieve the objective of this research, the scope of work is to:

- Investigate a practical and reliable method to measure concrete moisture content for real concrete elements in the field.
- Investigate the effect of concrete moisture content on the sorptivity index.
- Investigate the effect of temperature on the sorptivity index.
- Evaluate previous laboratory investigations by outdoor exposed and in-situ measurements.
- Propose a practical method to prevent misleading results in concrete durability evaluation using in-situ water absorption test.

1.3 ORGANIZATION OF THE THESIS

This thesis is composed of six chapters. Chapter 2 reviews the available literature in order to understand the concept of water flow theory thorough porous materials like concrete and reviews the previous research on water absorption tests and Standards as well as the influence of the conditioning on the sorptivity index. Chapter 3 describes the experimental program which was performed in this research. The detailed concrete samples' manufacturing process and testing procedure is presented in this chapter and compared with some other approaches used in previous research and Standards. Chapter 4 shows the obtained data from experimental program. These data are discussed and compared with

other related research. Chapter 5 contains conclusions based on the obtained results in order to develop a practical and reliable method for in-situ water absorption measurement on concrete elements. Moreover, some recommendations are suggested for future researchers in this field

2 LITERATURE REVIEW

2.1 INTRODUCTION

From the various studies available in the field of concrete durability and its related testing methods, a review of the references related to the concept of water absorption, both laboratory and in-situ testing methods, for sorptivity measurements and the influence of environmental conditioning on concrete water absorption rate are presented in this chapter.

2.2 CONCRETE DURABILITY

The unique combination of steel and concrete has made reinforced concrete one of the most popular construction techniques in the world. Most of the huge and critical structures are made of this combined material. Over time, it was found that both plain and reinforced concrete are not maintenance-free structural members. The lack of knowledge about the long-term performance of concrete and the severity of environmental impacts has caused serious problems. Chloride attack and carbonation lead to reinforcement corrosion. Sulphate attack, freeze-thaw cycles and alkali aggregate reaction deteriorate the concrete microstructure. The use of inappropriate materials, incorrect design, improper detailing, insufficient quality control and inadequate curing all have reduced the service life of the structures or have resulted in extensive repairs, with a huge economic costs. Every year, deterioration of the concrete structures imposes hundreds of million dollars cost for these structures. The U.S. Department of Transportation reported that \$90 billion dollars in 1991 and 212 billion dollars in 1997 were required for the rehabilitation and repair of the highway structural system (Mehta and Monterio, 2006). According to CSCE (Canadian

Society for Civil Engineering) report card in 2012, an amount of 50.7 billion dollars of total infrastructure assets in Canada are in poor or very poor condition (CSCE, 2012). In order to both increase the sustainability and to decrease the repair costs of concrete structures during their service life, it is mandatory to use durable materials in construction. As a result, more restrictive regulations were introduced in various codes.

Concrete durability is generally defined as ability to resist weathering action, chemical attack, abrasion, or any process of concrete deterioration. Durability is largely dependent on transport properties which are highly influenced by the pore system. As such, the transport resistance evaluation of the concrete cover can be a good index to ensure as to whether the concrete structure element is durable enough or not.

Researchers refer to the surface concrete as “covercrete” which itself can be divided into three layers (Kreijger, 1984). The first layer is known as cement skin which is about 0.1 mm thick. The second layer is called mortar skin which is about 5 mm thick; this is followed by the last skin which is concrete skin for about 30 mm thick. These layers are caused by formwork, segregation and sedimentation. Increased porosity of the skin layers causes greater erosion and wear, while aggressive substances may penetrate quicker in concrete and increase chemical reactions in the skin. Generally, it is considered that the covercrete thickness as 25-50 mm which itself does not have a uniform microstructure (DeSouza, 1996). This zone of a particular concrete element is exposed to more environmental effects and mechanical influences due to tensile stresses and cracks which occur in this zone. It is typically defined as that outside the steel reinforcement. As such, this layer can be thought as a protective layer against reinforcement corrosion.

Many test methods and techniques have been developed over the years can be used to directly or indirectly measure transport mechanisms. Some of the most common ASTM Standard methods are as follows:

- 1- Chloride resistance (ASTM C1202, Standard test method for electrical indication of concrete's ability to resist chloride penetration)
- 2- Water absorption (ASTM C1585, Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, and C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete)
- 3- Electrical resistivity (ASTM C1760, Standard Test Method for Bulk Electrical Conductivity of Hardened Concrete)
- 4- Frost & freeze-thaw resistance (ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing)
- 5- Resistance to de-icing salts (ASTM C672, Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to De-icing Chemicals)
- 6- Ponding (C1543, Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding,)

Most often, these methods are conducted at the pre-qualification stage of concrete mixture design. Many are not suitable as tests for as placed concrete. Generally concrete durability and mechanical tests for evaluation or performance monitoring of existing structures are divided into two main groups (Bungey et al., 2006):

1. In-situ testing, generally non-destructive.
2. Tests on members removed from structure, which will generally be destructive.

In-situ measurements are usually rapid and the whole testing procedure will be done in the field. The second group of tests are performed in laboratory conditions which is easier in terms of the control of environmental factors. The choice of method depends on required testing conditions, but coring or any other destructive test method will be done if there is no possibility for in-situ measurements.

Non-destructive testing (NDT) methods are a wide group of analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage. In last decades, the focus on NDT methods for concrete evaluation has increased impressively. This fact is due to NDT's low expense and short testing time advantages compared to destructive methods. Water absorption is one promising technique that meets these criteria (Torrent and Luco, 2007).

2.3 TRANSPORT MECHANISMS

To understand the theory behind water absorption, it is necessary to review the ways by which fluids can be moved in a porous material. Transport mechanisms in cementitious materials are divided to three main modes: permeability, absorption and diffusion (Rose, 1965; Castro et al., 2011). Permeability is flow of fluid in a saturated porous material due to an external pressure gradient while absorption is the ability of an unsaturated porous material to absorb fluids due to its capillary suction. Diffusion is the movement of dissolved ions due a concentration gradient in a saturated porous material. All of these three

mechanisms are highly influenced by both the volume of pores and their connectivity. Water penetration based tests can be classified into two groups; those based on permeability or those based on sorptivity (Torrent and Luco, 2007).

2.3.1 Diffusion

Diffusion is the passing of substances through the concrete as a result of concentration gradient. In this case, the mass transfer is due to random motion of free molecules or ions in solution. This causes a net flow from regions of higher concentration to regions of lower concentration of the diffusing substance (Hilsdorf and Kropp, 1995). For pure diffusion, the concrete must be fully saturated. For field placed concrete, cores must be taken and then tested by methods such as ASTM C1543, ASTM C1556 or AASHTO 259. These tests require at least a month to carry out and therefore are not most suitable for quality control tests.

2.3.2 Permeability

Water permeability is water flow through a saturated homogeneous material under an externally applied pressure which can be described by Darcy's law, Equation 2.1 (Goual et al., 2000).

$$\vec{i} = -\frac{D}{s} \nabla p \quad \text{[Equation. 2.1]}$$

where:

\vec{i} : Vector flow velocity (m/s),

K_s : Conventional saturated permeability (m^2), and

P : Potential pressure head (Pa/m).

Permeability does not have a Standard laboratory method. It can be measured in the field by a few commercial devices, which will be discussed later.

2.3.3 Absorption or Sorptivity

The process in which molecules of substances adhere to the concrete surface either by physical bonds or as result of chemical bonds is called adsorption (Feldman and Sereda, 1968). Water absorption, or sorptivity, is water flow in unsaturated porous materials due to pressure differences caused by capillary and gravitational forces. Hall (1989) proposed that the physics of one-dimensional, unsaturated flow can be expressed as an extended Darcy Equation as follows:

$$\vec{q} = -K(\theta) \nabla \psi \quad \text{[Equation. 2.2]}$$

where:

$\nabla \psi$: Capillary potential gradient, and

$K(\theta)$: Isotropic conductivity at water content of θ

Capillary potential is highly dependent on the volume of empty pores which are able to absorb fluid. Relative humidity and concrete moisture content affect the volume of empty capillary pores. So, it can be concluded that concrete moisture content has a significant effect on water absorption rate.

2.4 WATER ABSORPTION MECHANISM

Fluid flow in porous media, like concrete, in unsaturated conditions in the absence of an external pressure is called water absorption. This process depends on following factors (Nolan, 1996);

1. Surface energy
2. Surface tension
3. Capillarity
4. Concrete sorptivity

The Lucas-Washburn Equation (Washburn, 1921) proposes a theoretical model regarding water absorption into a porous media based on some significant assumptions. Neglecting air resistance is one of these assumptions. Equation 2.3 describes that the rate of flow of a liquid in a horizontal pore is dependent on the radius of the capillary, the contact angle, liquid surface tension and viscosity as well as the length of filled capillary as follows:

$$\frac{dl}{dt} = \frac{r}{\eta} \frac{\gamma}{4l} \cos \varphi \quad [\text{Equation. 2.3}]$$

where:

$\frac{dl}{dt}$: Rate of flow in a capillary (m/s),

r : Capillary radius (m),

η : Viscosity of the liquid (N·s/m²),

γ : Surface tension of the liquid (N/m),

l : Length of pore already filled with the liquid (m), and

φ : Contact angle (degrees)

The Hagen-Poiseuille Equation (Poiseuille, 1844) is also another model investigated by researchers regarding capillary action in cement paste materials.

$$Q = \frac{\pi r^4 H}{8\eta l} \quad [\text{Equation. 2.4}]$$

where:

Q : Flow rate (m³/s),

r : Radius of capillary (m),

η : Liquid viscosity (N·s/m²),

l : Length of the capillary pore filled with the liquid (m), and

H : Head of pressure (m).

As mentioned previously, water absorption in concrete is an action which happens only due to capillary suction in absence of any external pressure. But, because of technical limitations for in-situ measurement devices, it is necessary to apply a small pressure head in water absorption tests. These technics and the limit of applying pressure head will be

discussed later. Therefore, the head of pressure (H) is composed of two forces (Nolan, 1996);

1. Capillary pressure, H_c .
2. Applied pressure head, H_a .

The Jouren Equation states the capillary attraction forces as follows (Levitt, 1971):

$$H_c = \frac{2\gamma \cos \varphi}{gdr} \quad [\text{Equation 2.5}]$$

where:

H_c : Liquid rise in the capillary (m),

r : Capillary radius (m),

φ : contact angle (degrees),

γ : Surface tension (N/m),

d : Density of the liquid (kg/m^3), and

g : Gravity acceleration (m/s^2).

It has been found out that using 100 mm to 200 mm external pressure head does not affect the sorptivity test result (Basheer et al., 1995). In order to check this experimental result validity, one can assume a concrete capillary pore radius as 2 μm , a water surface tension of 74 N/m, 0° for angle of contact, a density of water of 1000 kg/m^3 , gravity acceleration

of 9.81 m/s^2 which gives the capillary pressure head as 7.5 meters (Nolan, 1996). Comparing this pressure head with an external pressure head of about 200 mm which is proposed by researchers shows that this amount of external pressure is negligible and does not change the absorption mechanism.

As so, the total pressure head can be measured as follows (Nolan, 1996):

$$H = H_a + H_c \quad \text{[Equation. 2.6]}$$

Where:

H_a : Applied external pressure head (m), and

H_c : Pressure head due to capillary forces which can determined from Jouren Equation (m).

Thus, the Hagen-Poiseuille Equation can be rewritten as follows:

$$Q = \frac{\pi.r^4}{8.\eta} \frac{\left[H_a + \frac{2\gamma \cos \varphi}{gdr} \right]}{l} \quad \text{[Equation. 2.7]}$$

Typically, the rate of water absorbed into a porous media due to capillary forces is called sorptivity. Theoretically, considering a constant cross-sectional area and radius for a capillary pore, Equation 2.7 can be rewritten as follows:

$$\frac{l^2}{t} = \frac{\pi.r^4}{8.\eta} \frac{\left[H_a + \frac{2\gamma \cos \varphi}{gdr} \right]}{A} \quad \text{[Equation. 2.8]}$$

where:

l : Length of the capillary pore filled with water (m),

A : Capillary pore section area (m²), and

t : Time (s).

Equation 2.8 can be rewritten as follow:

$$l = \sqrt{\frac{\pi.r^4}{8.\eta} \left[\frac{H_a + \frac{2\gamma \cos \varphi}{gdr}}{A} \right]} . t^{0.5} \quad \text{[Equation. 2.9]}$$

Differentiating both sides in respect to t, gives:

$$\frac{dl}{dt} = S.t^{-n} \quad \text{[Equation. 2.10]}$$

where:

n : Constant value which is equal to 0.5 regarding above assumption, and

S : Constant named as sorptivity that combines the physical properties of water as well as the pores.

This relation has been found by previous researchers (Gummerson et al., 1980). Other researchers found various values for n due to the kind of material used as the porous media. A n value has been stated as 0.3 for concrete with high cement content and 0.7 for concrete with a filler material (Levitt, 1971). Hall (1981) investigated that n is almost equal to 0.5

for initial concrete water absorption in one dimensional capillary rise experiments. So, Equation 2.10 can be rewritten as;

$$i = S.t^{-0.5} \quad \text{[Equation. 2.11]}$$

where:

i: Cumulative volume of absorbed water per unit of area (mm^3/mm^2).

Equation 2.11 is now commonly used for both in-situ and laboratory water absorption measurements. The most frequently used approach is ASTM C1585, which is a laboratory test method. In this approach, the relation of the quantity of absorbed water plotted against the square root of time is investigated to find the sorptivity value of concrete (Figure 2.1). The sorptivity is the slope of the resulting line fitting the points. More discussion of other methods follows.

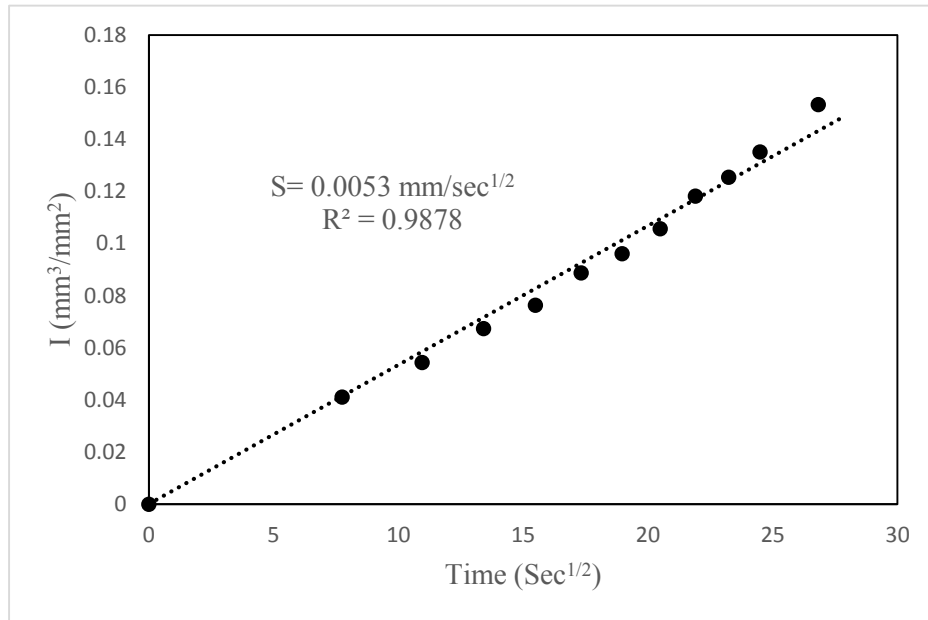


Figure 2.1 Example plot of water absorption test data.

2.5 CONCRETE WATER ABSORPTION TEST METHODS

The rate at which water is absorbed into concrete by capillary suction can provide useful information related to the pore structure, permeation characteristics and durability of the concrete surface zone that is penetrated (Parrott, 1992). Basheer et al. (2001) studied the relationship between different water absorption indices and other concrete corrosion factors. As is shown in Figures 2.2 to 2.5, carbonation depth, corrosion initiation time, freeze and thaw resistance and chloride ingress are strongly correlated to the water absorption capacity of the concrete. This valuable correlation between the water absorption test results and other concrete durability indices makes the water absorption test one of the most reliable measurements which can be used to evaluate concrete durability performance. The only drawback of this study was that all tests were conducted in the laboratory; it is desired to measure durability on as-placed concrete.

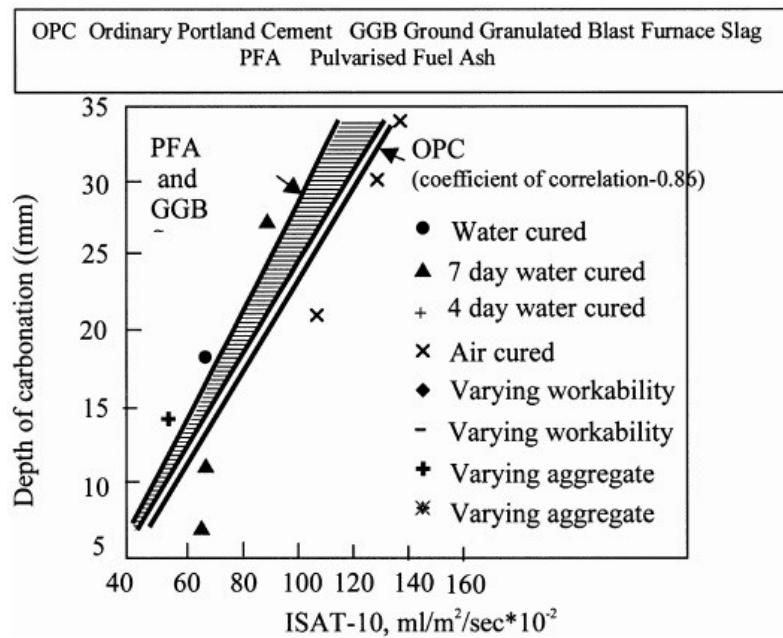


Figure 2.2 Relationship between carbonation depth and water absorption (Basheer et al., 2001)

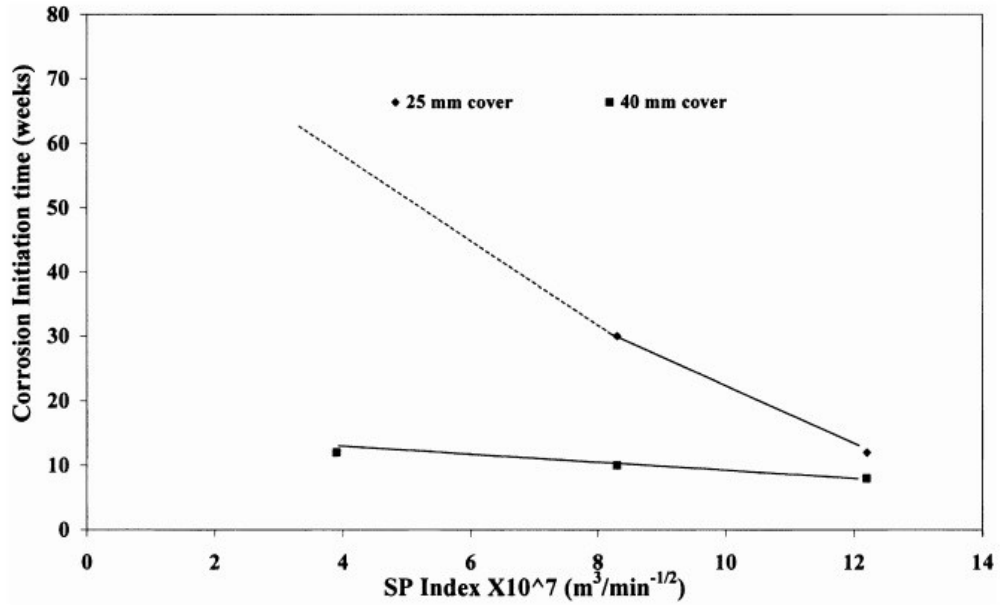


Figure 2.3 Relationship between sorptivity index and corrosion initiation time (Basheer et al., 2001)

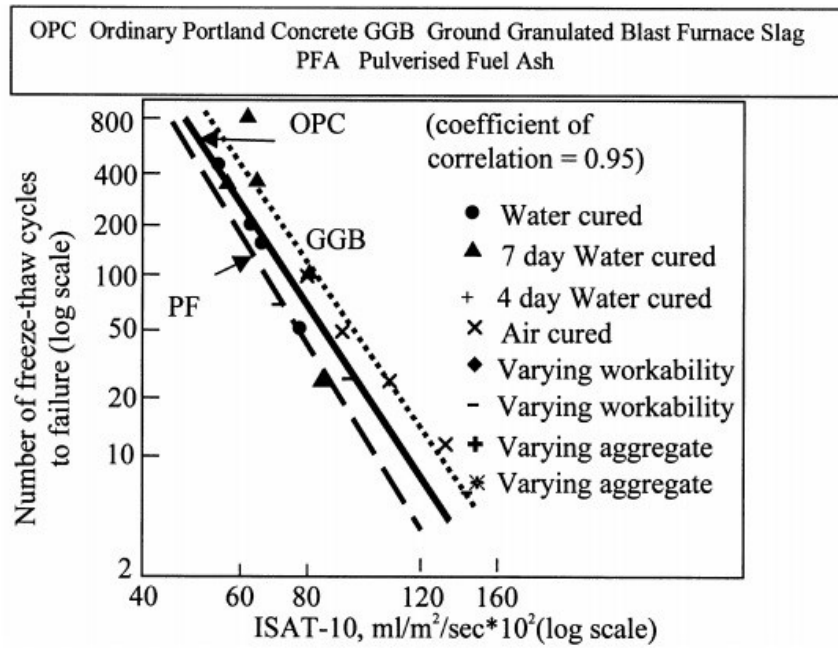


Figure 2.4 Relationship between freeze-thaw resistance and water absorption (Basheer et al., 2001)

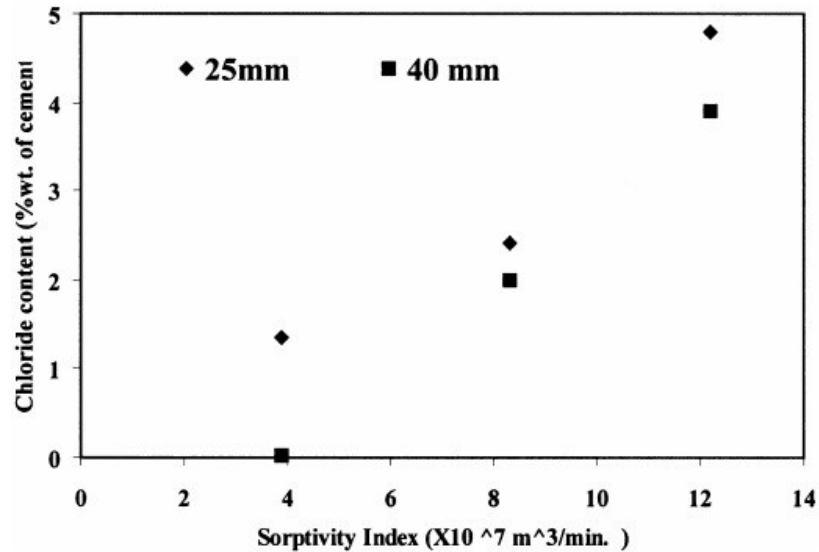


Figure 2.5 Relationship between sorptivity index and chloride ingress (Basheer et al., 2001)

Concrete water absorption tests are potentially fast and practical tests in the means of durability evaluation. Results of these measurements can provide engineers with information to estimate the pore structure in a concrete element, especially in the coverconcrete zone. Thus, during the last decades researchers have completed several investigations regarding Standardizing test methods and providing new devices for in-situ measurements. Generally water absorption test methods can be divided to two main groups:

1. Laboratory tests, and
2. In-situ measurements.

2.5.1 Laboratory tests

There are a few Standard methods for water absorption measurement in laboratory conditions. ASTM C1585 and ASTM C642 are the most used Standard approaches for

concrete water absorption. Although there are some other British Standards like BS 7263 and LUM A4, their testing principles are similar to ASTM Standards (Wilson et al., 1999). The need for cylindrical concrete samples in both of these former methods generally limits them to laboratory situations. In order to perform these tests on existing structures, it is necessary to take cores from concrete elements. This limitation makes these approaches to be categorized as destructive testing methods for existing structures.

