Doctoral Dissertation
博士論文

Proposal of Threshold Value of Moisture Content of Concrete For Appropriate Measurement of Surface Water Absorption Test

「表面吸水試験の適切な計測のためのコンクリートの含水率の閾値の提案」

By

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Contents

ABSTRACT

Cover concrete plays an essential role in enhancing the concrete durability. It is like a first barrier to prevent the ingress of aggressive substances into concrete causing deterioration in terms of corrosion of steel reinforcement which results in spalling of covercrete. Therefore, it is important to ensure the covercrete with good quality and high surface absorption resistance. In this context, the evaluation of the resistance of cover concrete against the permeation of deleterious substances from the subjected environment is indispensable.

There are several methods to estimate the surface absorption of covercrete. Surface Water Absorption Test (SWAT) and double chamber air permeability test are fully non-destructive tests of covercrete which can evaluate the surface absorption resistance of concrete in real structures with short measurement duration. However, moisture content in covercrete of real structures changes when weather changes affecting water absorption and air permeability of concrete. Furthermore, it needs to define the rational threshold values of moisture content to apply for surface water absorption test (SWAT) and double chamber air permeability test (Torrent). Moreover, when concrete is stored in wet condition for long duration, the inner moisture profile becomes complex. In this case, it is not sufficient to evaluate the water absorption resistance of covercrete in 10 minutes. Therefore, define the rational threshold values of HI-100 for SWAT is important to investigate. In addition, the effect of rehydration of concrete stored in humid condition for long duration on the absorption of covercrete was investigated in the present study.

First, the present research deals with the investigation of the effects of moisture profiles of covercrete on the surface absorption quality of concrete. In order to investigate the effects of moisture contents on surface absorption of concrete, several moisture profiles were created similar to the real conditions of outdoor structures. Three kinds of water to cement ratios of concrete specimens with three curing conditions were adopted. The specimens were stored in three types of relative humidity in order to create different moisture profiles in concrete. It was observed that concrete with different moisture contents, water absorption and air permeability results are apparently smaller when measured values of moisture content by some

moisture meters, such as the AC impedance method (CMEX-II) and handy high-frequency moisture meter (HI-520-2) are greater than the threshold values. When, moisture content measured by the AC impedance method is higher than 6.0%, water absorption and air permeability results become unreliable. Similarly, when moisture content measured by handy high-frequency moisture meter is higher than 5.0% and 5.5%, water absorption and air permeability results are unreliable, respectively.

Second, to investigate the effects of inner moisture content on water absorption and air permeability of concrete, the moisture content of concrete in 5mm, 10mm, 20mm, 30mm and 50mm depth were detected by electric resistance sensors embedded inside the specimens. The specimens were divided into two series such as Series-1 and Series-2 following two different processes to create several types of moisture profiles. The Series-1 is cured about 60 days in curing room then moved to high relative humidity condition for one or two days before conducting SWAT and double chamber air permeability test. The Series-2 is cured around 90 days in curing room. Then, they were stored in a high relative humidity room for 7 days and returned to curing room again. SWAT and double chamber air permeability test were conducted after 3 days, 7 days, and 14 days in curing room. In each process, moisture contents were measured at surface and inside of specimens by moisture meters. It has been revealed that moisture contents in 5mm depth detected by count values of HI-800 through sensors affects the results of SWAT and air permeability, while moisture contents measured by moisture meters cannot detect the moisture contents inside the concrete. The rehydration of concrete due to prolonged storing in high R.H. was also simulated. The result showed that concrete with good curing conditions, there is no rehydration occurred after prolonged curing in high R.H. Alternatively, in poor curing conditions, the rehydration occurs when stored in high R.H for a long time. However, since the rehydration is not considerable, it does not effect on the surface absorption of concrete.

When moisture content measured by moisture meters at surface is low and count values measured by HI-800 through sensors in concrete are high, and p_{600} values are low also. This means moisture contents in the inner concrete might be high since p_{600} is low, but moisture meters such as CMEX-II and HI-520-2 could not detect those moisture contents of inner concrete. Therefore, in third phase of research, HI-100 was used to measure moisture contents of specimens. Different specimens with several moisture profiles were created. Moisture contents were measured by HI-100 at surfaces of specimens. Inner moistures of specimens were detected by HI-800 through sensors embedded at 5mm, 10mm, 20mm, 30mm, and 50mm from surface of specimens. SWAT was conducted after long time curing in curing room when surface of specimens were dry. After that, they were stored in high R.H. room until count values related to moisture content of sensor at 5mm depth was stable. They were moved back to curing room for drying for 2 to 5 days. Some specimens showed the same original count values measured by HI-100 before conducting SWAT. It was found that when HI-100 values are higher than 190, p_{600} was apparently small. Therefore, it is revealed that SWAT can be utilized to evaluate water absorption resistance of concrete when count value in concrete measured by HI-100 is lower than 190.