2.5.1.1 **ASTM C1585**

ASTM C1585 was developed based on Hall's (1989) investigations and became a Standard in 2004. This test defines the rate of water absorbed by concrete samples due to capillary forces in unsaturated conditions. This rate, as discussed before, is called sorptivity.

According to the ASTM C1585 Standard, the test should be done using disc concrete specimens of 100 ± 6 mm diameter with length of 50 ± 3 mm. These samples may be obtained from either molded cylinders or drilled cores of concrete elements. Samples should be conditioned in an environment with temperature of 50 ± 2 °C and RH of 80 ± 3 % for 3 days. This preconditioning results in providing samples with 50 to 70 % of internal relative humidity which is found to be the typical RH in covercrete zone of some in field structures (DeSouza et al., 1997, DeSouza et al., 1998). Next, each sample is placed in a sealed container at 23 ± 2 °C for at least 15 days. This step provides enough time for moisture to be well distributed throughout the specimen. This avoids a moisture gradient in concrete depth which can cause misleading sorptivity values (Bentz et al., 2001).

After the conditioning steps, the samples are removed from containers and the mass determined. The side surfaces of the samples are sealed and a plastic sheet is used to cover

the top surface of the specimens to prevent water evaporation of concrete. Lastly, the sealed concrete sample is placed in pan which filled with water as is shown in Figure 2.6.

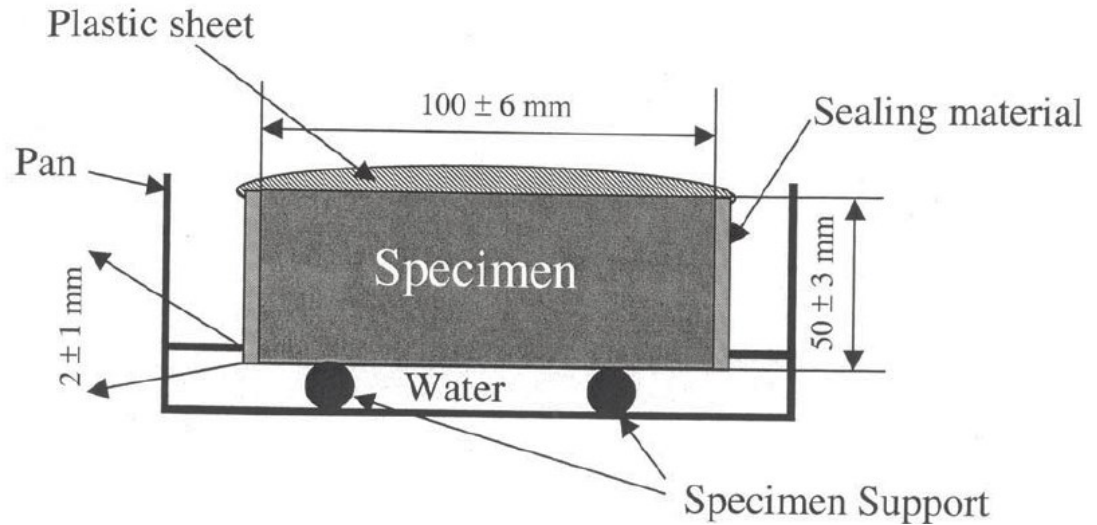


Figure 2.6 Schematic of ASTM C1585 test procedure (ASTM C1585).

The specimens are removed from the pan and their mass recorded at intervals up to 7 to 9 days. Equation 2.12 presents the calculation of the absorption, I , which is the change in specimen's mass divided by the product of the cross-sectional area of the sample and the density of water which is considered as 0.001 g/mm^3 .

$$I = \frac{m_t}{a.d} \quad [\text{Equation. 2.12}]$$

Where:

I = absorption (mm),

m_t = specimen mass in grams at time t (g),

a = exposed area of the sample (mm^2),

d = the density of water in (g/mm^3).

The calculated absorption value at each time will be plotted against the square root of time (\sqrt{t}) to investigate the slope of its linear trend, sorptivity. This index is determined in two stages; initial and secondary absorption due to the absorption time (Figure 2.7). Most commonly, the initial sorptivity is reported in the literature.

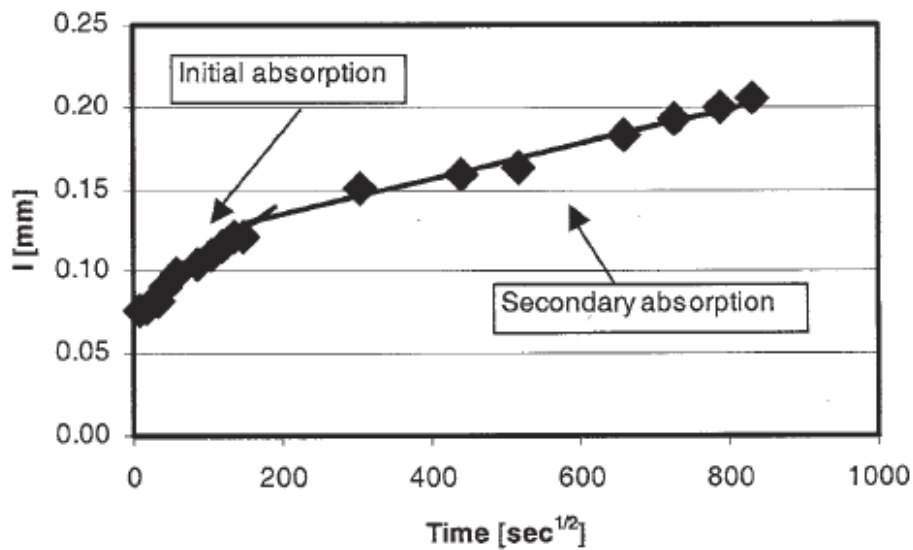


Figure 2.7 Absorption test data points in ASTM C1585 method (ASTM C1585).

As mentioned before, the most important limitation of this approach is being destructive for use on existing concrete structures. Although the mentioned preconditioning procedure results in 50 to 70% internal RH for concrete samples, it is not the RH of field concrete elements in all environmental conditions (Parrott, 1994, Basheer and Nolan, 2001).

2.5.1.2 ASTM C642

Unlike ASTM C1585, which determines the rate of concrete water absorption, ASTM C642 determines the total amount of water absorption using two saturation methods. As

such, use of the ASTM C642 approach does not lead to obtain sorptivity index of the concrete specimens.

According to this method, there is no shape limitation for testing concrete specimens other than each sample volume is not less than 350 cm³ (approximately equal to 800 g). In the first step, the oven-dry mass of each specimen should be obtained by placing them in an oven at a temperature of 100 to 110 °C not less than 24 h. Later, the saturated mass (using immersion) of samples will be determined by immersing them in water at approximately 21 °C for not less than 48 hours and until two successive measurements of mass of the surface-dried samples at intervals of 24 hours indicate constant mass. The second method obtains the saturated mass by using immersion in boiling water. Samples are covered by tap water and boiled for 5 hours. After that, they will be allowed to cool to a final temperature of 20 to 25 °C for a period of not less than 14 hours (ASTM C642).

Two different values of the concrete samples' capability of water absorption will be calculated as follows:

$$\text{Absorption after immersion, \%} = [(B - A) / A] \times 100 \quad [\text{Equation. 2.13}]$$

$$\text{Absorption after immersion and boiling, \%} = [(C - A) / A] \times 100 \quad [\text{Equation. 2.14}]$$

where:

A: mass of oven-dried sample (g),

B: mass of surface-dry sample in air after immersion (g), and

C: mass of surface-dry sample in air after immersion and boiling (g).

Although this test method determines the total potential to absorb water and some other useful information of the concrete pore structure such as volume of permeable voids, it does not help to determine the absorption rate in concrete. In addition, similar to the ASTM C1585 test Standard, it requires cores to be taken from concrete elements to evaluate the existing concrete structure's durability.

2.5.2 In-situ measurements

As discussed above, in-situ measurements are usually preferred due to their non-destructive nature and rapid procedure. In order to make the water absorption test possible for in-situ measurements, several commercial devices have been produced since 1931 (Torrent and Luco, 2007). A brief description of them is presented below and later some Standard instructions of them are discussed.

2.5.2.1 ISAT method

ISAT was originally developed by Glanville in 1931 and later modified by Levitt for a concrete sorptivity test (Glanville, 1931, Levitt, 1971). As is shown in Figure 2.8, the device consists of a plate sealed onto the concrete surface. There is an inlet connected to a reservoir and an outlet connected to a capillary tube with a horizontal scale on it. The water contact area on the concrete surface must be at least 5000 mm^2 , the capillary tube should be at least 200 mm long with 0.1 to 0.4 mm radius and the horizontal scale must be set at 200 mm above the concrete surface (Bungey et al., 2006). This is to provide 200 mm water pressure head.

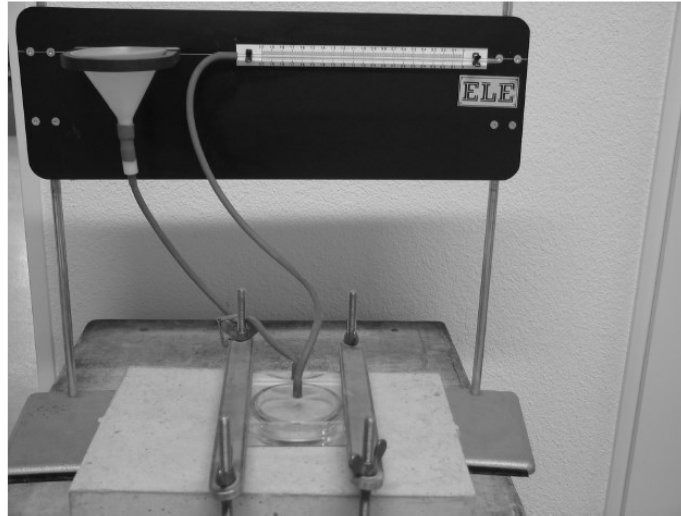


Figure 2.8 View of ISAT water absorption apparatus (Torrent and Luco, 2007).

With the inlet tap opened, water flows to fill the cap and then through the outlet it climbs up to the horizontal scale (Figure 2.9). After 10 min initial absorption, the tap will be closed and the amount of absorbed water will be determined by monitoring the capillary tube and it's above scale at 30, 60 and 120 minutes from the start of the test. This 2 hour test duration may be reduced to 10 or 30 minutes depending on the concrete water absorption rate (Torrent and Luco, 2007).

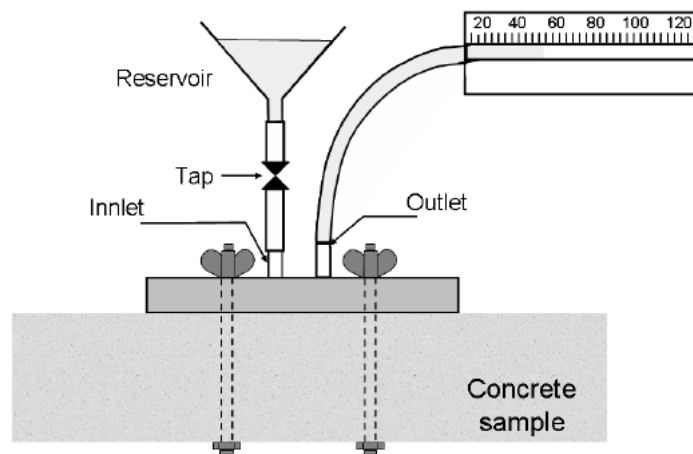


Figure 2.9 Sketch of ISAT water absorption apparatus (Torrent and Luco, 2007).

The result of the test is called ISA-Value and is calculated as follows (Torrent and Luco, 2007):

$$ISA = \frac{0.6D}{\delta t} \quad \text{[Equation. 2.15]}$$

Where:

ISA: Rate of water absorption (sorptivity) in ml/m²/s

D: Number of scale units covered by the reaction of the meniscus

δt : Time taken for the meniscus to move D scale units of the capillary tube in s.

2.5.2.2 Autoclam method

The water pressure head in ISAT device is just sufficient for absorption. The need of in-situ air and water permeability test methods led to the development of the Autoclam or CLAM device which is similar in principle to ISAT, but able to apply more pressure head to change the absorption system to permeability. It was originally developed by Montgomery and Adams, and modified later by Basheer and Long from Queen's University of Belfast, Northern Ireland, U.K. (Montgomery and Adams, 1985, Basheer et al., 1991).

Using the Autoclam test method can determine related coefficients for air and water permeability and also the sorptivity index for water absorption. The test duration in this method is 15 minutes. The device is able to apply hydrostatic pressure up to 1.5 bar (~1.5m H₂O) for permeability and alternatively 0.01 bar (102mm H₂O) in order to measure the

concrete absorption rate. Like the ISAT method, this apparatus can be used for surface penetration measurements (Bungey et al., 2006).

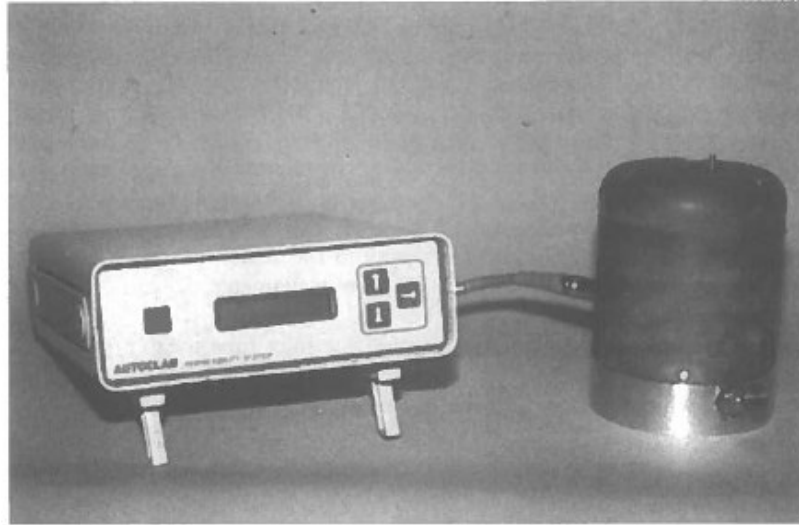


Figure 2.10 Autoclam air and water permeability instrument (Bungey et al., 2006).

2.5.2.3 GWT method

Like ISAT and Autoclam, the GWT testing method is used for concrete surface penetration measurements. It can be used for air and water permeability and sorptivity tests. Figure 2.11 shows a view of the GWT-4000 instrument.

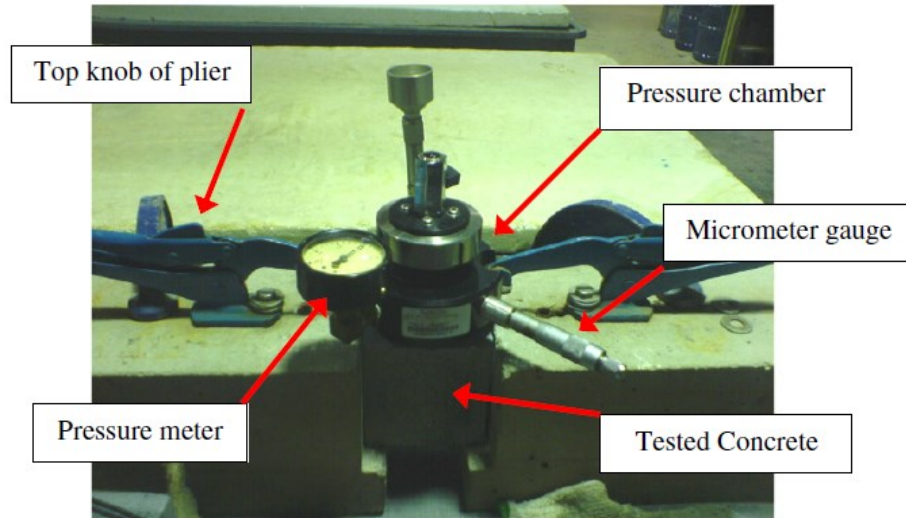


Figure 2.11 View of GWT-4000 instrument (Tam et al., 2012).

As is shown in Figure 2.12, the chamber must be sealed to the concrete surface using two anchored clamping pliers or by using a vacuum suction plate. In order to use the device for irregular or porous surfaces or in high pressure ranges, the chamber should be sealed using water resistant glues. The chamber is then filled with water. After considering a period for initial absorption, the top lid of the chamber is turned until the desired water pressure is achieved. The pressure will be monitored with the pressure gauge attached to the chamber. During the penetration process, the pressure should be maintained by the means of a micrometer gauge pressing a piston into the chamber, substituting the water penetrating into the concrete.

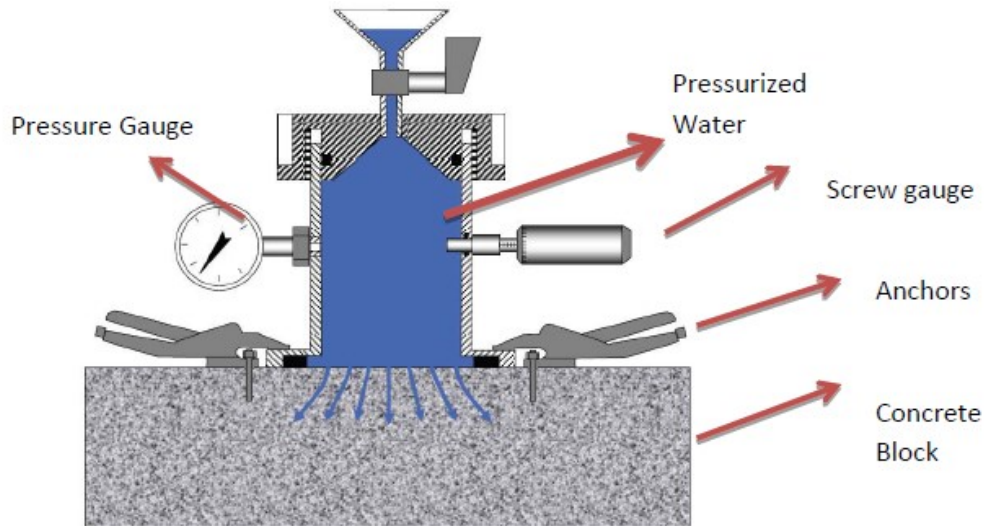


Figure 2.12 Schematic of GWT concrete test device (GWT-4000 Manual, 2010).

The micrometer travel value will be recorded at specific periods of penetration time. The total duration of the absorption can be from 10 min up to 1 hr. The cumulative amount of absorbed water can be calculated as follow:

$$i = \frac{B.(g_1 - g_2)}{A} \quad \text{[Equation. 2.16]}$$

where:

I: Cumulative volume of absorbed water per unit of area (mm),

B: Section area of the micrometer pin being pressed into the chamber which is 78.6 mm² for the 10 mm of pin diameter,

g₁ and g₂: Micrometer gauge readings at start of the test and after the reading time (mm), and

A: Water contact surface area which is 3018 mm² for gasket inner diameter of 62 mm.

In order to use the device for water absorption, the pressure gauge can be changed to that of a smaller scale.

2.5.2.4 Figg method

In spite of previous methods, the Figg method is performed at a depth into the coverconcrete zone not on the concrete surface. This device can be used for both air permeability and water absorption tests. Figg (1973) originally described the development of a test for air and water penetration which involved a hole drilled into the concrete surface. Later, Cather et al. (1984) proposed a modified version of Figg method basis on extensive experimental research on the primary approach.

According to the modified Figg method test, a hole of 10 mm diameter is drilled 40 mm deep normal to the concrete surface. After dust removal, a 3 mm thick disc is pressed 20 mm into the hole and a catalyzed silicone rubber is added (Figure 2.13).

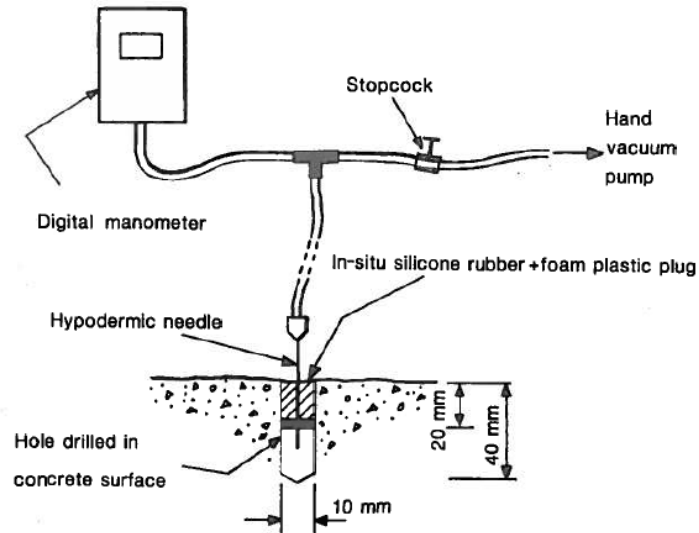


Figure 2.13 Sketch of modified Figg method (Bungey et al., 2006).

Water absorption is measured at a water pressure head of a 100 mm. The time taken for concrete to absorb 0.01 ml of water is recorded as the result of the test from which sorptivity index may be calculated as follows (Torrent and Luco, 2007);

$$s = \frac{10}{\sqrt{t \cdot A}} \quad \text{[Equation 2.17]}$$

where:

s: sorptivity index (mm/s^{0.5})

t: time taken for concrete to absorb 0.01 ml of water (s)

A: contact surface area of concrete with water (mm²)

2.5.2.5 Other methods

Researchers have investigated the significant difference between one dimensional and three dimensional sorptivity measurements (Wilson, 2003). Comparing results of one dimensional absorption methods with 3 dimensional absorption measurements does not give a direct comparison of sorptivities. Figure 2.14 shows the difference between absorption geometry of some of the discussed in-situ test methods.

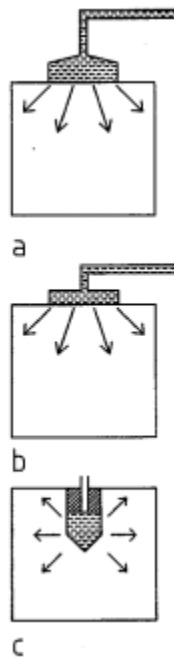


Figure 2.14 Schematic representation of the test methods: (a) ISAT, (b) Autoclam and (c) Figg (Wilson, 2003)

In order to solve this problem, new in-situ approaches should be used to simulate one-dimensional absorption mechanism. DeSouza (1996) developed a device to simulate in-situ measurements to a one-dimensional absorption mechanism. As it is shown in Figure 2.15, an outer chamber or “guard-ring” is designed around the inner main chamber. Prior to absorption, water flow through the main chamber, the outer chamber will be filled with

water for 2.5 minutes. This initial saturation in the annular space helps the main water flow not to get deviated from its straight path. Using this method will lead to obtain more accurate sorptivity values, comparable with one-dimensional absorption test results.

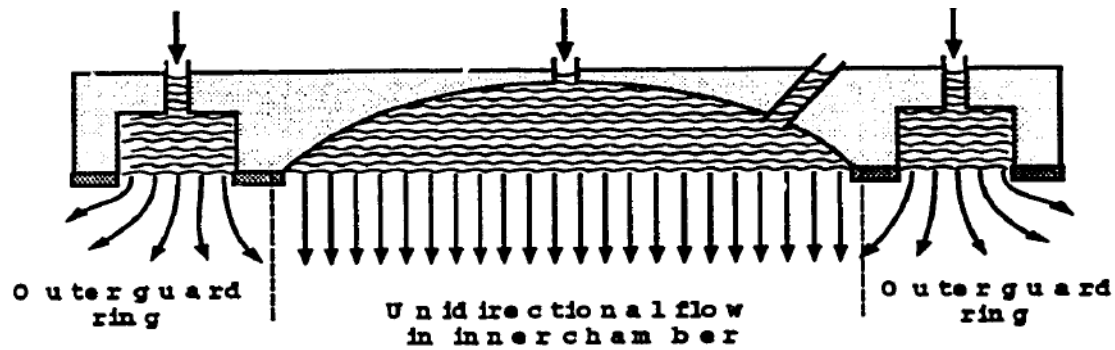


Figure 2.15 Schematic overview of DeSouza sorptivity measurement device (DeSouza, 1996)

2.5.2.6 In-situ water absorption test instruction

Generally, the test procedure concept for all in-situ water absorption test apparatuses is the same and most of them are able to be used for both water absorption as well as permeability and even air permeability measurements. Thus, usually the investigated calibrations and Standards for each of these devices can be used for others. Following are some criteria which should be taken into consideration in the use of in-situ sorptivity tests.

1. Specimen geometry

Basheer et al. (1995) used a finite element model to investigate the influence of specimen geometry on the sorptivity test using the Autoclam method. Based on his results, the size of concrete sample does not affect the sorptivity test as long as the edge distance of sample

and water contact surface is greater than 40 mm. Also, it was observed that the concrete thickness has no influence on water flow when it is more than 50 mm.

2. Test duration

Research on the Autoclam method showed that tests at both high pressure (permeability) and low pressure (absorption) could be done for a duration of up to 30 minutes (Basheer et al., 1995). Based on these results, it was concluded that a test duration of 20 minutes can provide sufficient number of data points in order to calculate related indices.

3. Initial time delay

Hall (1989) suggested a short time delay of 2 to 3 min prior to starting the measurement of the water flow. It was investigated that this initial delay does not affect the sorptivity index in water absorption tests (Basheer et al., 1995). However, Basheer et al. (1995) recommended that the test data for 10 to 20 minutes should be used for sorptivity calculation. This time period may decrease to 5 - 15 minutes if the duration of test had to be reduced. The device of DeSouza et al. (1997) uses 2 ½ minutes of pre-saturation in the guard ring area.

4. Water pressure head

Basheer et al. (1995) found that at pressure heads less than 0.1 bar (~1m H₂O), the capillary forces overcome the water pressure head forces. This pressure could be as small as 0.01 (102 mm H₂O) to eliminate any influence of external pressure. Other researchers have found similar conclusions (Glanville, 1931, Nyame and Illston, 1981). The Figg method uses 0.01 bar of water pressure head as external pressure as well (Figg, 1973). Another

common pressure head is 0.02 bar (202 mm H₂O) which is used in the ISAT method. Researchers have determined that concrete moisture content is highly affected by the capillary suction pressure head (Castro et al., 2011). The capillary pressure head value decreases with increasing moisture content of capillary pores. Consequently, the amount of water absorbed due to this force decreases (Nokken and Hooton, 2002). In order to evaluate concrete durability using water penetration based tests, it is suggested to use higher external pressure head when the concrete is in a wet condition (Penner, 1965). Using a very high external pressure head changes the water penetration mechanism from absorption to permeability.

2.6 INFLUENCE OF ENVIRONMENTAL CONDITIONS ON SORPTIVITY

As it is impossible to control environmental factors during in-situ concrete water absorption measurements, it is necessary to study these parameters on test results. Previous research shows temperature and concrete moisture content seriously affect the sorptivity index obtained by absorption measurements.

2.6.1 Concrete moisture content

Concrete's capability to absorb water is due to capillary forces in concrete pores. The amount and rate of concrete water absorption is influenced by volume of the pores, pore size distribution and size of partially empty capillary pores (Castro et al., 2011). There have been several investigations to study the relationship between concrete moisture content and water absorption test results using different testing approaches. A brief review of these studies is presented as follows.

Figg (1973) studied the influence of moisture content on water absorption results for concrete samples with w/c ratios of 0.68, 0.78 and 0.88. Samples were placed in sealed containers with salt solution for different periods of time. Later, water absorption test were performed on each specimen using the Figg method. Finally, samples were dried at 40° C to reach a constant weight. Mass difference between tested and dried specimen was considered as the sample moisture content.

As is shown in Figure 2.16, a linear relationship between absorption index and specimen moisture content was found. It was also concluded that moisture content has lesser effect on water absorption in more permeable concrete (higher w/c ratio). This is due to the greater number continuous capillary channels in concretes with higher w/c ratio (Figg, 1973).

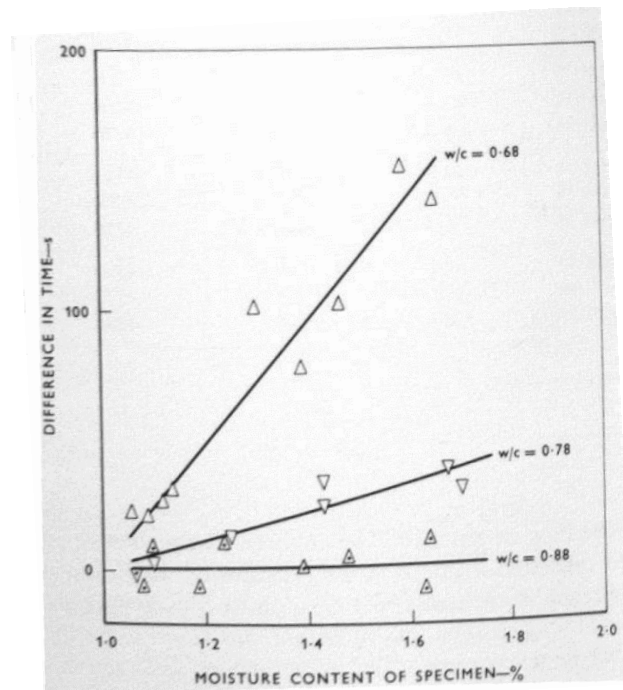


Figure 2.16 Effect of water content of concrete upon results for Figg method water absorption index (Figg, 1973)

Figure 2.17 shows the results of an experimental study on clay bricks' water absorption dependence on moisture content (I'Anson and Hoff, 1986). It can be concluded that capillary potential decreases with increasing moisture content. Moreover, there is a difference between capillary potential at the same moisture level due to the difference between wetting and drying characteristics of the brick.

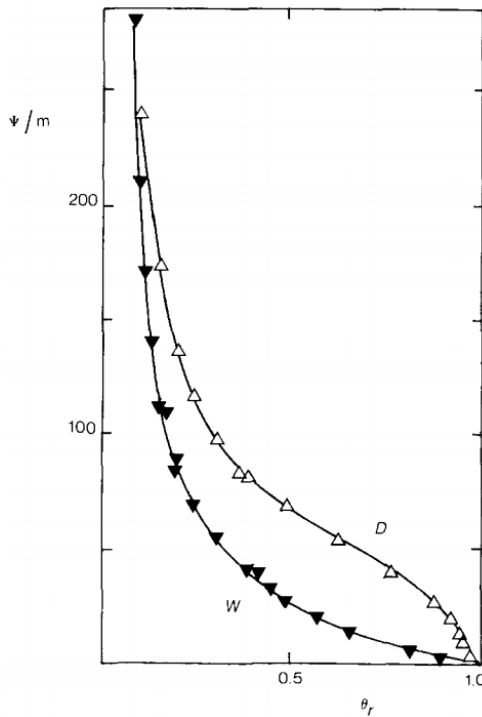


Figure 2.17 Dependence of clay brick capillary potential Ψ on water content Θ . Curve W is the wetting characteristic and curve D is drying characteristic (I'Anson and Hoff, 1986).

Basheer et al. (1995) found a linear relationship between concrete water content (by percentage of dry weight) and sorptivity index obtained from Clam method measurements (Figure 2.18).

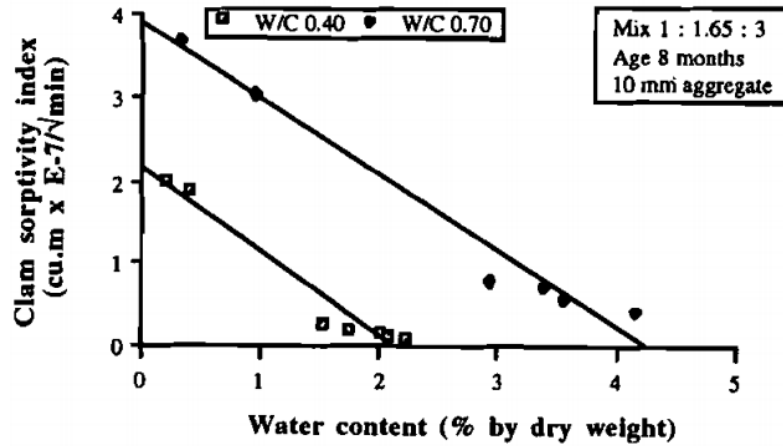


Figure 2.18 Effect of water content on Clam sorptivity index (Basheer et al., 1995).

Nolan (1996) measured the sorptivity index of three different w/c ratio concrete samples using the Autoclam method in different RH stages. Samples were first saturated and later moved to an oven at 40 °C for different periods of time to obtain four different moisture content stages. In order to avoid a moisture gradient through the concrete depth, as is recommended by ASTM C1585, samples were stored in a sealed container for a period of 3 months. RH was measured at three different depths from the concrete surface (0, 10, and 20 mm).

As is presented in Figure 2.19 for concrete sample of W/C=0.45, the Autoclam sorptivity index decreases linearly with increasing of RH values in different depths.

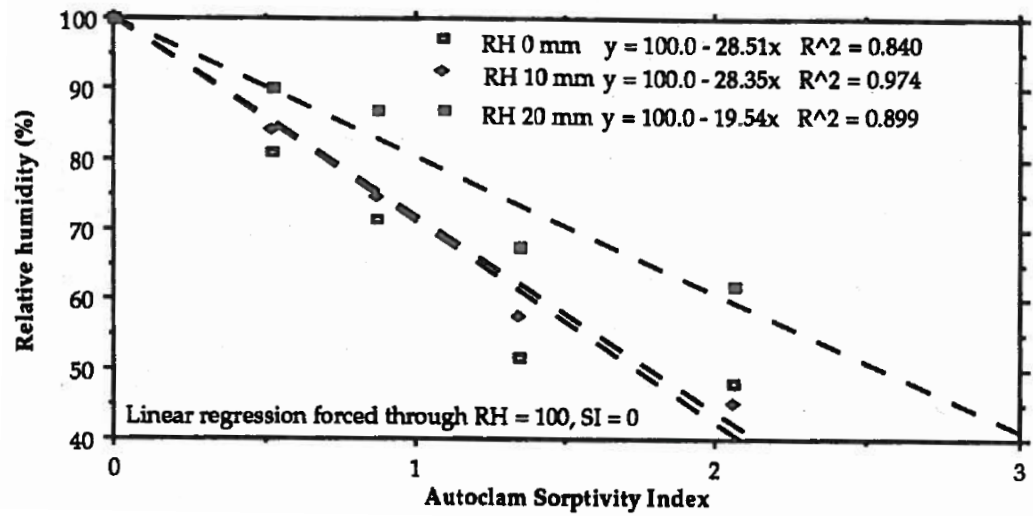


Figure 2.19 Sorptivity index versus RH (Nolan, 1996).

Later, Basheer and Nolan (2001) used this approach on outdoor exposure samples and found a significant deviation between exposed and laboratory sample results (Figure 2.20). It was concluded that laboratory results are not transferable to in-situ measurements due to the difference of percentage of cement hydration in outdoor and laboratory concrete samples. The other possible reason might be both moisture hysteresis and RH gradient within the field concrete.

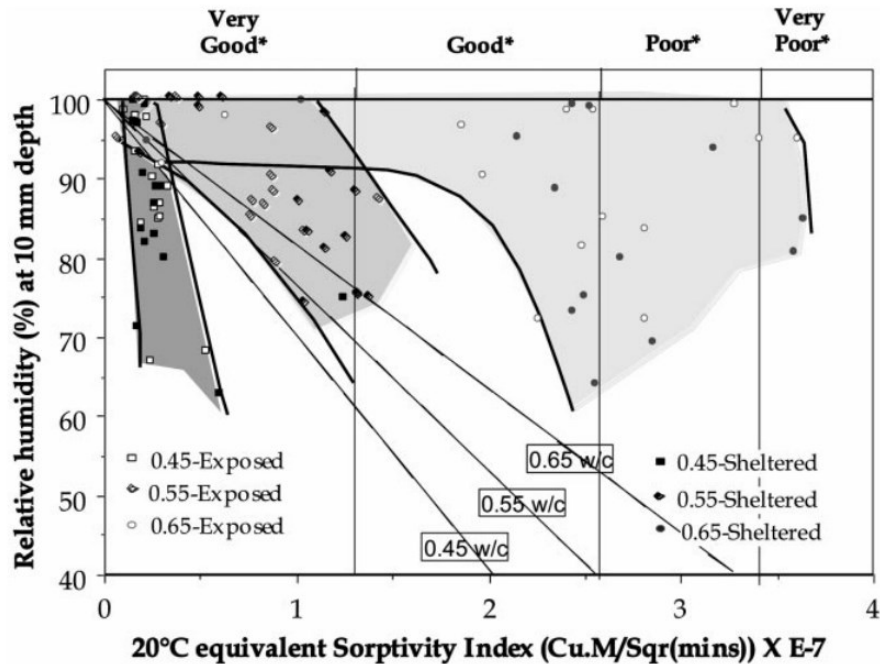


Figure 2.20 Dependence of Autoclam sorptivity index on 10 mm depth RH (Basheer and Nolan, 2001).

DeSouza et al. (1997) studied the effect of moisture content on sorptivity index for four different concrete mixtures applying two different curing methods (Moist curing and using curing compound). In first step, all the samples were saturated (by immersion in water) and their saturated sorptivity index was confirmed to be zero. Then concrete specimens were subjected to different drying regimes to obtain different moisture contents. Later, according to a method similar to ASTM C1585 (which did not exist at the time), their initial sorptivity was recorded.

Nokken and Hooton (2002) analyzed this data and found that sorptivity decreases linearly with increasing levels of saturation degree, Figures 2.20 and 2.21. In addition, a decrease of sorptivity with w/c ratio can be observed for all values of sorptivity indices in different saturation degrees.

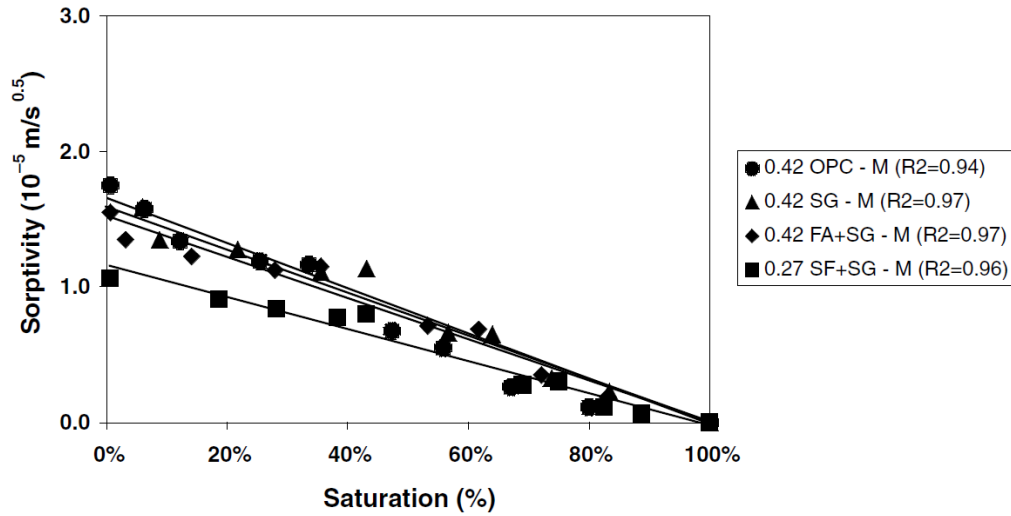


Figure 2.21 Sorptivity variation with change in concrete saturation degree for moist cured samples (Nokken and Hooton, 2002)

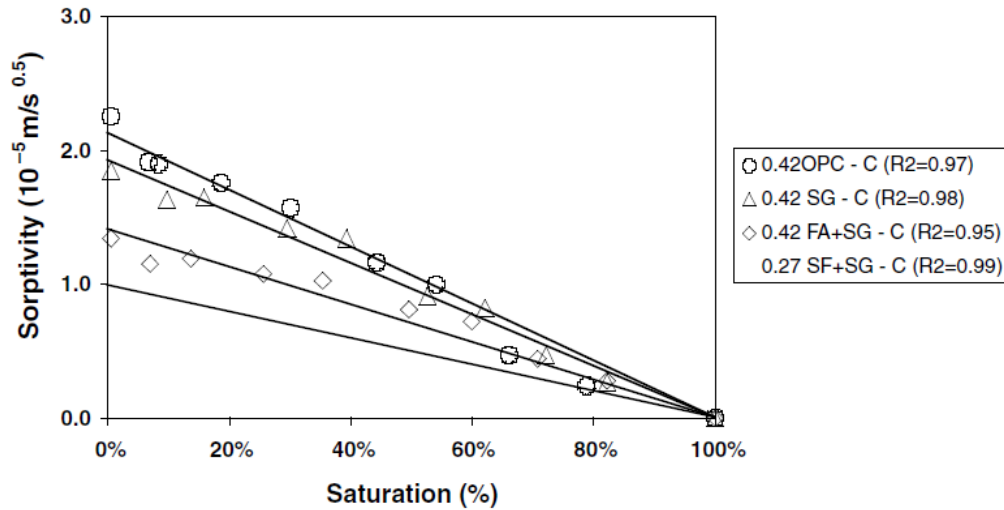


Figure 2.22 Sorptivity variation with change in concrete saturation degree for curing compound samples (Nokken and Hooton, 2002)

Using a method similar to the ASTM C1585 testing method, Nokken and Hooton (2002) studied the effect of concrete moisture content on water absorption test results. Samples were exposed to water for different periods of time ranging from 15 min to 18 hours. Later they were placed in sealed containers for four weeks to allow the absorbed water to be

redistributed throughout the samples. Afterwards, the sample's initial sorptivity index (up to 25 min of absorption) was obtained using ASTM C1585 procedure. It was found the concrete sorptivity index decreased linearly by increasing saturation degree (Figure 2.23). Comparing the conditioning procedures of the previous two studies, it can be seen that the linear relationship holds whether the samples were dried from a saturated state or wetted from an unsaturated state.

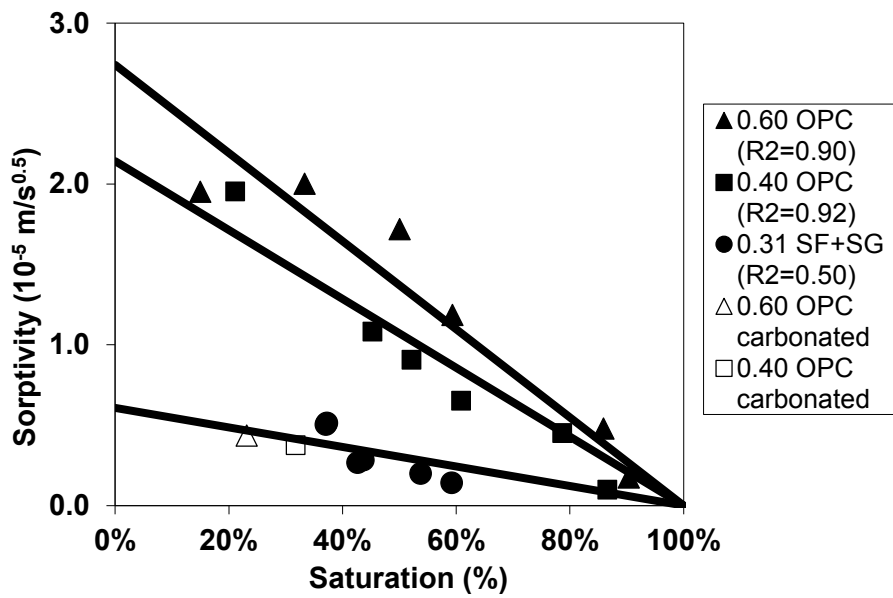


Figure 2.23 Sorptivity versus concrete saturation degree (Nokken and Hooton, 2002).

An in-situ study on the Autoclam approach performed by Romer (2005), showed sorptivity index was strongly affected by concrete moisture content (Figure 2.24). This conditioning influence of moisture content caused poor correlation between concrete's sorptivity index and other durability indices, such as air permeability.