Moreover, a new index to evaluate water absorption resistance of covercrete in case of concrete is dried for some days after keeping in a humid condition for a long time is proposed. It is considered as slope of cumulative water absorption with respect to time square root exhibiting linear behavior. It is called water absorption coefficient which may reduce the measurement time for SWAT and can evaluate quality of covercrete reliably.

Several conclusions have been derived from the present investigation. In dry to wet process, CMEX-II, HI-520-2 can be used to detect moisture content for SWAT when moisture contents are lower than 6.0%, and 5.0% respectively. When using CMEX-II and HI-520-2 to measure moisture contents for double chamber air permeability test, threshold values of moisture contents should be lower 6.0% and 5.5%, respectively. CMEX-II and HI-520-2 cannot be used to measure moisture content before measuring SWAT and double chamber air permeability test in wet to dry process. HI-100 can be utilized to detect moisture content for SWAT when count values are lower than 190. Count values measured by HI-800 may be useful to evaluate drying condition of covercrete in case of laboratory investigations only. A new index called water absorption coefficient which may reduce the measurement time for SWAT and can evaluate quality of covercrete reliably is proposed.

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Chapter 1

INTRODUCTION

1.1 Backgrounds

Long service life is an important issue for sustainability of construction materials. Concrete, as known to be the most widely used material in construction industry, its durability is as important as its mechanical properties are. The durability of RC structures depends on the easy movement of both liquids and gases into the concrete. Since durability of RC structures cannot be measured directly, it is, however, measured in terms of permeability by determining the resistance against penetration of various harmful substances into the concrete. Three mechanisms such as permeability, diffusion and sorption are responsible for the movement of the fluids (gases and liquids) into the concrete. Permeability is the flow under pressure, while diffusion is the flow taking place due to the difference in concentration and the sorption phenomenon is also a process of diffusion in which main mechanism is capillary suction. The covercrete of RC structures is the first barrier that comes in contact with the aggressive substances. Hence, the quality of covercrete must be evaluated with respect to permeability for rating of durability of the structures.

(a) (b)

Fig.1.1 Durability problems: (a) Spalling of covercrete; (b) Corrosion of Reinforcement [1.1]

Japan is an island country possessing long coast lines and located in cold weather area where most of the structures are exposed to the marine and freezing environment in severely aggressive condition. Because of the aggressive environment, the main problem regarding durability is chloride induced reinforcement corrosion.

Diffusion is considered as one of the main mechanisms of transportation of chloride ions into covercrete. Water ingress into the concrete accelerates the process of transportation. Therefore, preventing and restricting water movement into concrete are essential.

Further, covercrete may have poor resistance against the permeation of aggressive substances, chemical, abrasion and frost action due to several factors such as poor curing, segregation, inadequate compaction, bleeding, micro-cracking etc. Poor quality causes deterioration of concrete in terms of reinforcement corrosion that may result in spalling of covercrete, cracking in concrete due to corrosion (Fig.1.1), alkali silica reaction (ASR) and freeze-thaw action. Therefore, durability of concrete structures must be verified to ensure the long service life. The penetration resistance of existing damaged concrete structures in aggressive environment must be investigated to propose appropriate repair techniques.

In Japan, surface water absorption test (SWAT) and air permeability test are popular for evaluating covercrete quality. SWAT and double chamber air permeability test are non-destructive methods used to determine surface absorption resistance of covercrete. However, a noticeable drawback of using SWAT and double chamber air permeability test in surface absorption measurement is that surface absorption results of covercrete changes when moisture content into concrete changes, which causes overestimate surface absorption resistance of concrete.

1.2 Objectives of the Research

Surface water absorption test by SWAT and air permeability test by double chamber air permeability need to be investigated for appropriate measurement with respect to the threshold value of moisture content. In this context, objectives of the present research are:

1) To investigate the effects of different moisture profiles of covercrete on the resistance of water absorption and air permeability of concrete
2) To propose an appropriate moisture meter (HI-100) to check whether covercrete is sufficiently dry or not for SWAT measurement
3) To propose a threshold value of moisture content when conducting SWAT and double chamber air permeability measurement
4) To confirm the appropriate measurement time for SWAT

5) To propose a new index for evaluation of covercrete quality using SWAT.