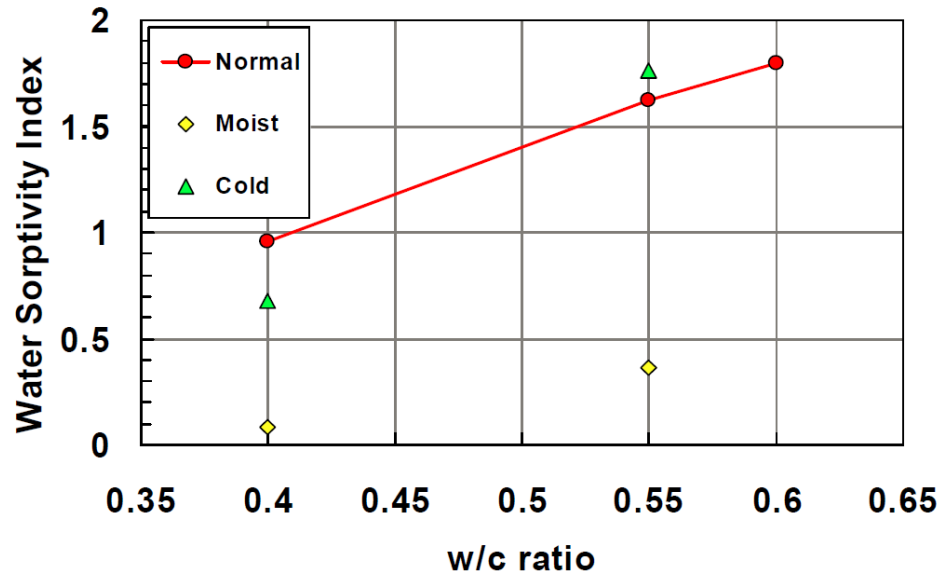


Figure 2.24 Effect of moisture and ambient temperature on Autoclam water sorptivity index (Romer, 2005).

Castro et al. (2011) studied the effect of concrete moisture content on both ASTM C1585 and ASTM C642 test results. Concrete samples of four different w/c ratios were placed in environmental chambers with RH of 0%, 50%, 65%, and 80%. Samples were removed from the chamber and tested when they reached mass equilibrium, defined as a mass change less than 0.02% over a 15 day period of time.

It was found out the total absorption of samples (through ASTM C642) with RH of 50% are 6 times greater than samples with 80% RH. As shown in Figure 2.25, the initial sorptivity is highly affected by preconditioning RH of the samples. Moreover, it was concluded that the ASTM C1585 preconditioning procedure can not eliminate the effect of moisture history. Thus, it was suggested that the field samples obtained by cores be pre-saturated prior to the ASTM conditioning regime.

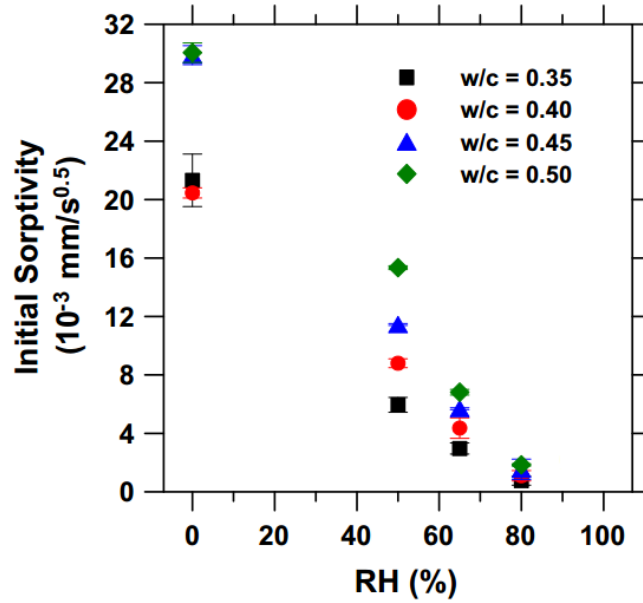


Figure 2.25 Dependence of concrete samples initial absorption rate on pre-conditioning RH (Castro et al., 2011).

2.6.2 Conditioning temperature

Temperature as an uncontrollable environmental factor for in-situ tests has significant influence on water absorption test results. This effect is due to change in both water physical properties and concrete pore sizes with change in temperature.

From Equations 2.8 it can be concluded (Nolan, 1996):

$$S \propto \frac{\pi.r^4}{8.\eta} \left[\frac{H_a + \frac{2\gamma \cos \varphi}{gdr}}{l} \right] \quad \text{[Equation 2.18]}$$

where:

S: sorptivity index (m/s^{0.5}),

r : Capillary radius (m),

η : Viscosity of the liquid (N·s/m²),

H_a : Applied external pressure head (m),

γ : Surface tension of the liquid (N/m),

φ : Angle of contact (degrees),

γ : Surface tension (N/m),

d : Density of the liquid (kg/m³), and

g : Gravity acceleration (m/s²).

r : Capillary radius (m), and

l : Length of pore already filled with the liquid (m).

Assuming a constant angle of contact between the pore wall and water surface at different temperatures, the following parameters are expected to change with temperature:

1. The density of absorbed water.
2. The viscosity of absorbed water.
3. The surface tension of the water in contact with the air.

Based on the changes of these factors with temperature obtained through published tables, Nolan (1996) obtained a correction factor to equivalent sorptivity at 20° C (Figure 2.26).

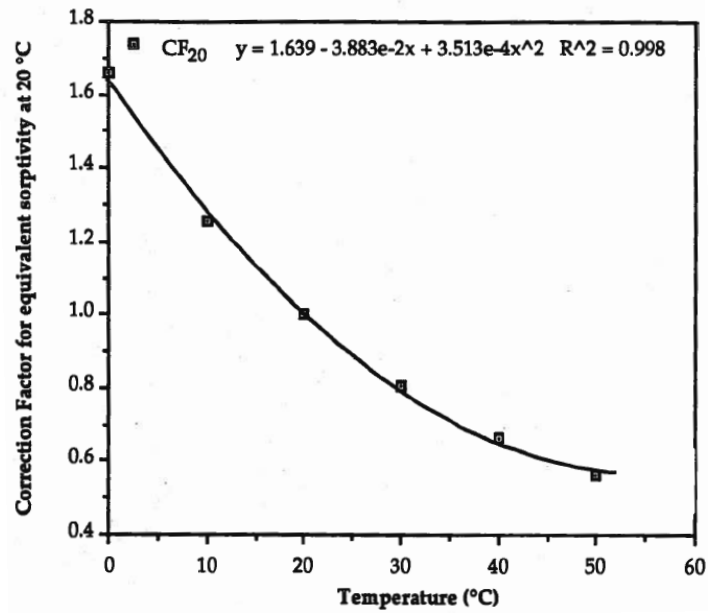


Figure 2.26 Correction factor to obtain the equivalent sorptivity at 20 °C.

However, Nolan (1996) performed an experimental study using Autoclam method with two different w/c ratios of concrete which showed a linear relationship between sorptivity index and conditioning temperature (Figure 2.27). This contradicts the polynomial expression suggested by theory.

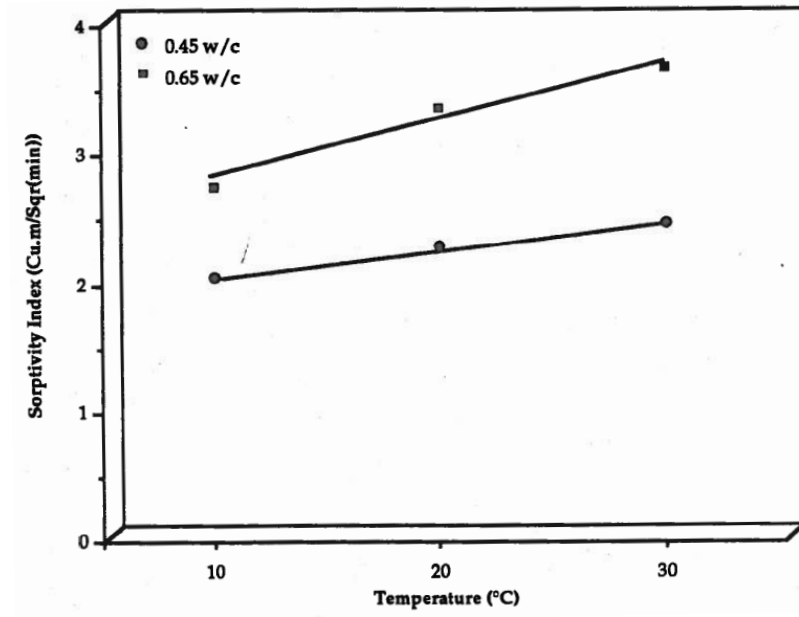


Figure 2.27 Variation of Autoclam sorptivity index with temperature.

Basheer (1992) studied the effect of temperature on Autoclam sorptivity index at three different moisture contents (Figure 2.28). His observations showed that the effect of temperature on sorptivity index is different due to amount of concrete water content. No effort was given to develop an equation to fit the data; however, it is clear that the relationship becomes less linear as the RH decreases.

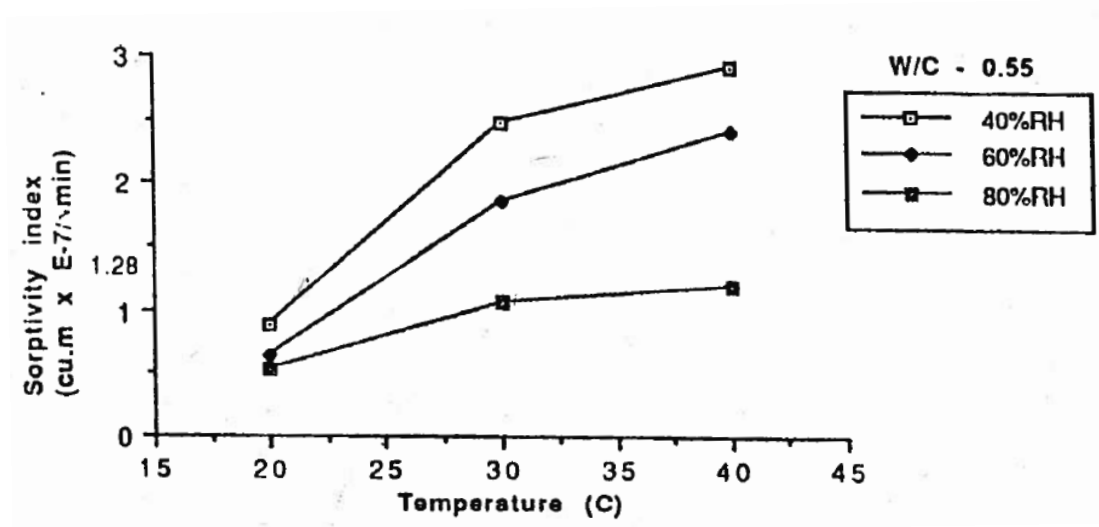


Figure 2.28 Effect of moisture and temperature on sorptivity (Basheer, 1992).

Bungey et al. (2006) also obtained linear relationships using the ISAT method in an experimental study between 20 and 50°C (Figure 2.29).

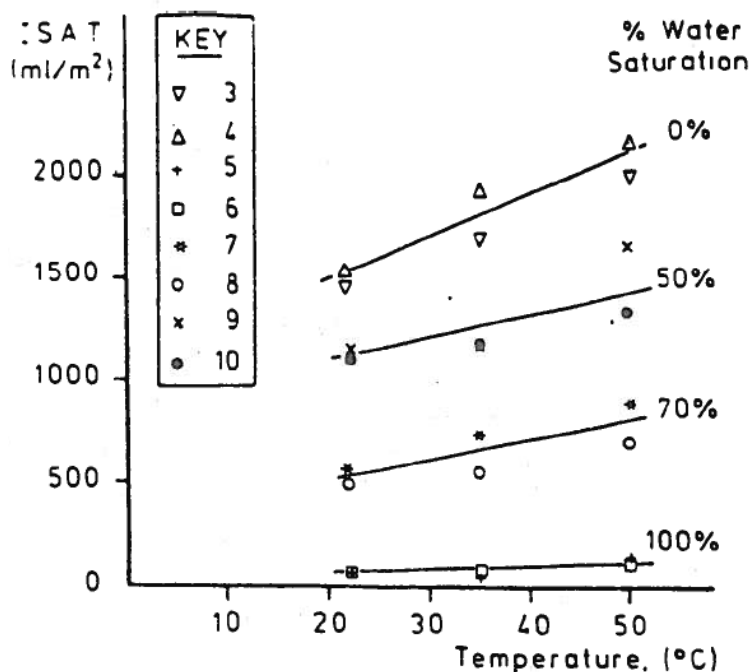
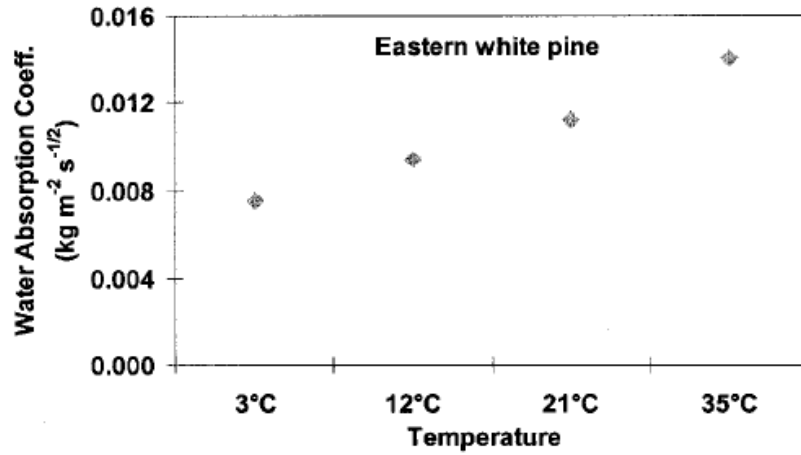


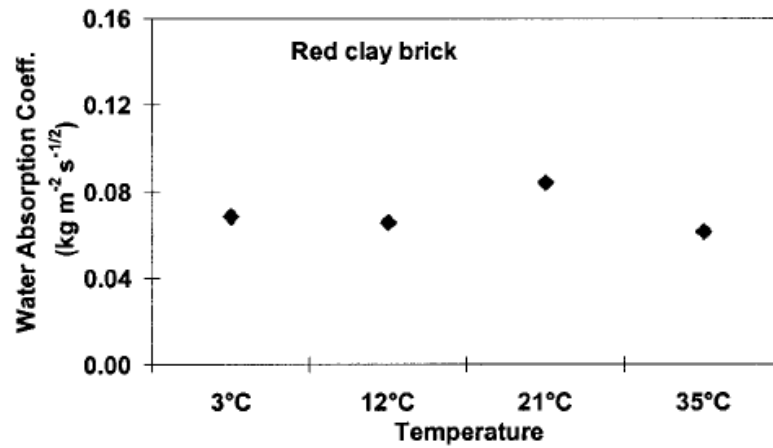
Figure 2.29 Variation of ISAT sorptivity measurements with temperature (Bungey et al., 2006).

Mukhopadhyaya et al. (2002) concluded different results from an experimental study on specimens of eastern white pine, red clay brick and concrete. Each sample was fixed in a position just touching the surface water, while the specimen's contacting surface area was 25 cm². The absorption test of each material was conducted at 3, 12, 21 and 35 °C. The temperature levels were obtained by a change in the temperature of the water in contact with the surface of the specimens. Although, the specimen's temperature remained as ambient room temperature (23 °C), the surface area of the samples in contact with water had been exposed to different temperature conditions.

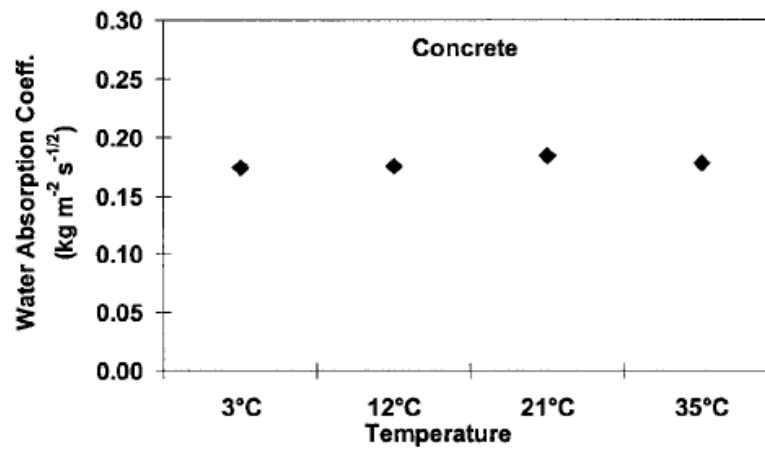
As presented in Figure 2.30, Mukhopadhyaya et al. (2002) investigated, that except in concrete, the water absorption coefficient changes with change in specimens conditioning temperature in the other two construction materials. It was concluded that materials with higher water absorption coefficient show less susceptibility to the effect of temperature variation.



(a)



(b)



(c)

Figure 2.30 Three different construction materials water absorption coefficient at various temperatures (Mukhopadhyaya et al., 2002)

3 EXPERIMENTAL AND TEST PROCEDURES

3.1 INTRODUCTION

A description of the concrete manufacturing procedures, the equipment that was used and tests procedures is given below. This chapter will provide the important technical information necessary to reproduce accurately the experimental work of this project. Moreover, it will contain discussions regarding test method verifications.

3.2 GENERAL

In this study, tests were performed in three major stages;

1. Laboratory measurements

In this stage, concrete specimens were tested to study the influence of moisture content and temperature on concrete sorptivity. Samples were pre-conditioned using laboratory equipment at 6 different levels of moisture content and 3 different levels of conditioning temperatures.

Moreover, in addition to tests performed using a commercial device, the GWT-4000, water absorption tests were performed following the ASTM C1585 procedure to be compared with in-situ test method results.

2. Outdoor exposure measurements

In this part of experimental project, samples of all mixtures were placed in outdoor exposure conditions. Several water absorption tests were performed at different temperatures and RHs.

3. In-situ measurements

In order to verify the results of two previous test stages, in-situ sorptivity tests were performed on the real concrete element from which the laboratory testing concrete samples were obtained. Due to accessibility and weather condition limitations, this part of experimental program was only performed on project A (concrete walkway with w/c of 0.42).

3.3 CONCRETE MANUFACTURE

Test specimens were manufactured using concrete mixtures of three construction projects in the Greater Montréal region, QC, Canada. Obtaining specimens directly from the construction site, allowed for a practical case study for laboratory measurements. Moreover, the mixtures are the common mixture designs used in construction projects, and mixed by full-scale concrete mixers. As such, the test results are closer to real in-situ measurement results rather than the results from laboratory mixed concrete. A brief description of samples' manufacturing process is described as follows.

3.3.1 Specimen details

Sample dimension was bounded by certain physical requirements. The moisture content measurements required a relatively small sample so that small changes in mass could be measured accurately. Basheer et al. (1995) found that specimen sizes do not affect the sorptivity index over the test duration of 20 minutes. However, it was recommended for the concrete specimen thickness to be larger than 50 mm and for edge distance (the distance between the edge of the specimen and the outer edge of the base ring) to be greater than 40mm (Basheer et al., 1995). A cylindrical size of 75mm height and 150mm diameter was found to meet both criteria. Twenty seven specimens were manufactured at each site using cardboard tube formwork. Concrete samples were provided from the following concrete casting projects;

1. Project A; walk way concrete casting project

The concrete casting location was at the intersection of Rue Saint-Vallier and Rue Des Carrieres, Montréal, QC. The scope of the project was to provide a side walk for Rue Des Carrieres (Figure 3.1). The project was completed on September 5, 2012 at noon. A volume of 12 m³ concrete was produced by Lafarge Co. and carried to the project location by truck mixers (Figure 3.2). Samples were obtained from the middle of the batch and placed at the project location for 24 hours (Figure 3.3). Curing compound was used as the means of curing for both manufactured samples and the walkway itself.



Figure 3.1 Project A; walkway project location [45.53076,-73.595632] (Google Maps, 2013)



Figure 3.2 Project A; walkway concrete casting project.



Figure 3.3 Project A; samples provided form walkway concrete casting project.

2. Bridge deck concrete casting project

The bridge construction project was located at intersection of Henri-Bourassa and Métropolitain, Montréal, QC (Figure 3.4). The project was completed on October 27, 2012 in the evening. Samples were provided from the concrete mixture used for the deck part of the bridge. A volume of 87 m³ concrete was produced by Béton Provincial Co. and carried to the project location using truck mixers and moved to bridge deck elevation using a concrete pump (Figure 3.5). As a one week wet curing was necessary for the concrete due to usage of supplementary cementing materials, the samples were placed beside the project location under a curing regime the same as the concrete of bridge deck (Figure 3.6).

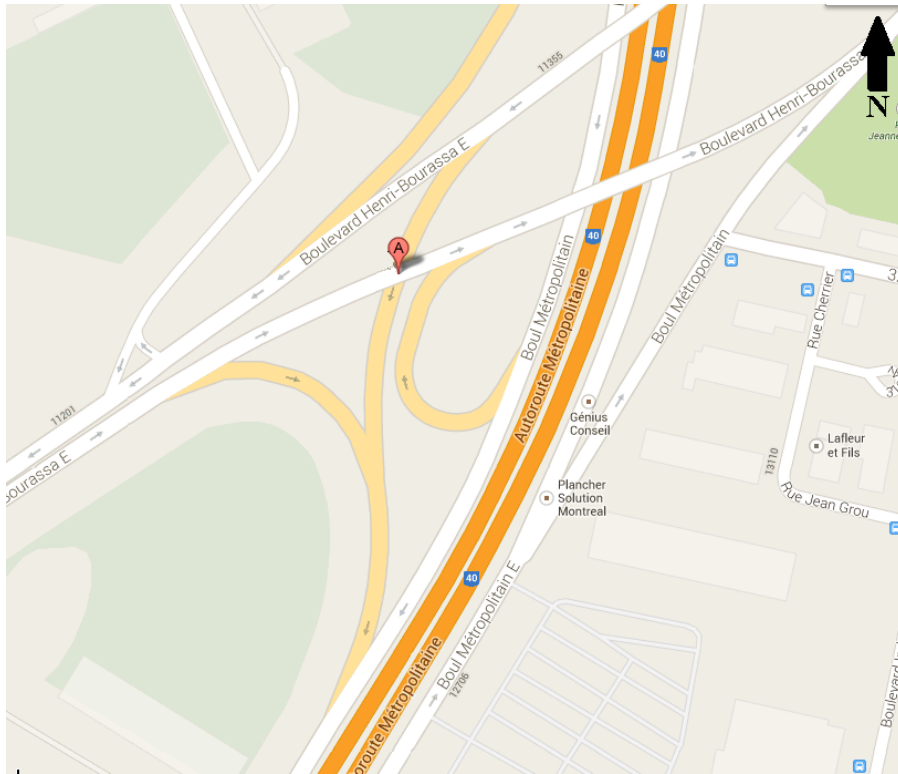


Figure 3.4 Project B; bridge construction project location [45.659516,-73.520632] (Google Maps, 2013)



Figure 3.5 Project B; bridge construction project.



Figure 3.6 Project B; samples provided from the bridge construction project.

3. Bridge side wall concrete casting project

This project was done to retrofit an existing bridge located at the end of Rue Jolicoeur over Canal de l'Aqueduc, Montréal, QC (Figure 3.7). As is shown in Figure 3.8, the concrete material was used in the side wall part of the bridge. Due to position limitations for concrete vibration, SCC (Self Consolidating Concrete) was used for this part of the project. The project was completed on June 19, 2013 at noon. A volume of 2 m³ concrete mixture was provided by Lafarge Co. and was carried to the project location by truck mixers. The concrete samples were obtained from middle of the batch and remained under wet curing regime for one week in the same project location as the real project concrete element (Figure 3.9).

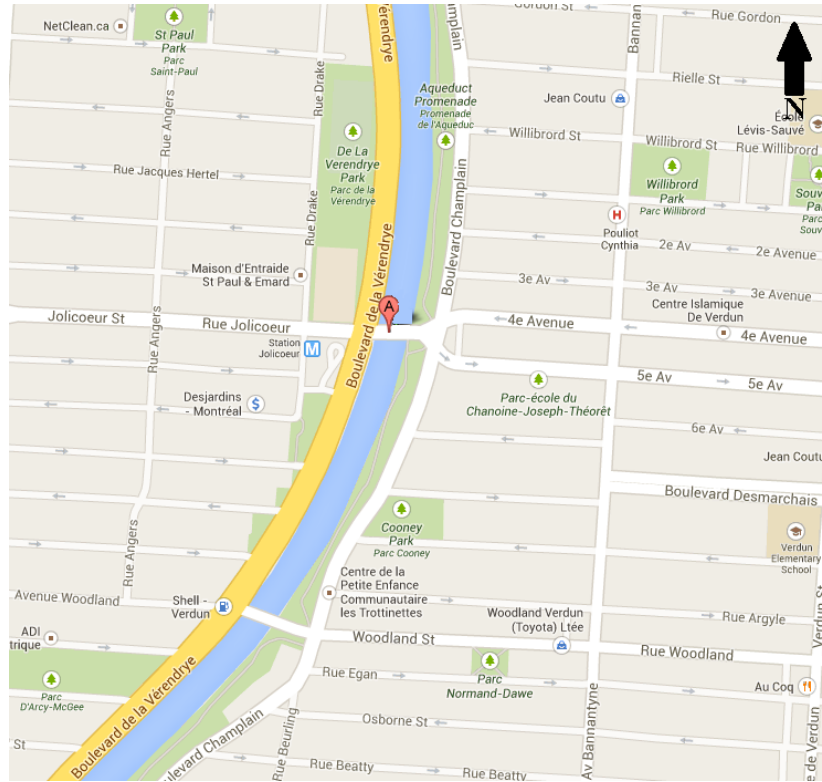


Figure 3.7 Project C; bridge side wall concrete casting project location [45.457011,-73.580507] (Google Maps, 2013)



Figure 3.8 Project C; bridge side wall concrete casting project.



Figure 3.9 Project C; samples provided from the bridge retrofitting project.

3.3.2 Concrete mixtures specifications

Concrete samples series A and B were obtained from normal concrete mixtures which needed to be vibrated in the forms. But concrete mixture C, was SCC concrete with additional fibers. The last mixture was selected to confirm if the water absorption test and its dependence on environmental conditions are the same for other types of concrete mixtures. All three mixtures had similar water to cementing materials ratio, but differed in component materials and curing. A description of three concrete mixtures used in this study is presented in Table 3.1. Chemical admixtures were added for workability, set control and corrosion resistance regarding each project condition.

Table 3.1 Concrete mixture designs and properties.

| Specifications | | Contents (kg/m ³) | | | | | | Properties | | |
|----------------|------|-------------------------------|-------------------------------------|-------------------------|-------|--------|------|------------|---------------|-------------------|
| Project | w/c | Portland Cement | Ternary Cement (22% SG and 5%SF) | Supplementary Materials | Water | Gravel | Sand | Air (%) | Slump (mm) | Strength (MPa) |
| A | 0.42 | 283 | 71 | - | 149 | 1051 | 810 | 6.0 | 90 | 42.8 |
| B | 0.40 | - | 292 | 73 (Class F fly ash) | 131 | 975 | 819 | 6.0 | 115 | 45.9 |
| C | 0.39 | - | 460 | - | 178 | 828 | 817 | 6.2 | 650 | 48.5 |

3.3.3 Specimen curing and conditioning

The specimens were cured identically as the real project concrete elements and remained on the construction site one day for project A, and for one week for projects B and C. In the case of the project A, a curing compound was applied and for the projects B and C, wet burlap and plastic were used at the time of casting. After this, the samples were moved to a secure open field position which had the same weathering condition as the project site for three weeks. At 28 days after casting, they were moved to the laboratory and were unmolded and exposed to the conditioning regime. The curing compound for samples of project A was removed at this time using a metal brush.

Initially, all specimens for laboratory measurements were saturated by immersion in water for a period of 3 days. This period of immersion is considered to be sufficient to obtain saturated concrete samples (ASTM C642, 2006). Afterwards, samples were removed from water and the bottom face and round sides of specimens were painted with epoxy coating to be water resistant and to simulate uniaxial water flow during the sorptivity test. In the case of project C, the top face was painted with epoxy as poor weather on the day of casting caused damage to the top surfaces. Drying of the specimens was carried out in a fan-assisted drying cabinet. Samples were placed to dry (at 45°C) for periods of 2, 3, 5, 7, 10

and 14 days to obtain six different moisture contents in the concrete. The temperature was selected to provide gradual drying without microstructural damage. After drying, each specimen was tightly wrapped in plastic and left for a period of one month in the laboratory to minimize the moisture gradient in the concrete cylinders. During this time, it was expected that the moisture in the capillary pores of the concrete would become well distributed through the specimen's depth. According to Parrott (1994), three days of drying at 50° C followed by 4 additional days in a sealed container will provide reasonable moisture uniformity. One month used in this research exceeds the 15 day period recommended in ASTM C1585. In order to obtain dried mass of the samples to obtain saturation degree, the specimens were subjected to be oven drying for three days at 110°C once sorptivity testing was completed. In addition, another set of specimens were dried to one moisture content (for 7 days) to be tested at three different temperatures of 5, 23 and 40° C. Samples, water and the instrument parts were placed in the proposed testing temperature for at least 24 hours prior to testing to have the same temperature condition.

For ASTM C1585, water absorption test samples were placed in an environmental chamber at 50° C and RH of 80% for 3 days. Afterwards, samples were removed from the cabinet and sealed in plastic and stored for 20 days at 23° C. Later, samples were removed from plastic sheets and were tested following ASTM C1585 test procedure.

In the outdoor exposure trial, in order to validate laboratory results, three samples of each mixture were located in an exposed weathering condition as well as to rain and sunlight. Several sorptivity measurement tests were performed at different conditioning temperatures and RHs. Lastly, for the on-site measurements, no attempts at conditioning

were undertaken. However, in both these experimental stages, tests were performed at least 2-3 days after a rain event as recommended by Basheer and Nolan (2001).

3.4 TESTING PROCEDURE

3.4.1 Moisture content measurement

Two indices were used to evaluate the concrete moisture content:

1. Saturation degree

Saturation degree was determined by mass measurements taken after the epoxy painting process (saturated surface dry, W_{SSD}), and before sorptivity testing (W_{TEST}) and after the oven drying stage (W_{DRY}). The mass was measured with a scale with 0.1 g accuracy. The saturation degree was determined using Equation 3.1.

$$Saturation = \frac{W_{TEST} - W_{DRY}}{W_{SSD} - W_{DRY}} \quad [Equation 3.1]$$

2. Relative humidity

RH measurements were carried out at the test surface of concrete specimens using a humidity measuring device. A commercial humidity indicator, Vaisala HUMICAP indicator HMI41 and its probe HMP45 with accuracy of this probe is $\pm 0.1\%$ RH was used to measure the RH of the sealed air chamber above the concrete surface allowing 45 minutes to 2 hours to reach equilibrium (Figure 3.10). This value is considered as the concrete surface relative humidity. A similar method of concrete RH measurement was used in previous studies (Nolan, 1996, Basheer and Nolan, 2001).

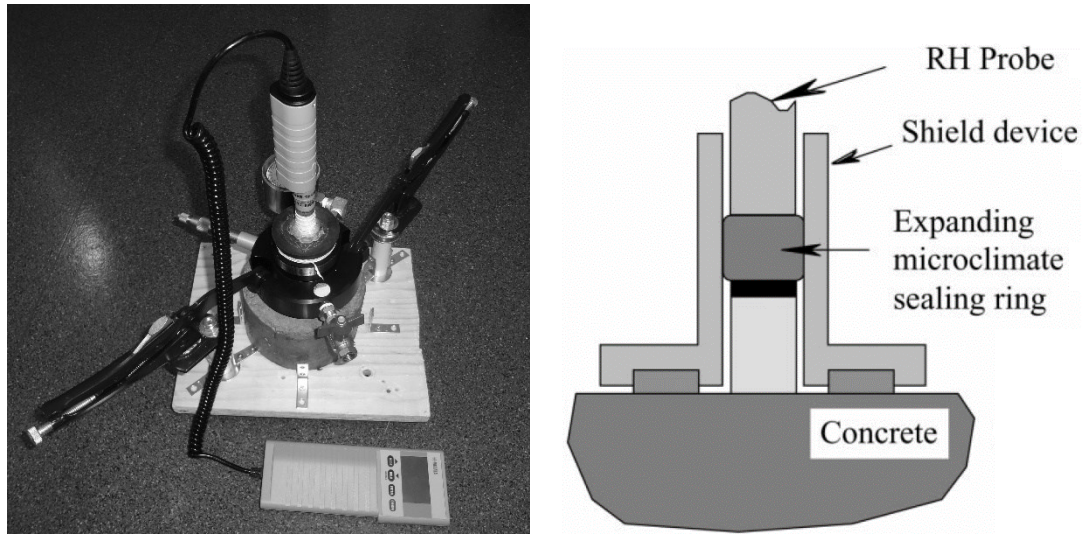


Figure 3.10 Concrete surface RH measurement (right) and schematic from Nolan (1996) (left).

Both RH and saturation degree measurements were used for the laboratory stage of this research. But after investigating a satisfying correlation between these two moisture content indices, it was decided to just use RH measurement for outdoor exposure measurements. Obviously, it was impossible to calculate saturation degree for a real in-situ concrete element using mass measurements. As such, surface RH measurement was used for in-situ measurements for the concrete walkway. Sorptivity measurements above 80% RH can cause misleading results in concrete durability evaluation (Basheer and Nolan, 2001). As such, tests were not performed above this conditioning RH level for outdoor exposure and in-situ tests.

3.4.2 Temperature measurement

In the laboratory, measurements of the concrete samples' surface temperature were measured using an infrared thermometer (Fluke 62 MAX IR Thermometer) at the initiation and termination of sorptivity testing. The water absorption measurements were performed

at a temperature of 23 °C for all the 6 different moisture stages. For temperature stages, as described above, samples (sealed in the plastic bags), water and test equipment were placed at temperatures of 5, 23 and 40 °C 24 hours prior to the test.

For outdoor exposure and in-situ measurements, water and test equipment were left in the exposed condition to reach the same temperature level as the concrete surface. The concrete surface temperature was measured using the infrared thermometer. For valid results, testing should be carried out at temperatures above 5 °C (GWT-4000 Instruction and Maintenance manual). As such, tests were not performed at temperatures below 5 °C for outdoor exposure and in-situ tests.

3.4.3 Sorptivity measurement

Sample sorptivity was measured after the RH measurement for each sample. This measurement was carried out using a commercial apparatus, GWT 4000, developed by Germann Instruments. As mentioned in section 2.5.2.5, the recommended water pressure for water absorption test is 0.01 bar. At this pressure head, it can be assumed that all water absorbed by the specimen surface is due to concrete capillary suction (Basheer et al., 1995). It is also recommended by Basheer et al. (1995) to consider 2 to 5 minutes for an initial time delay in starting the test after water first is introduced into the test area. For this project, 2 minutes initial water contact was used prior to all measurements. Regarding the test duration, it was decided to use 20 minutes because it was observed that a test lasting for 20 minutes would yield sufficient number of data points in order to calculate the sorptivity index.

For laboratory and outdoor exposed samples, in order to install the GWT-4000 device on concrete surface, a platform was built using a wooden plate as base and two bolts to carry the device clamps (Figure 3.11). The in-situ measurements were performed using a vacuum plate to attach the GWT-4000 instrument to the concrete surface (Figure 3.12). The working principle of GWT-4000 is as described in part 2.4.2.3.

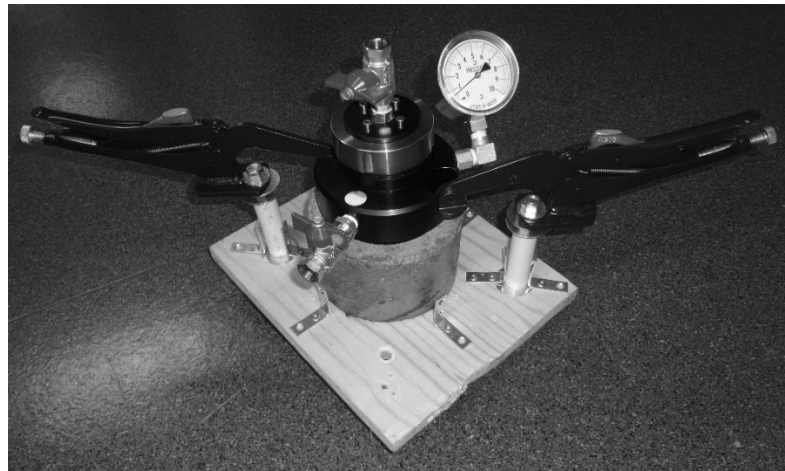


Figure 3.11 Laboratory sorptivity measurement.



Figure 3.12 In-situ water absorption measurement.

4 RESULTS AND DISCUSSION

4.1 INTRODUCTION

Results obtained from laboratory, outdoor exposed and in-situ measurements following principles mentioned in chapter 3, are presented in this chapter. Later, results are discussed and compared to some of relevant previous studies in this field.

4.2 GENERAL

In this chapter, except for in-situ measurements, each value is an average of three measurement results. In some cases, results were discarded as water leaked through the gasket of the GWT device. In those cases the average values were calculated from two measurements. Sorptivity measurements were in the range of 10% from the average values. In ASTM C1585, 6% differences are given for a single operator; most replicate results were within this range. Saturation degree, surface RH and temperature measurements were in the range of with 10% from the average values.

For all three mixtures, laboratory results for moisture variation are presented in Table 4.1; laboratory measurements data for temperature variation are presented are in Table 4.2; and outdoor exposure test results are presented in Table 4.3. Due to weathering and physical limitations, in-situ measurements were performed only on project A. Table 4.4 is presenting the in-situ test data for mixture A. The range in measured values from the average is shown as $\pm\%$. These data are separately studied and discussed later in this chapter. In addition, detailed values of measurements are presented in appendix A of this thesis.

Table 4.1 Laboratory results for moisture variation

| Mixture | Drying days | Saturation degree (%) | RH (%) | Sorptivity ($10^{-06} \text{ m/s}^{0.5}$) |
|------------------------------|-------------|-----------------------|-----------|---|
| A; w/c=0.42 | 2 | 78.7±1.0% | 65.2±3.4% | 4.9±4.1% |
| | 3 | 74.9±2.7% | 60.8±4.1% | 5.9±3.4% |
| | 5 | 72.4±1.5% | 55.6±2.7% | 6.3±9.1% |
| | 7 | 70.2±1.9% | 50.3±4.6% | 7.2±4.2% |
| | 10 | 66.9±8.9% | 43.1±3.5% | 8.2±2.4% |
| | 14 | 62.2±1.6% | 35.7±1.1% | 9.1±1.1% |
| B; w/c=0.40 | 2 | 84.3±1.0% | 72.1±1.5% | 2.7±7.4% |
| | 3 | 81.4±1.2% | 67.1±3.1% | 3.4±2.9% |
| | 5 | 77.8±3.0% | 56.3±9.6% | 4.4±4.5% |
| | 7 | 73.5±4.8% | 48.4±9.3% | 5±1.5% |
| | 10 | 68.2±1.1% | 38.5±7.2% | 5.9±3.4% |
| | 14 | 67.3±0.8% | 33.5±3.2% | 6.9±5.8% |
| C; w/c=0.39 | 2 | 86.9±0.7% | 70.1±1.9% | 1.4±7.1% |
| | 3 | 83.9±2.4% | 67.2±1.0% | 2.1±9.5% |
| | 5 | 77.7±2.8% | 54.3±5.2% | 3.4±8.8% |
| | 7 | 75.0±1.5% | 46.1±3.3% | 4.2±9.5% |
| | 10 | 70.6±3.2% | 38.4±4.4% | 4.9±4.1% |
| | 14 | 68.3±3.1% | 34.1±4.7% | 6.4±1.6% |

Table 4.2 Laboratory results for temperature variation

| Mixture | Temperature (°C) | Sorptivity ($10^{-06} \text{ m/s}^{0.5}$) |
|------------------------------|-------------------------|---|
| A; w/c=0.42 | 7.3±3.0% | 4.4±4.5% |
| | 23.0±0.6% | 7.2±4.2% |
| | 40.3±1.7% | 9.3±8.6% |
| B; w/c=0.40 | 7.7±3.7% | 3.0±6.7% |
| | 23.0±0.4% | 5.0±1.5% |
| | 41.6±1.1% | 7.0±4.3% |
| C; w/c=0.39 | 7.2±3.0% | 2.6±7.7% |
| | 23.0±0.6% | 4.2±9.5% |
| | 39.0±2.3% | 5.9±3.4% |

Table 4.3 Outdoor exposure test results

| Mixture | Temperature (°C) | RH (%) | Sorptivity (10 ⁻⁰⁶ m/s ^{0.5}) |
|------------------------------|------------------|-----------|--|
| A; w/c=0.42 | 17.9±0.6% | 48.1±3.5% | 6.4±4.7% |
| | 27.6±0.7% | 40.1±6.0% | 10.4±1.0% |
| | 28.8±0.3% | 58.7±2.2% | 7.4±4.1% |
| | 33.4±0.6% | 53.2±5.8% | 9.4±4.3% |
| | 30.1±0.7% | 45.3±3.8% | 9.6±4.2% |
| B; w/c=0.40 | 17.8±0.6% | 52.4±3.4% | 4.7±4.3% |
| | 27.5±0.4% | 46.2±3.0% | 6.2±4.8% |
| | 34.8±0.3% | 64.3±3.9% | 5.2±5.8% |
| | 37.5±0.3% | 57.4±1.9% | 5.1±5.9% |
| | 30.1±0.3% | 49.7±5.8% | 4.9±6.1% |
| C; w/c=0.39 | 24.2±1.7% | 56.9±2.8% | 3.2±9.4% |
| | 20.7±3.4% | 61.1±3.2% | 2.3±8.7% |
| | 17.1±4.1% | 67.3±2.0% | 1.4±7.1% |
| | 25.7±2.3% | 52.4±2.3% | 3.7±2.7% |
| | 24.0±3.3% | 68.7±2.6% | 1.6±6.3% |

Table 4.4 In-situ measurement test results

| Mixture | Temperature (°C) | RH (%) | Sorptivity (10 ⁻⁰⁶ m/s ^{0.5}) |
|------------------------------|------------------|--------|--|
| A; w/c=0.42 | 25.4 | 51.3 | 8.1 |
| | 21.3 | 57.9 | 5.7 |
| | 18.9 | 68.5 | 4.4 |

4.3 LABORATORY RESULTS

4.3.1 Moisture content variation with drying duration and surface relative humidity

Figure 4.1 shows the concrete saturation versus the square root of the drying duration at 45 °C for three mixtures. The trend lines do not intercept to the boundary conditions data points (zero days drying and 100% saturation). This is due to highly non-linear behaviour at either very low or very high moisture conditions (see, Figure 2.17 for an example). Obviously, the saturation degree decreases with increasing drying duration. It suggests a linear relationship between saturation degree and square root of drying duration for this range of data. This relationship has also been investigated by other researchers and can be described by a falling drying rate where the drying rate is limited to the rate of unsaturated water flow towards the drying surface. In other words, the water movement from depth to concrete surface is due to capillary forces in low (room) temperatures. This linear relationship is similar to water flow through unsaturated concrete due to capillary suction and that determined in ASTM C1585 (Hall and Raymond Yau, 1987). The slope of this trend is related to concrete pore structure properties.

Moreover, the mixture with higher w/c shows a lower saturation degree at all stages due to a more porous structure it has compared to the other mixtures. This result was also obtained in previous research (Nolan, 1996). This can be referenced to water capillary movement in drying in low temperature conditions. Mixtures with higher w/c have a larger average pore size and greater pore connectivity which results in a higher rate of water capillary movement.