1.3 Significances of the Research

In most of the deterioration processes of concrete structures, water is considered as the driving force for aggressive substances into the concrete. Therefore, surface absorption resistance is a durability indicator to evaluate the quality of covercrete. Water head in SWAT (the non-destructive simple, rapid and variable water head Test developed by Hayashi and Hosoda) [1.2] induces almost the same pressure as that of the driving pressure of rain and wind representing the actual phenomenon. The time to complete a measuring location for water absorption by SWAT and air permeability by double chamber air permeability test is short (only from 1 to 10 minutes). It is observed in some previous researches that at the same relative humidity, degree of saturation in coverconcrete of dry to wet and wet to dry process is different [1.3]. It can be imaged that SWAT results at 600 seconds (10 minutes) are also different for dry to wet and wet to dry process at the same concrete. To conduct SWAT in all conditions at the site and at the laboratory, it is necessary to propose a threshold moisture content assuring the accurate results for SWAT. In this context, the present study needs -

1) To choose the moisture meters that are sufficient for measuring moisture content in concrete before conducting SWAT and double chamber air permeability test
2) To propose a new index to evaluate water absorption resistance of covercrete
3) To recommend the appropriated duration for conducting SWAT in case concrete is dried some days after long time wetting.

1.4 Dissertation Arrangement

The complete research study has 6 chapters.

Chapter 1 ‘Introduction’ provides general details about water absorption and air permeability which mainly cause deterioration of concrete structures. The overall idea of the research is provided with objectives, and significances.

Chapter 2 ‘Literature Reviews’ reviews knowledges relating to the water absorption and air permeability test, characteristics of microstructure, moisture content, transport mechanisms of fluid into the concrete, the current problems affected to SWAT results will be shown in chapter 2.

Chapter 3, “Development of Surface Water Absorption Test (SWAT) Method to Evaluate the Quality of Covercrete” describes the development of SWAT. Test device details, setup details, test procedure, the method to analyze the test data, mechanism of water absorption, comparison of SWAT and Initial surface water absorption test (ISAT) are described in the first part of Chapter 3. Development of test procedure, calibration method and advantages of auto measure SWAT system are also described. Further, the significance of the starting and ending time of the test is included. Finally, the chapter compares the design and results of the old and new SWAT framework.

Chapter 4, “The Effects of Moisture Content on Water Absorption Test and Air Permeability Test”, the rational thresholds of moisture meters are defined to apply them to detect moisture content of covercrete before conducting SWAT and double chamber air permeability test. Moreover, a part of this chapter represents the effect of curing condition and water to cement ratios on water absorption and air permeability results. Also, Chapter 3 includes a new method of evaluating the quality of concrete by SWAT.

Chapter 5, “Effects of Long-term Wetting on Moisture profile of Covercrete and on Surface Water Absorption Test” explain the intensive laboratory investigations regarding varieties of moisture distribution for both wetting and drying process of concrete in order to know the possible practical uses of SWAT. This chapter explains how inner moisture of covercrete affects on water absorption and air permeability test through measuring the count values of sensors embedded into concrete. Moreover, the effect of long-term storing of concrete in humid condition on rehydration of concrete is simulated by DuCOM software.

Chapter 6, “Proposal of Threshold Value of Moisture Content by an Appropriate Moisture Meter and A New Index to Evaluate Water Absorption Resistance”, the threshold value of moisture content measured by moisture meter HI-100 is identified to detect moisture content of covercrete before conducting SWAT. Furthermore, a new SWAT index called water absorption coefficient to evaluate water absorption resistance instead of p_{600} and appropriate measurement time of SWAT was also proposed in this chapter.

Chapter 7, “Conclusions and Recommendations”, abstracts the significant findings and conclusions. Essential recommendations for further works are also shown in this chapter.

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Chapter 2

LITERATURE REVIEWS

2.1 Introduction

This chapter is based on the knowledge obtained from numerous investigations conducted in the past. Thus, a concise view of durability of concrete, transportation of liquid into concrete and methods of absorption and durability measurement are incorporated in the present chapter.

2.2 Objectives

The objective of Chapter 2 is to illustrate water absorption and air permeability test techniques for covercrete utilized previously and identify the disadvantages of those methods to utilize in real environmental conditions of concrete structures.

2.3 Durability of Concrete

The capacity of concrete to resist weathering activities, chemical attack, and abrasion while keeping up its ideal designing properties is defined as the durability of concrete [2.1], [2.2]. Distinctive concretes require diverse degrees of toughness dependent on the environmental conditions and properties desired. For instance, concrete presented to extreme conditions will have unexpected prerequisites in comparison to an indoor concrete floor. Moreover, the durability relied upon concrete ingredients, their proportioning, interactions between them, placing and curing practices, and the service environment. Several investigations have revealed that the permeability of concrete both concerning air and water is an excellent indicator for the resistance of concrete against the ingress of aggressive media in the gaseous or in the liquid state and in this manner, it is a strategy for the potential strength of a specific concrete [2.3].