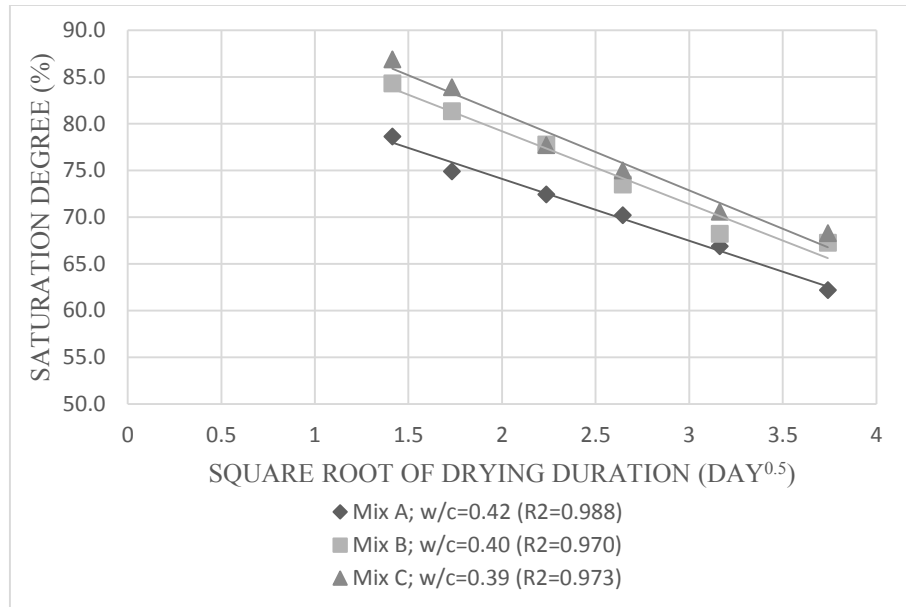


Figure 4.1 Saturation degree versus square root of drying time at 45 °C

Figure 4.2 shows the linear relationship between surface RH values and saturation for the three mixtures. RH measurements were performed after the sealed air above the concrete surface reached a constant value, defined as less than 0.1% RH over 5 minutes. This means the percentage of water molecules in the air sealed above the concrete surface is the same value in the air sealed in the concrete pores. This is a result of movement of water molecules of higher concentration in concrete pores to regions of lower concentration. Thus, the surface RH value is representing the relative humidity of existing air in pores near the concrete surface. The very good correlation obtained from these experimental results also show that surface RH measurement can be used as a reliable index for concrete moisture content, enabling outdoor exposure measurements. As has been proposed by previous studies, sorptivity measurements at RH values greater than 80% may cause serious misleading results for durability evaluation (Basheer and Nolan, 2001). This linear relationship is valid for the range investigated; it is acknowledged that moisture isotherms

are highly non-linear at both high and low RH values. As such, saturation-surface RH correlation at high RH ranges is not taken into consideration in this study. This good correlation between specimen saturation degree and surface RH value is likely due to the additional storage period to avoid moisture gradient in concrete samples.

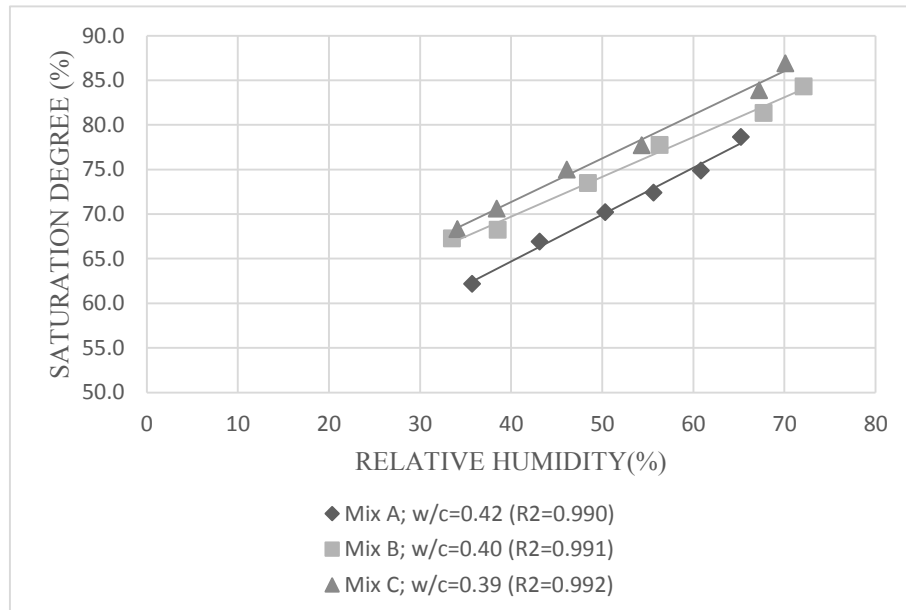


Figure 4.2 Saturation degree versus surface RH

4.3.2 Sorptivity dependence on moisture content

Sorptivity measurements were performed for samples of three concrete mixtures at 6 different moisture stages. Figures 4.3 to 4.5 shows expanded test results of these measurements for each concrete mixture. Each point in these graphs is an average of three readings. As can be seen, the expected linear relationship between cumulative absorption and the square root of time was obtained in all cases with correlation coefficients generally in excess of 0.96. The sorptivity was calculated as the slope of this line.

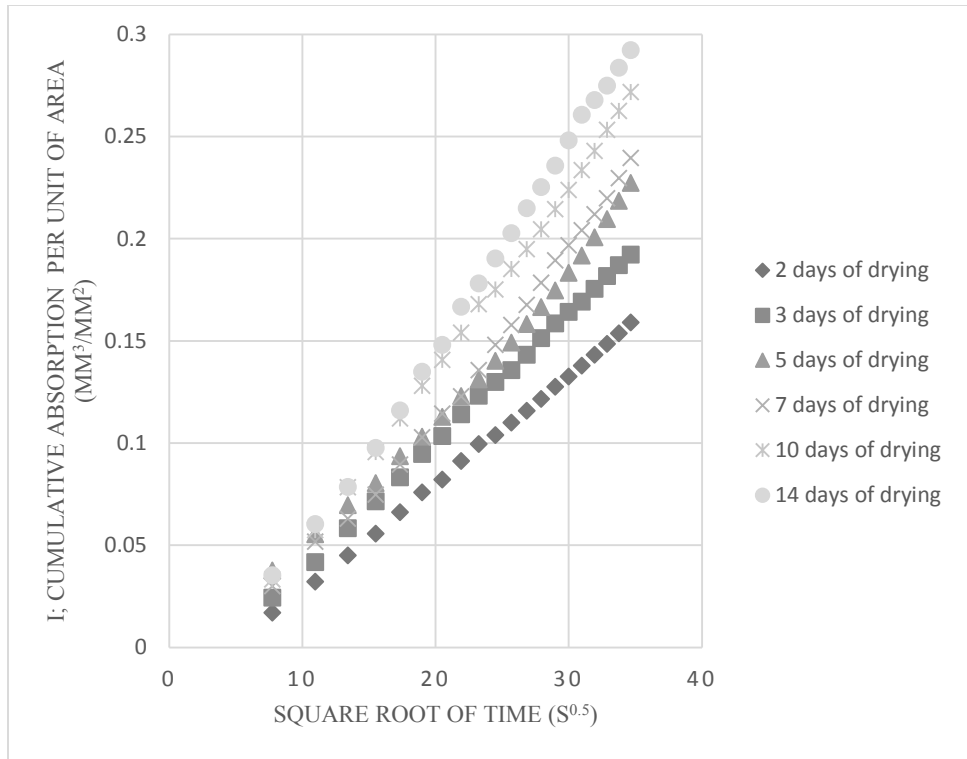


Figure 4.3 Water absorption test results for different moisture stages; Mix A, w/c=0.42

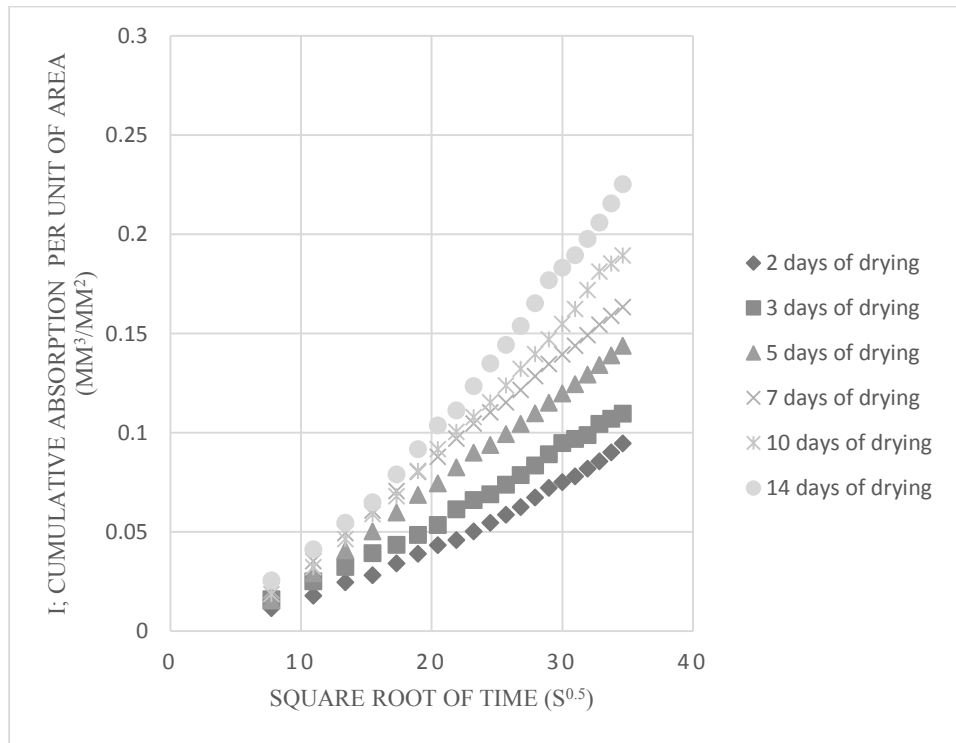


Figure 4.4 Water absorption test results for different moisture stages; Mix B, w/c=0.40

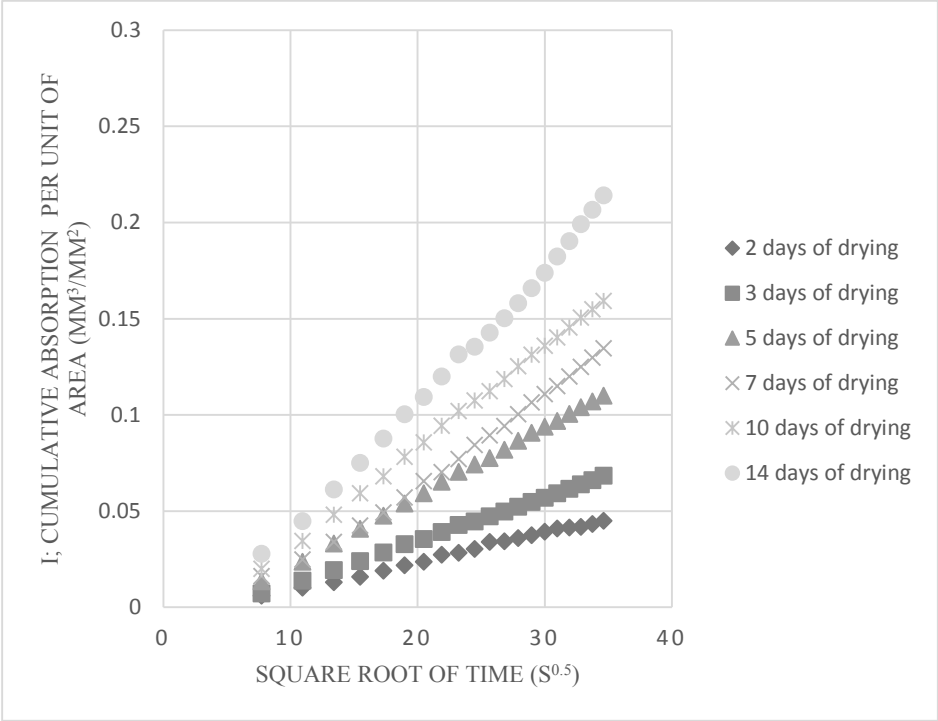


Figure 4.5 Water absorption test results for different moisture stages; Mix C, w/c=0.39

Dependence of sorptivity on saturation degree is presented in Figure 4.6 It shows a linear trend between the sorptivity index and saturation degree. The sorptivity index increases as the concrete saturation degree decreases for all mixtures. This is because of the loss of moisture from the capillary pores in the concrete which leaves capillary pore space free to absorb moisture during testing. Theoretically, this relationship could be expected to pass through 100% saturation degree and zero sorptivity. Thus, the trend line for each mixture is forced to pass this point. Not surprisingly, sorptivity increases with increasing w/c of mixtures in each saturation degree. Higher w/c ratios in concrete mixtures increase the pore percentage which leads to an increase of the water absorption rate.

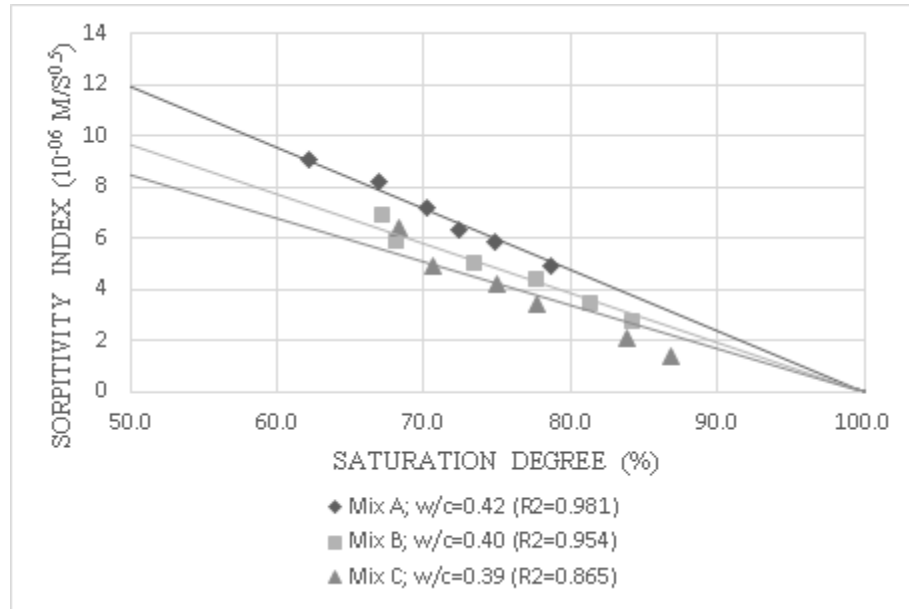


Figure 4.6 Relationship between concrete saturation degree and sorptivity in laboratory samples

As is mentioned in section 2.6.1, DeSouza et al. (1997) and Nokken and Hooton (2002) also studied the influence of concrete moisture content using saturation degree index on sorptivity measurements. Figure 4.7 shows their results for different mixtures compared to results obtained for three mixtures in this study using normalized sorptivity. Sorptivity value normalization for DeSouza et al. (1997) and Nokken and Hooton (2002) is performed compared to samples dried at 110°C. Sorptivity measurements in this study are normalized by the sorptivity intercept of each mixture's trend line of sorptivity versus saturation degree presented in Figure 4.6. As is shown, the sorptivity index has a reasonable linear correlation with concrete saturation degree. Water absorption rate decreases with increasing in concrete saturation degree for all the presented mixtures. This normalization procedure is interesting as all data, regardless of mixture, fall on a single line with good correlation.

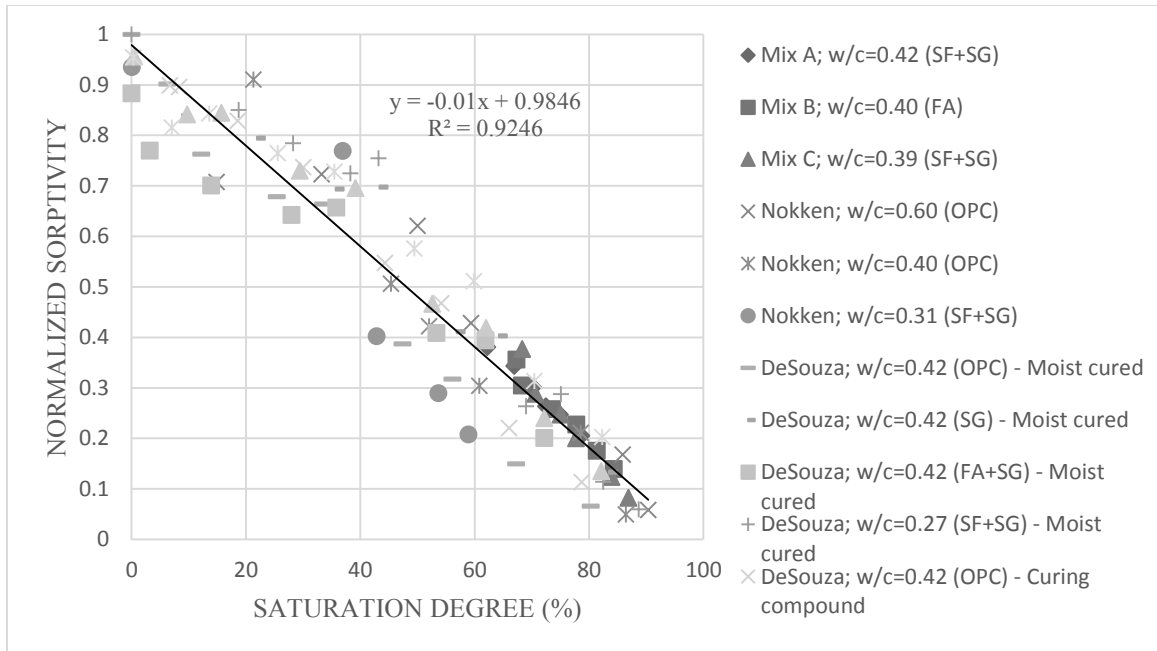


Figure 4.7 Sorptivity data versus saturation degree, normalized to 0% saturation degree

According to results presented in section 4.2.1, surface RH measurements show a reasonable correlation with saturation degree (in the case of uniform moisture distribution). As it is shown in Figure 4.8, like sorptivity behavior with saturation degree, sorptivity is also increasing linearly with increasing in surface RH value. Figure 4.8 shows that less than 20% change in surface RH makes 100% change in sorptivity measurement. This sorptivity variation changes due to mixture designs. Like saturation degree, at the same surface RH, sorptivity increases by increases in concrete w/c ratio.

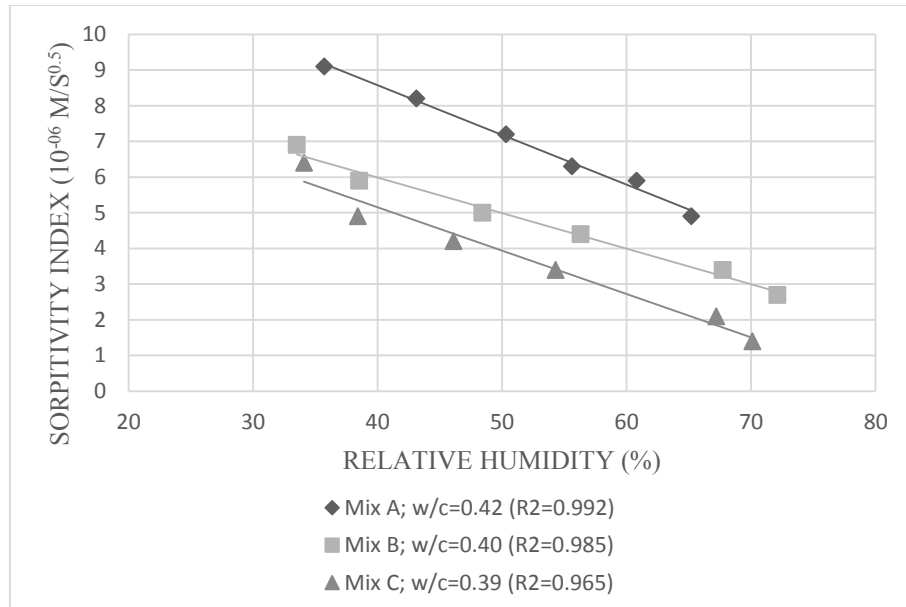


Figure 4.8 Relationship between concrete surface RH value and sorptivity in laboratory samples

Nolan (1996) also found similar behavior of sorptivity with change in surface RH measurements. Three different mixtures were tested at four different moisture content conditions. Moreover, Castro et al. (2011) investigated the dependence of sorptivity index on exposure RH following the ASTM C1585 Standard method. As is shown in Figure 4.9, Nolan's and Castro's data points are compared to these research results. In all cases, sorptivity values are normalized to 0% surface RH obtained from the trend lines. Results are showing sorptivity index is increasing linearly with decreasing in surface RH values.

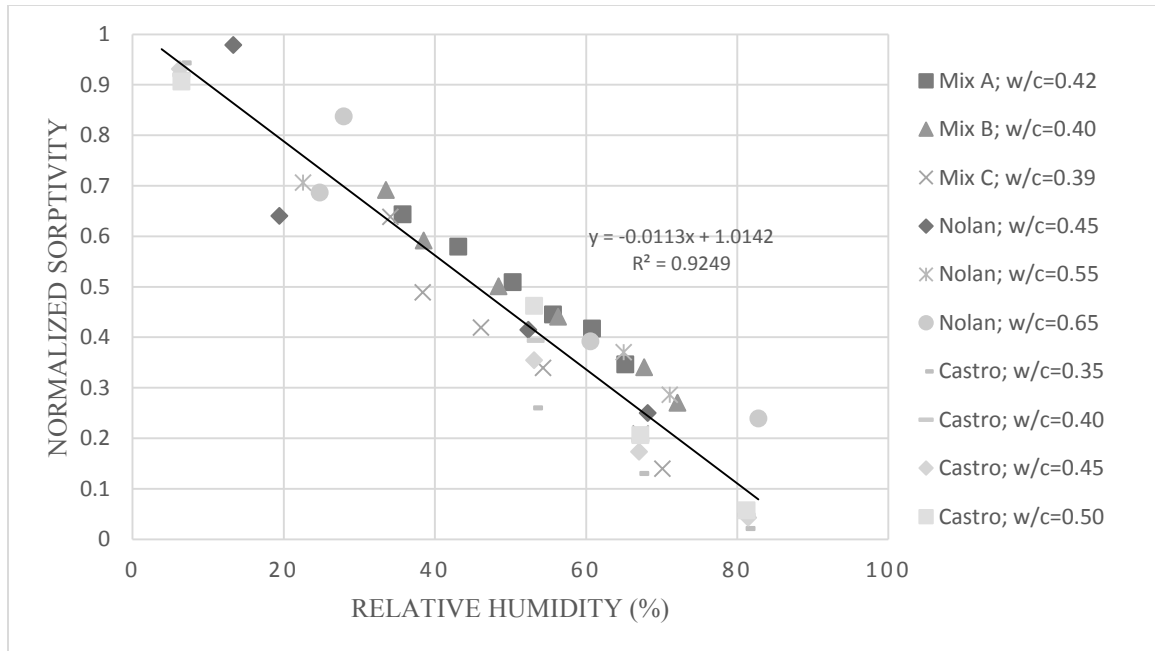


Figure 4.9 Sorptivity data versus surface RH, normalized to 0% relative humidity

According to the ASTM C1585 water absorption measurement Standard, concrete specimens should be conditioned in a specific RH and temperature regime. It has been found, this conditioning regime will provide 50 to 70% of internal RH in concrete samples (ASTM C1585).

In order to compare test results obtained by the ASTM C1585 Standard method with the results obtained in this study, three samples of each mixture were tested after the pre-conditioning regime detailed provided in ASTM C1585 and mentioned in part 3.3.3. Figure 4.10 shows ASTM C1585 initial absorption test results compared with sorptivity-RH trends. It also shows although the ASTM pre-conditioning procedure results in 50 to 70% of internal RH in concrete specimens, but even this 20% range of concrete RH may cause serious misleading results in durability evaluations based on sorptivity measurements.

In addition, results show that 3 days of preconditioning in environmental chamber at 80% of RH, as it is proposed in ASTM Standard, does not guarantee a certain amount of moisture content in concrete samples. Castro et al. (2011) found it takes longer periods of time (14 months) for concrete specimens to reach mass equilibrium (less than 0.02% over a 15 day period). It shows that concrete moisture history is affecting the concrete moisture content even with the conditioning process using ASTM test method. Meaning, the initial moisture content of the sample prior to the conditioning step will influence its moisture content when tested for water absorption. Castro et al. (2011) suggest that samples should be fully saturated prior to preconditioning to minimize the differences.

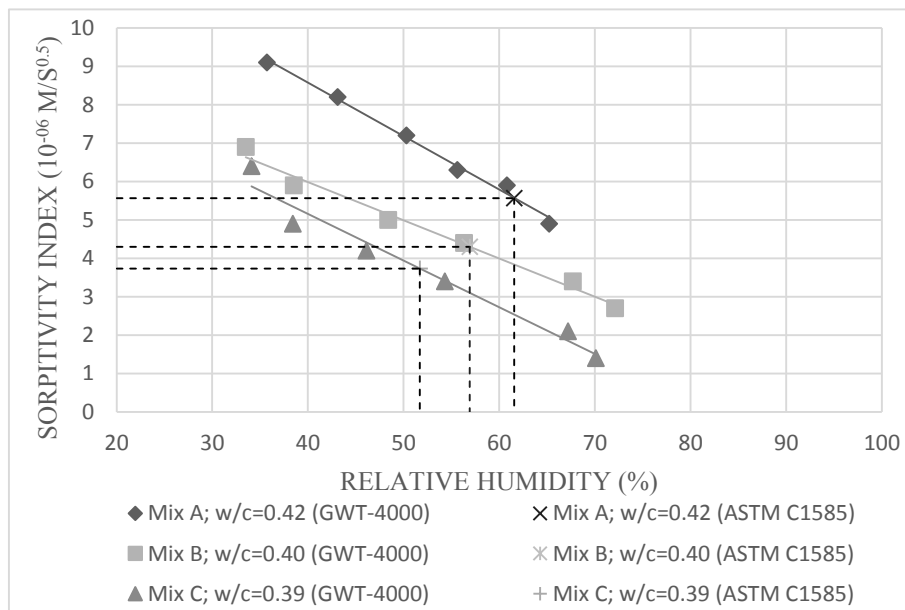


Figure 4.10 ASTM C1585 test results comparing with sorptivity-RH trends

4.3.3 Sorptivity dependence on temperature

Sorptivity measurements were performed for samples of three concrete mixtures at 3 different temperatures. All samples investigated were subjected to drying for 7 days, and

approximately similar saturation degrees were obtained for samples from same projects. Figures 4.11 to 4.13 shows expanded test results of these measurements for each concrete mixture. Each point in these graphs is an average of three readings. The temperatures on these figures represent the exposure condition; further analysis was done using the average temperature at the initial and termination of absorption testing. High linear correlations resulted, with the slope of the line defined as the sorptivity.

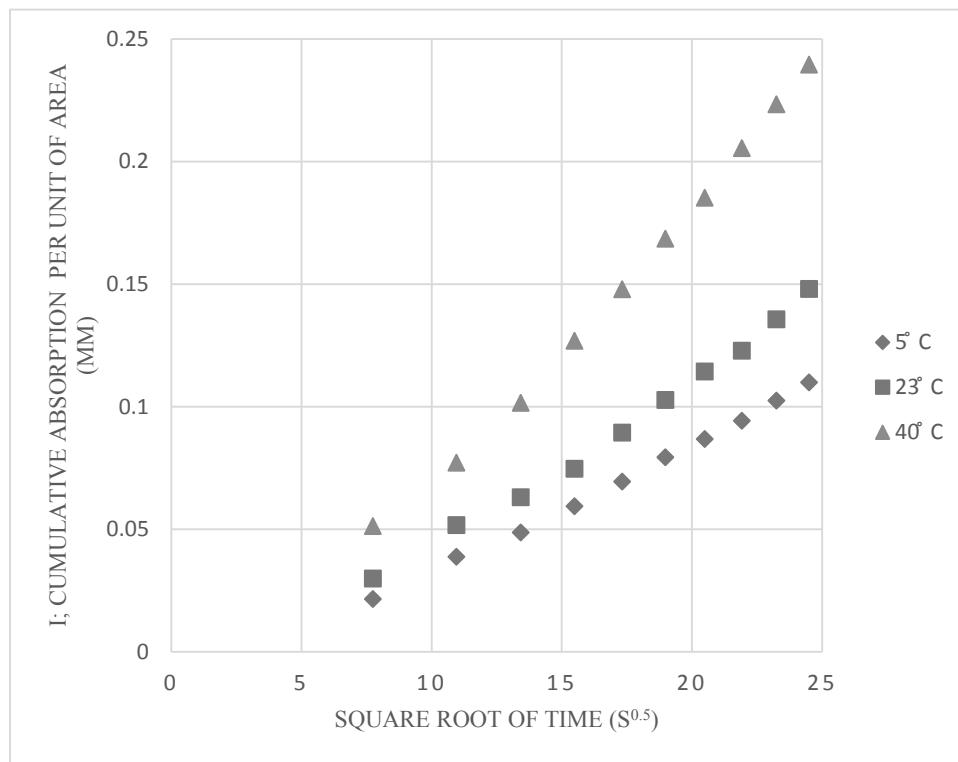


Figure 4.11 Water absorption test results for different temperature stages; Mix A, w/c=0.42

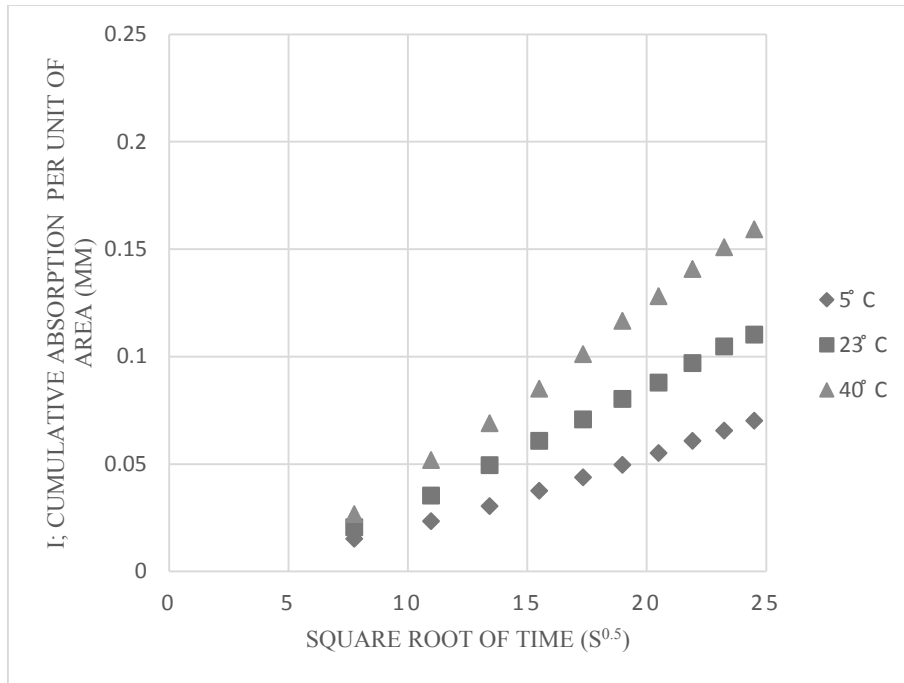


Figure 4.12 Water absorption test results for different temperature stages; Mix B, w/c=0.40

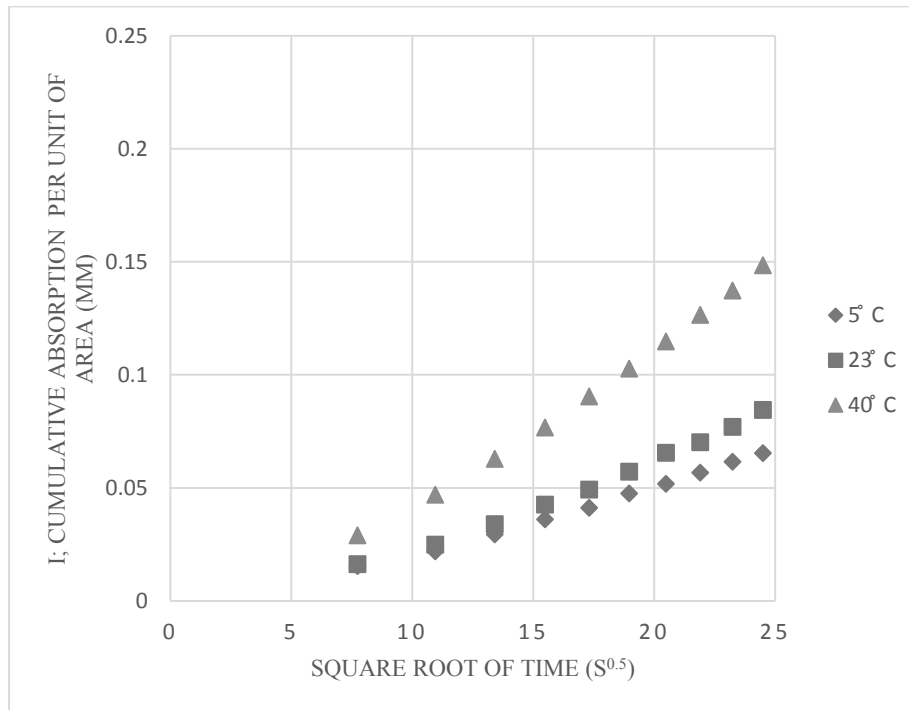


Figure 4.13 Water absorption test results for different temperature stages; Mix C, w/c=0.39

As presented in Figure 4.8, the sorptivity index increases with increasing conditioning temperature. The three selected temperatures represent the range likely encountered while testing on site. It was found that a change in temperature of about 4°C towards room temperature occurred over the test period (the samples starting at 5°C increasing in temperature and those at 40°C decreasing). The average of the two temperatures was used for Figure 4.8 graph and further calculations. As it can be observed, the sorptivity index may increase more than 100% over approximately a 30°C increase.

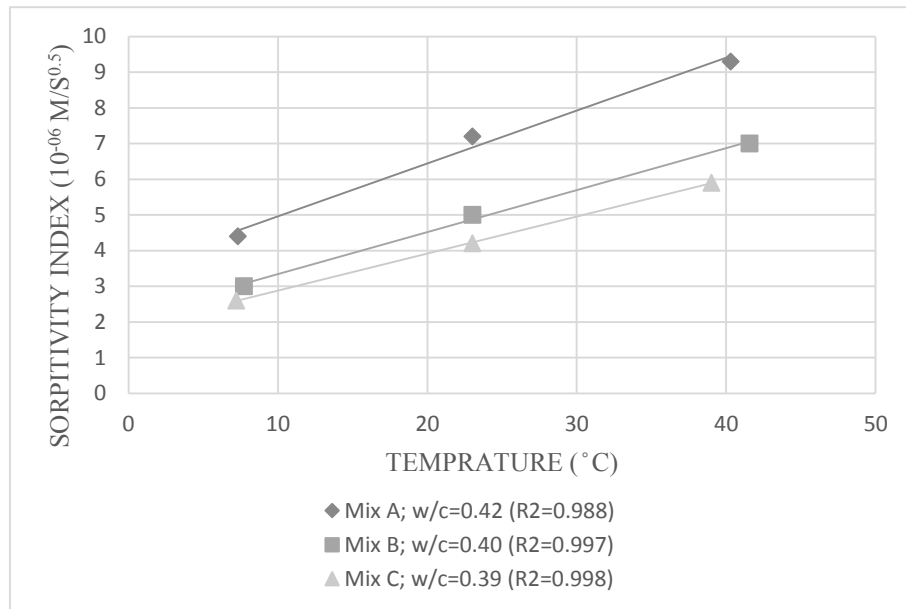


Figure 4.14 Relationship between conditioning temperature and sorptivity in laboratory samples

This relationship between water absorption and temperature is due to both water and concrete temperature dependent properties. Although, a second-order polynomial suggested by Nolan (1996) obtained from Equation 2.17, could be used to fit the data, linear behavior also has been observed in previous research for ISAT sorptivity measurements (Bungey et al., 2006).

Assuming negligible changes in pore radius and length, it can be concluded that in absorption mechanism which is using small amount of external pressure (negligible value for H_a), a correction factor to sorptivity at 23 °C is calculated as follows as an extension from Equation 2.18:

$$CF_{23} = \frac{S_{23}}{S_T} = \frac{\frac{\gamma_{23}}{d_{23} \cdot \eta_{23}}}{\frac{\gamma_T}{d_T \cdot \eta_T}} \quad [\text{Equation 4.1}]$$

CF_{23} : Correction factor to sorptivity at 23 °C,

S_{23} and S_T : Sorptivity in conditioning temperature of 23 and T °C,

γ_{23} and γ_T : Surface tension at 23 and T °C (N/m),

d_{23} and d_T : Density of the liquid at 23 and T °C (kg/m³), and

η_{23} and η_T : Liquid viscosity at 23 and T °C (N/m.s).

Water temperature dependent properties presented in Table 4.5 are used to obtain a correction factor based on the trend similar to that suggested by Nolan (1996) (see Figure 2.26).

Table 4.5 Physical water properties at different temperatures (Vukalovich et al., 1969)

| T (°C) | Density (kg/m³) | Viscosity (N/m.s) | Surface tension (N/m) |
|---------------|-----------------------------------|--------------------------|------------------------------|
| 0 | 999.82 | 0.017580 | 0.07564 |
| 5 | 1000.00 | 0.014911 | 0.07495 |
| 10 | 999.77 | 0.012831 | 0.07423 |
| 15 | 999.19 | 0.011174 | 0.07350 |
| 20 | 998.29 | 0.009839 | 0.07275 |
| 23 | 997.71 | 0.009290 | 0.07237 |
| 25 | 997.13 | 0.008741 | 0.07199 |
| 30 | 995.71 | 0.007828 | 0.07120 |
| 35 | 994.08 | 0.007063 | 0.07041 |
| 40 | 992.25 | 0.006406 | 0.06960 |
| 45 | 990.22 | 0.005847 | 0.06878 |
| 50 | 998.02 | 0.005366 | 0.06794 |
| 55 | 985.65 | 0.004944 | 0.06710 |
| 60 | 983.13 | 0.004581 | 0.06624 |
| 65 | 980.45 | 0.004258 | 0.06536 |
| 70 | 977.63 | 0.003963 | 0.06447 |
| 75 | 974.68 | 0.003708 | 0.06358 |
| 80 | 971.60 | 0.003483 | 0.06267 |
| 85 | 968.39 | 0.003277 | 0.06175 |
| 90 | 965.06 | 0.003090 | 0.06082 |
| 95 | 961.62 | 0.002923 | 0.05987 |

Figure 4.8 shows dependence of the sorptivity correction factor on temperature for both theoretical calculations and experimental investigations in this research. Theoretical sorptivity correction factor in different temperatures obtained from Equation 4.1, shows a second-order polynomial trend versus temperature. Equation 4.2 shows this trend line results in the following equation.

$$CF_{23} = 1.7037 - 0.0322 \times T + 0.0002 \times T^2 \quad \text{[Equation 4.2]}$$

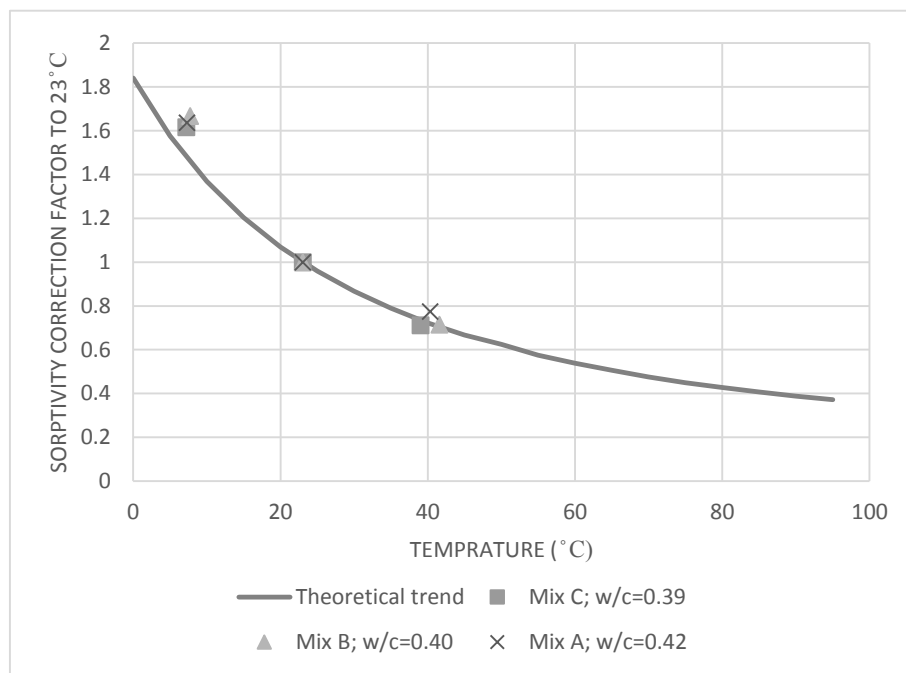


Figure 4.15 Sorptivity correction factor to 23°C versus temperature

It can be concluded from Figures 4.15 and 4.14 that although experimental results are showing reasonable correlation with the theoretical trend (Equation 4.2), more experimental data points are needed to determine if the linear or polynomial correction is more appropriate.

Using the experimental results presented in Figure 4.14, linear CF_{23} -temperature equations (in the range of 5 to 40 °C) were obtained for each mixture as follows:

$$CF_{23, MixA} = -0.0214T + 1.5368 \quad \text{[Equation 4.4]}$$

$$CF_{23, MixB} = -0.0243T + 1.6175 \quad \text{[Equation 4.5]}$$

$$CF_{23, MixC} = -0.0247T + 1.6290 \quad \text{[Equation 4.6]}$$

4.4 OUTDOOR EXPOSURE RESULTS

Three samples of each mixture were placed in exposed weathering conditions and subsequently RH and water absorption measurements were performed at five different temperature and moisture conditions. In order to compare the outdoor exposure test results with laboratory measurements, data should be calibrated to the laboratory condition temperature. Linear calibration formulas (Equations 4.3 to 4.5) were obtained for each mixture based on experimental data in Figure 4.6. The calibrated sorptivity results are shown in Figure 4.16. The outdoor measurements' average difference from predicted laboratory results at the same RH level is 8.9 % for mixture A, 11.8% for mixture B, and 5.6% for mixture C. The outdoor exposure measurement values show reasonable correlation with laboratory test results.

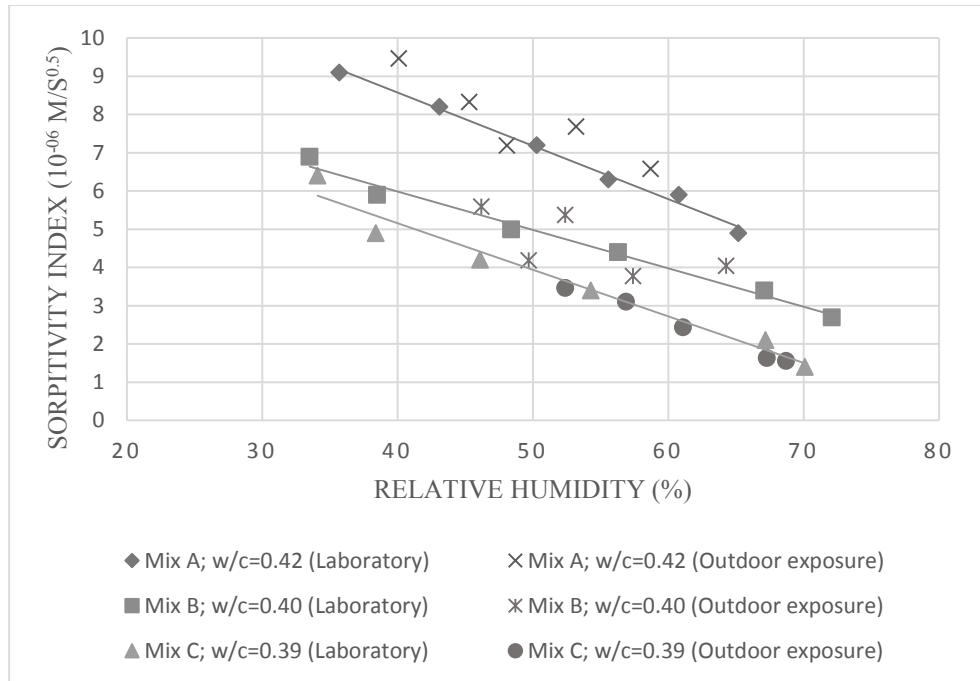


Figure 4.16 Dependence of sorptivity index on surface RH for laboratory and outdoor exposed samples, calibrated to laboratory condition temperature

Basheer and Nolan (2001) found significant differences between laboratory measurements and outdoor exposure tests (Figure 4.11) which can be partially explained by the finding that the laboratory specimens were found not to be fully hydrated whereas the outdoor exposed concrete could be considered as fully hydrated. In their experiments, laboratory specimens were approximately three months of age, while the outdoor tests were performed over a period of 18 months. In the current research, lab specimens and outdoor exposure specimens were at most a few months different in age. Another possible reason may be the effects of both the moisture hysteresis and RH gradients within the field concrete. However, in the outdoor tests performed in this research, no attempt was made for moisture equilibrium and a good correlation was still observed. Outdoor exposure results in this study show more reasonable correlation with laboratory results rather results obtained by

previous researchers. It is anticipated that if used for quality control purposes, water absorption testing would occur within a short time frame from casting (perhaps at 28 days).