2.4 Significance of Covercrete in Durability

As defined before "The durability of concrete is the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties" [2.1], [2.2]. Covercrete is the minimal distance between the surface of embedded reinforcement and the outer surface of the concrete (ACI 130). The role of covercrete is the first barrier against the entrance of aggressive substances like chloride particles, carbon dioxide, chemicals, frost attack or abrasion (Fig.2.1). Covercrete normally has a different composition, microstructure, and properties as compared with the core concrete, its vital role in the durability performance recently been recognized [2.4-2.7].

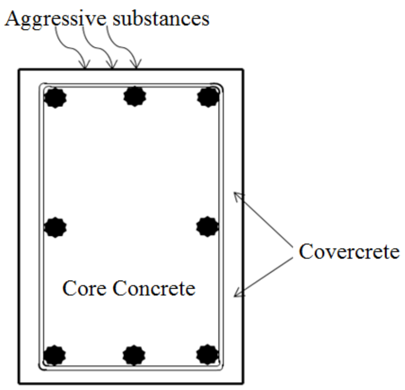

Fig.2.1 Penetration of aggressive substances through covercrete

Primary causes for the distinction between core and covercrete include segregation, improper placement of concrete, inadequate compaction, type of finishing and most importantly due to poor curing condition. Presence of micro-cracks also increases vulnerability towards the deterioration of covercrete. The durability of covercrete depends upon some factors such as segregation, bleeding, compaction, curing, finishing, micro-cracking etc. [2.8].

2.5 Fluid Transport Mechanisms in Concrete

Fluids such as pure water, aggressive ions, carbon dioxide and oxygen which can enter concrete principally relevant to durability of concrete [2.1]. The movement of these fluids through concrete takes place not only by flow through the porous system but also by diffusion and sorption. Hence, it is essential to differentiate the transport mechanisms by which the fluids penetrate in concrete. Transport mechanisms include diffusion, permeation, sorption /capillary suction etc. The difference between these mechanisms depends on the driving forces for the transport as explained below:

1) Diffusion: diffusion is the process in which a fluid moves under a differential in concentration. The ingress of ions into concrete is treated in general as a diffusion process.

2) Permeation: liquids and gases can percolate through interconnected pore spaces or crack networks of cementitious materials under the driving force of an absolute pressure gradient
3) Sorption: there is no even external absolute pressure. Porous media such as concrete can take up liquids by capillary forces. Surface forces of the liquids and solids are responsible for this action which leads to wetting of the internal solid surface in the capillary pores.

2.6 Test Methods to Measure Water Absorption and Air Permeability Resistance of Concrete

In this section, a brief introduction to the tests methods that are currently being used to measure the permeation resistance of concretes will be explained. Each test method works on a certain principle, however, all the tests face problem due to specific properties of concrete, such as:

1) Aging of concrete due to on-going hydration.
2) Reactivity of concrete with penetrating substances studied, for instance, water, carbon dioxide, chloride ions etc.
3) Variability of concrete properties with the moisture content of concrete.
4) Sensitivity of concrete pore structure to preconditioning, e.g. micro cracking upon drying.
5) Pore water composition, its effect on, and interaction with, transport processes.

2.6.1 Tests Depend on Water Permeability

There are many test methods of water absorption or air permeability for covercrete developed in the past. Some methods are surface tests which are non-destructive methods. Others are carried out in the concrete by drilling hole or slitting the specimens. Merits and demerits of these test methods are highlighted as follows:

1) Initial surface water absorption test (ISAT):

BS 8110 [2.9] describes a non-destructive test method to measure the initial surface water absorption. Actually, it measures the water absorption rate by the covercrete in a certain period under a constant water head of 200 mm. the rate of initial surface absorption is normally reported in units of ml/m^2/sec. This test method is discussed separately in detail in section 2.8.