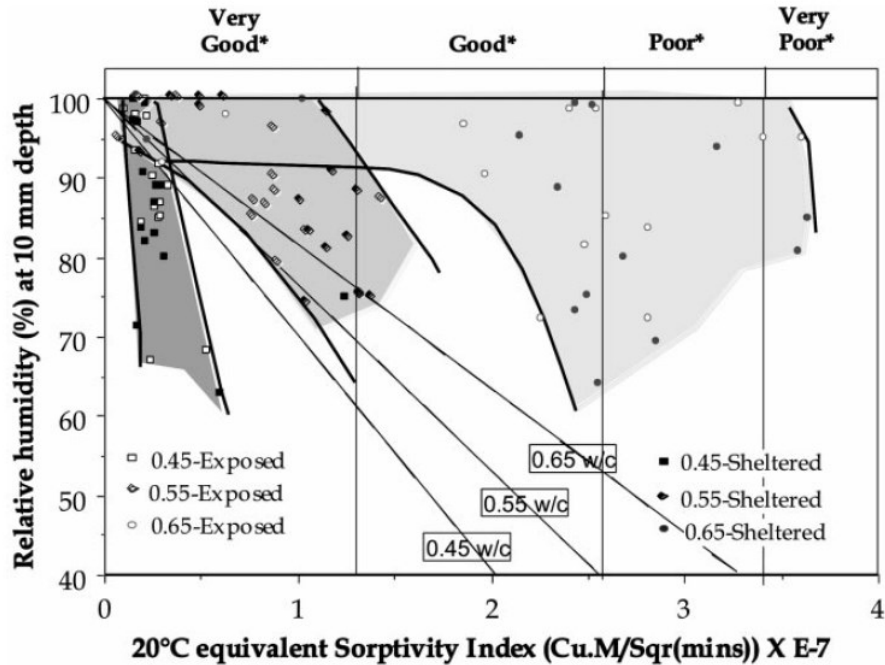


Figure 4.17 Dependence of sorptivity index on RH for laboratory and outdoor exposed measurements (Basheer and Nolan, 2001)

4.5 IN-SITU RESULTS

Three in-situ sorptivity, surface RH and temperature measurements were performed on the actual concrete walkway for project A. Figure 4.18 shows in-situ results compared with laboratory data points from mixture A. Sorptivity values for in-situ measurements are normalized to 23° C using Equation 4.3, obtained from laboratory results. In-situ normalized sorptivity values show an average of 5.8% difference from the laboratory trend line. In-situ results were obtained between 9 and 11 months after concrete casting.

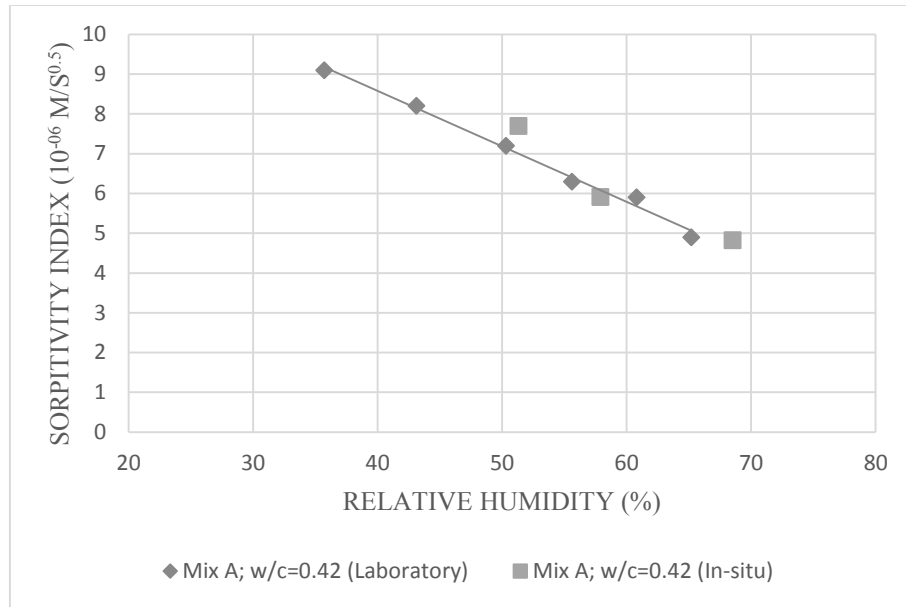


Figure 4.18 Dependence of sorptivity index on surface RH for laboratory and in-situ measurements, calibrated to laboratory condition temperature

Like laboratory and outdoor exposure measurements, in-situ sorptivity index is also increasing with decreasing in surface RH. Reasonable correlation between in-situ measurements and laboratory tests shows laboratory results may be transferable to in-situ measurements for calibration purposes. However, more in-situ tests are needed to verify this idea.

5 CONCLUSIONS AND RECOMENDATIONS

5.1 CONCLUSIONS

The objective of this research was to investigate the use of water absorption tests for quality control purposes for concrete durability. The rapid nature of the test combined with good correlations between sorptivity in laboratory-based tests with other durability methods makes it a good candidate as an in-situ NDT method. Previous research using the test in the field did not give good correlations, providing motivation for the current study. Conclusions based on the investigations presented in this thesis are presented as follows.

5.1.1 Investigation into the correlation of surface RH and moisture content`

Regarding test results presented in part 4.2.1, surface RH measurements show reasonable correlation with concrete saturation degree. It can be concluded that, surface RH measurement can be a reliable representation of concrete moisture content.

5.1.2 Investigation into the relationship between sorptivity and concrete moisture content

1. Laboratory measurements in this study show concrete sorptivity index is increasing linearly with decreasing saturation degree. Although this result was previously found by Desouza et al. (year) and Nokken and Hooton (2002) for laboratory methods (similar to ASTM C1585), the current research verifies the relationship for in-situ devices.

2. Laboratory, outdoor exposure and in-situ measurements verified that sorptivity index is increasing linearly with decreasing in concrete surface RH value. This result agrees with that of Nolan (1996) and Castro et al. (2011). The latter study used the laboratory method and measured the RH of the environment rather than of the sample.
3. Laboratory results show that although the preconditioning process for water absorption rate measurement proposed by ASTM C1585 leads to concrete specimens with 50 to 70% internal RH, this range of moisture content can result in significant misleading evaluations in concrete durability. It was previously shown by Castro et al. (2011) the sample's moisture history seriously affects the final concrete moisture content in this method. Therefore, the results obtained by this method are not directly comparable between concrete mixtures.

5.1.3 Investigation into the relationship between sorptivity and temperature

Test results show experimental measurements verify the theoretical trend for sorptivity calibration to laboratory temperature (23 °C) obtained from Hagen-Poiseuille equation as follows;

$$CF_{23} = 1.7037 - 0.0322T + 0.0002T^2 \quad \text{[Equation 5.1]}$$

However, a linear relationship was found to be adequate to develop the correction factor in this research. More data points are needed to come to a more accurate and reliable conclusion in this area.

5.1.4 Investigation into correlation between laboratory, outdoor exposure and in-situ measurements

Outdoor exposure and in-situ calibrated results show reasonable correlation with laboratory measurements. It can be concluded that laboratory results can be transferred to in-situ measurements to calibrate the sorptivity index to a standard value at a certain moisture content and temperature. Small deviations between outdoor exposure and in-situ results with laboratory measurements may be due to difference in concrete ages and uniformity of moisture distribution. However, more in-situ measurements are needed to come to final conclusion in this part. The correlation of the outdoor and in situ measurements with the laboratory results are in stark contrast to that of Basheer and (2001). The previous study found little relationship between sorptivity and relative humidity for field samples. As there is great interest in the development of NDT methods for quality control purposes, the relationship found in the current research give indication that in situ water absorption testing can be developed for this purpose.

5.2 RECOMMENDATIONS FOR IN-SITU SORPTIVITY MEASUREMENTS

For in-situ concrete durability evaluations using water sorptivity measurements, it is recommended to perform 3 or more tests in different environmental conditions. Concrete surface RH and temperature should be measured parallel to each sorptivity measurement. Each result should be first adjusted to a Standard temperature by the theoretical equation. Later, a Standard value of water absorption rate would be obtained from investigated trends found from the various tests. It is suggested that results be normalized to 23°C and 60% RH which would allow direct comparison with ASTM C1585. For quality control

purposes, ASTM C1585 testing could be carried out at the prequalification stage on the selected concrete mixture to be used in a project, followed by in-situ testing for specification performance.

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

1. More data points should be investigated regarding the dependence of sorptivity on temperature. It is suggested to investigate several temperatures between 5 and 50°C. In this manner, the appropriateness of the simpler linear correction factor can be assessed. It is further suggested that this effect be examined for a range of initial moisture contents.
2. More in-situ measurements should be performed on real in field concrete elements to verify the linear relationship between concrete sorptivity and surface RH value. A further suggestion is to investigate the influence testing orientation (horizontal, vertical and overhead) as moisture distribution within the concrete may be different in these cases.
3. Research should be performed to evaluate moisture uniformity in in field concrete elements in different environmental conditions. This can be accomplished by drilling holes into the concrete and measuring humidity as in the Figg method.
4. Efforts should be taken to find a quicker approach for using the water absorption test in the field. Perhaps, two or three insitu measurements are sufficient to develop the relationship with a Standard method, such as ASTM C1585. From this, a study on the in-situ water absorption on several types of concrete mixture designs should

be undertaken on 3 separate occasions to assess the appropriateness of using only the in-situ method without any Standardized testing or laboratory calibration steps.

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APPENDIX A

This appendix presents individual results from the water absorption measurements carried out in this research. The measurements with the ‘strikeout’ indicate large variation from the other results and are not included in the determination of the average. In some cases, results were discarded as water leaked through the gasket of the GWT device.

Table 0.1 Project A; Laboratory test results for moisture variation

| Drying days | Replicates | Saturation degree (%) | Surface RH (%) | Sorptivity ($10^{-06} \text{ m/S}^{0.5}$) |
|-------------|----------------|-----------------------|----------------|---|
| 2 | 1 | 77.8 | 63.3 | 5.0 |
| | 2 | 78.8 | 64.9 | 4.9 |
| | 3 | 79.2 | 67.4 | 4.7 |
| | Average | 78.6 | 65.2 | 4.9 |
| 3 | 1 | 75.8 | 61.4 | 5.8 |
| | 2 | 72.9 | 58.3 | 6.1 |
| | 3 | 76.0 | 62.7 | 5.8 |
| | Average | 74.9 | 60.8 | 5.9 |
| 5 | 1 | 73.5 | 56.9 | 5.6 |
| | 2 | 72.2 | 55.8 | 6.7 |
| | 3 | 71.6 | 54.1 | 6.7 |
| | Average | 72.4 | 55.6 | 6.3 |
| 7 | 1 | 68.8 | 48.7 | 7.1 |
| | 2 | 71.1 | 49.6 | 7.1 |
| | 3 | 70.6 | 52.6 | 7.5 |
| | Average | 70.2 | 50.3 | 7.2 |
| 10 | 1 | 70.2 | 43.5 | 8.3 |
| | 2 | 53.9 | 44.2 | 8.3 |
| | 3 | 83.1 | 41.6 | 8.0 |
| | Average | 69.1 | 43.1 | 8.2 |
| 14 | 1 | 61.5 | 35.6 | 9.2 |
| | 2 | 63.2 | 36.1 | 9.0 |
| | 3 | 61.9 | 35.4 | 9.1 |
| | Average | 62.2 | 35.7 | 9.1 |

Table 0.2 Project B; Laboratory test results for moisture variation

| Drying days | Replicates | Saturation degree (%) | Surface RH (%) | Sorptivity ($10^{-06} \text{ m/S}^{0.5}$) |
|-------------|----------------|-----------------------|----------------|---|
| 2 | 1 | 85.1 | 73.2 | 2.5 |
| | 2 | 83.6 | 71.4 | 2.9 |
| | 3 | 84.2 | 71.7 | 2.6 |
| | Average | 84.3 | 72.1 | 2.7 |
| 3 | 1 | 82.3 | 67.3 | 3.4 |
| | 2 | - | - | - |
| | 3 | 80.4 | 66.8 | 3.3 |
| | Average | 81.4 | 67.1 | 3.4 |
| 5 | 1 | 77.3 | 60.1 | 4.5 |
| | 2 | 80.1 | 58.0 | 4.2 |
| | 3 | 75.9 | 50.9 | 4.5 |
| | Average | 77.8 | 56.3 | 4.4 |
| 7 | 1 | 72.1 | 45.5 | 5.1 |
| | 2 | 71.4 | 52.9 | 5.0 |
| | 3 | 77.0 | 46.7 | 5.0 |
| | Average | 73.5 | 48.4 | 5.0 |
| 10 | 1 | 68.4 | 39.0 | 6.1 |
| | 2 | 67.5 | 35.7 | 5.9 |
| | 3 | 68.9 | 40.7 | 5.8 |
| | Average | 68.2 | 38.5 | 5.9 |
| 14 | 1 | 67.3 | 34.6 | 7.0 |
| | 2 | 67.8 | 33.0 | 6.5 |
| | 3 | 66.7 | 33.0 | 7.2 |
| | Average | 67.3 | 33.5 | 6.9 |

Table 0.3 Project C; Laboratory test results for moisture variation

| Drying days | Replicates | Saturation degree (%) | Surface RH (%) | Sorptivity (10^{-06} m/S^{0.5}) |
|--------------------|-------------------|------------------------------|-----------------------|---|
| 2 | 1 | - | - | - |
| | 2 | 87.5 | 71.4 | 1.3 |
| | 3 | 86.3 | 68.8 | 1.5 |
| | Average | 86.9 | 70.1 | 1.4 |
| 3 | 1 | 85.2 | 66.5 | 1.9 |
| | 2 | 84.6 | 67.9 | 2.2 |
| | 3 | 81.9 | 67.2 | 2.2 |
| | Average | 83.9 | 67.2 | 2.1 |
| 5 | 1 | 78.5 | 56.2 | 3.6 |
| | 2 | 79.1 | 55.2 | 3.1 |
| | 3 | 75.5 | 51.5 | 3.5 |
| | Average | 77.7 | 54.3 | 3.4 |
| 7 | 1 | 76.1 | 47.6 | 4.5 |
| | 2 | 74.1 | 45.1 | 3.8 |
| | 3 | 74.8 | 45.6 | 4.2 |
| | Average | 75.0 | 46.1 | 4.2 |
| 10 | 1 | 72.3 | 40.1 | 5.1 |
| | 2 | 68.4 | 36.9 | 4.7 |
| | 3 | 71.1 | 38.2 | 4.9 |
| | Average | 70.6 | 38.4 | 4.9 |
| 14 | 1 | 66.2 | 35.7 | 6.5 |
| | 2 | 70.4 | 32.5 | 6.3 |
| | 3 | - | - | - |
| | Average | 68.3 | 34.1 | 6.4 |

Table 0.4 Project A; Laboratory test results for temperature variation

| Drying days | Replicates | Initial temperature (°C) | Final temperature (°C) | Saturation degree (%) | Sorptivity (10 ⁻⁰⁶ m/S ^{0.5}) |
|-------------|----------------|--------------------------|------------------------|-----------------------|--|
| 7 | 1 | 5.1 | 9.3 | 71.5 | 4.4 |
| | 2 | 4.8 | 9.5 | 72.2 | 4.6 |
| | 3 | 5.2 | 9.8 | 70.6 | 4.3 |
| | Average | 7.3 | | 71.4 | 4.4 |
| 7 | 1 | 22.6 | 22.6 | 68.8 | 7.1 |
| | 2 | 22.3 | 22.3 | 71.1 | 7.1 |
| | 3 | 22.8 | 22.8 | 70.6 | 7.5 |
| | Average | 22.6 | | 70.2 | 7.2 |
| 7 | 1 | 42.6 | 39.2 | 71.5 | 9.6 |
| | 2 | 41.6 | 38.4 | 69.8 | 9.9 |
| | 3 | 41.3 | 38.3 | 69.1 | 8.5 |
| | Average | 40.2 | | 70.2 | 9.3 |

Table 0.5 Project B; Laboratory test results for temperature variation

| Drying days | Replicates | Initial temperature (°C) | Final temperature (°C) | Saturation degree (%) | Sorptivity (10 ⁻⁰⁶ m/S ^{0.5}) |
|-------------|----------------|--------------------------|------------------------|-----------------------|--|
| 7 | 1 | 5.6 | 9.8 | 74.5 | 2.8 |
| | 2 | 5.3 | 9.6 | 73.8 | 3.0 |
| | 3 | 5.8 | 10.2 | 76.0 | 3.1 |
| | Average | 7.7 | | 74.8 | 3.0 |
| 7 | 1 | 22.5 | 22.5 | 72.1 | 5.1 |
| | 2 | 22.6 | 22.6 | 71.4 | 5.0 |
| | 3 | 22.6 | 22.6 | 77.0 | 5.0 |
| | Average | 22.6 | | 73.5 | 5.0 |
| 7 | 1 | 42.1 | 40.1 | 75.5 | 7.1 |
| | 2 | 44.6 | 39.0 | 73.8 | 7.1 |
| | 3 | 43.9 | 39.7 | 73.1 | 6.7 |
| | Average | 41.6 | | 74.2 | 7.0 |

Table 0.6 Project C; Laboratory test results for temperature variation

| Drying days | Replicates | Initial temperature (°C) | Final temperature (°C) | Saturation degree (%) | Sorptivity (10 ⁻⁰⁶ m/S ^{0.5}) |
|-------------|----------------|--------------------------|------------------------|-----------------------|--|
| 7 | 1 | 4.8 | 9.6 | 77.5 | 2.8 |
| | 2 | 4.7 | 9.4 | 75.7 | 2.6 |
| | 3 | 5.1 | 9.8 | 76.0 | 2.4 |
| | Average | 7.2 | | 76.4 | 2.6 |
| 7 | 1 | 22.6 | 22.6 | 76.1 | 4.5 |
| | 2 | 22.9 | 22.9 | 74.1 | 3.8 |
| | 3 | 22.8 | 22.8 | 74.8 | 4.2 |
| | Average | 22.8 | | 75.0 | 4.2 |
| 7 | 1 | - | - | - | - |
| | 2 | 41.5 | 38.3 | 73.7 | 6.1 |
| | 3 | 39.8 | 37.1 | 74.6 | 5.7 |
| | Average | 39.2 | | 74.2 | 5.9 |

Table 0.7 Project A; Outdoor exposure test results

| Test number | Replicates | Temperature (°C) | Surface RH (%) | Sorptivity (10^{-06} m/S ^{0.5}) |
|-------------|----------------|------------------|----------------|--|
| 1 | 1 | 17.9 | 46.4 | 6.7 |
| | 2 | 17.9 | 49.2 | 6.5 |
| | 3 | 18.0 | 48.7 | 6.1 |
| | Average | 17.9 | 48.1 | 6.4 |
| 2 | 1 | 27.6 | 59.6 | 10.5 |
| | 2 | 27.6 | 59.1 | 10.5 |
| | 3 | 27.6 | 57.4 | 10.3 |
| | Average | 27.6 | 58.7 | 10.4 |
| 3 | 1 | 28.7 | 37.7 | 7.7 |
| | 2 | 28.8 | 41.2 | 7.5 |
| | 3 | 28.8 | 41.4 | 7.1 |
| | Average | 28.8 | 40.1 | 7.4 |
| 4 | 1 | 33.3 | 54.9 | 9.0 |
| | 2 | 33.3 | 54.6 | 9.7 |
| | 3 | 33.6 | 50.1 | 9.6 |
| | Average | 33.4 | 53.2 | 9.4 |
| 5 | 1 | 30.1 | 46.4 | 9.2 |
| | 2 | 30.3 | 45.9 | 9.7 |
| | 3 | 30.0 | 43.6 | 9.9 |
| | Average | 30.1 | 45.3 | 9.6 |

Table 0.8 Project B; Outdoor exposure test results

| Test number | Replicates | Temperature (°C) | Surface RH (%) | Sorptivity (10^{-06} m/S ^{0.5}) |
|-------------|----------------|------------------|----------------|--|
| 1 | 1 | 17.9 | 54.2 | 4.8 |
| | 2 | 17.8 | 51.7 | 4.8 |
| | 3 | 17.8 | 51.3 | 4.5 |
| | Average | 17.8 | 52.4 | 4.7 |
| 2 | 1 | 27.5 | 47.4 | 6.1 |
| | 2 | 27.4 | 44.8 | 6.1 |
| | 3 | 27.6 | 46.4 | 6.5 |
| | Average | 27.5 | 46.2 | 6.2 |
| 3 | 1 | 34.9 | 66.3 | 5.3 |
| | 2 | 34.7 | 64.8 | 5.4 |
| | 3 | 34.8 | 61.8 | 4.9 |
| | Average | 34.8 | 64.3 | 5.2 |
| 4 | 1 | 37.6 | 58.5 | 5.4 |
| | 2 | 37.5 | 57.1 | 5.0 |
| | 3 | 37.5 | 56.6 | 4.8 |
| | Average | 37.5 | 57.4 | 5.1 |
| 5 | 1 | 30.2 | 49.9 | 4.9 |
| | 2 | 30 | 52.4 | 5.1 |
| | 3 | 30.1 | 46.8 | 4.6 |
| | Average | 30.1 | 49.7 | 4.9 |

Table 0.9 Project C; Outdoor exposure test results

| Test number | Replicates | Temperature (°C) | Surface RH (%) | Sorptivity (10 ⁻⁰⁶ m/S ^{0.5}) |
|-------------|----------------|------------------|----------------|--|
| 1 | 1 | 24.3 | 55.3 | 3.4 |
| | 2 | 24.5 | 58.2 | 3.3 |
| | 3 | 23.8 | 57.1 | 2.9 |
| | Average | 24.2 | 56.9 | 3.2 |
| 2 | 1 | 20.1 | 61.8 | 2.1 |
| | 2 | 20.7 | 59.2 | 2.2 |
| | 3 | 21.4 | 62.4 | 2.5 |
| | Average | 20.7 | 61.1 | 2.3 |
| 3 | 1 | 17.2 | 67.5 | 1.4 |
| | 2 | 17.6 | 65.9 | 1.3 |
| | 3 | 16.4 | 68.3 | 1.4 |
| | Average | 17.1 | 67.2 | 1.4 |
| 4 | 1 | 26.2 | 51.2 | 3.7 |
| | 2 | 25.1 | 53.4 | 3.6 |
| | 3 | 25.8 | 52.6 | 3.8 |
| | Average | 25.7 | 52.4 | 3.7 |
| 5 | 1 | 24.3 | 68.2 | 1.5 |
| | 2 | 23.2 | 67.4 | 1.6 |
| | 3 | 24.5 | 70.5 | 1.6 |
| | Average | 24.0 | 68.7 | 1.6 |

Table 0.10 Project A; In-situ test results

| Test number | Temperature (°C) | RH (%) | Sorptivity (10 ⁻⁰⁶ m/S ^{0.5}) |
|-------------|------------------|--------|--|
| 1 | 25.4 | 51.3 | 8.1 |
| 2 | 21.3 | 57.9 | 5.7 |
| 3 | 18.9 | 68.5 | 4.4 |

Table 0.11 Test results for ASTM C1585 sorptivity index

| Mixture | Replicates | Sorptivity (10⁻⁰⁶ m/S^{0.5}) |
|----------------|-------------------|--|
| A | 1 | 5.6 |
| | 2 | 5.4 |
| | 3 | 5.7 |
| | Average | 5.6 |
| B | 1 | 4.1 |
| | 2 | 4.4 |
| | 3 | 4.4 |
| | Average | 4.3 |
| C | 1 | 3.8 |
| | 2 | 3.5 |
| | 3 | 3.9 |
| | Average | 3.7 |