2) Autoclam water permeability test:

In early 1980s Clam test method was introduced for the first time [2.10]. At that time it was only applicable to measure the water absorption. Later in the early 1990s, it was modified to become fully automatic test by Basheer [2.11]. The Autoclam can be used to measure the air and water permeability and the water absorption (sorptivity) of concrete and other porous materials, for both in the laboratory and on site. When the equipment works, the rate of decay of air pressure is recorded for the air permeability test, whereas the volume of water penetrating into the concrete, at a constant pressure of 0.02 bar and 0.5 bar are recorded for the sorptivity and the water permeability tests, respectively. These tests are essentially non-destructive in nature and it does not need a skilled operator, therefore, it can be carried out quickly and effectively on site without prior planning. The Autoclam is supplied in a portable carrying case, and it consists of two parts, the Autoclam body, and its electronic controller and data recording system.

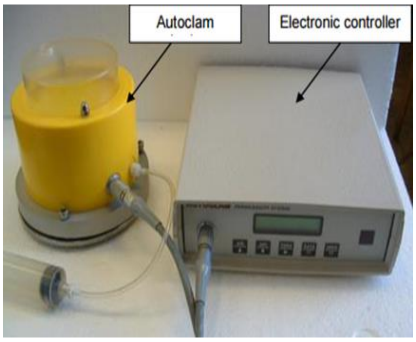

Fig.2.2a Autoclam permeability system

Fig.2.2b Bonding type ring

Fig.2.2c Bolt on type ring

The Autoclam body [2.12] comprises of base ring and base unit. Base ring can isolate a test area of 50mm diameter (Fig.2.2b) bonded to the test surface. Additional rings can be ordered separately and are available with a variety of test areas. Special bases (Fig.2.2c) for clamping to the test area rather than using adhesive are available. Inside the protective (yellow) cover the base unit accommodates an electronically controlled priming system.

The electronic control box contains all the custom designed electronic control and recording hardware. On the front panel (Fig.2.3), there is a back-lit digital liquid crystal display screen, test selection keys, a reset key, and a twelve pin circular socket to connect to the Autoclam base unit.

Fig.2.3 Front panel of the control box

The control box houses an internal battery to permit the use of the instrument on site without needing any external electrical facility. Also supplied with the kit is a DC power supply unit to permit extended site use and to charge the internal battery. The rear panel of the unit contains a standard RS 232 serial port computer connection and a two pin circular connector to connect a 12 to 24 volt DC supply or the mains power/charging unit and a power switch.

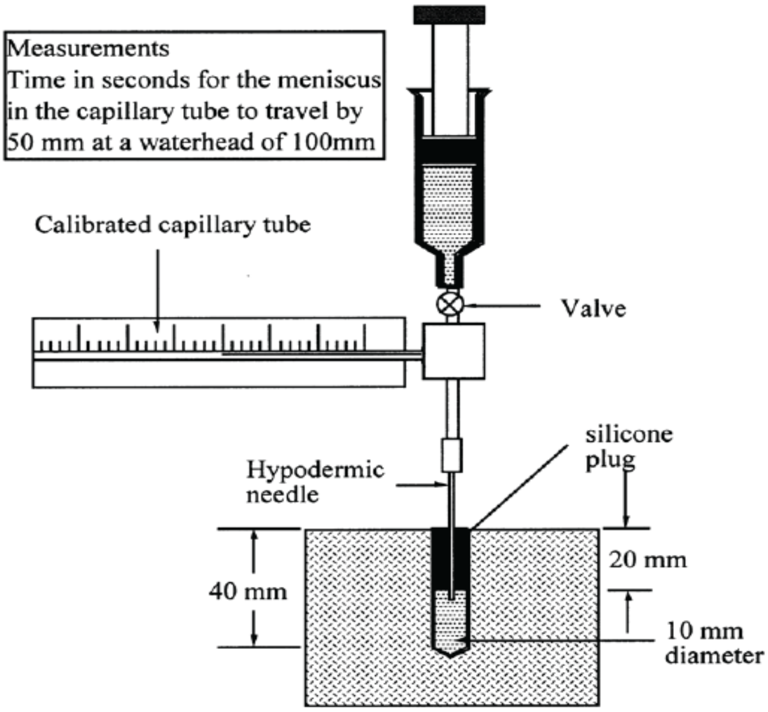

Fig.2.4 Schematic diagram of Figg water absorption test [2.14]

3) Figg water-absorption test:

Another test method for both air permeability and water absorption of covercrete is a destructive method. It was developed by J.W. Figg [2.13]. This test is also known as drilled holes test. A small hole is drilled and sealed with silicone rubber. Then a hypodermic needle is inserted in this hole through the seal (Fig.2.4). The needle is connected to a calibrated capillary tube. The hole and the capillary tube are filled with water using the syringe. The test is carried out under a water head of approximately 100 mm. The time is taken for the meniscus in the capillary tube to move 50 mm is taken as a measure of the water absorption of the concrete. This value obtained is called the absorption index and is measured in seconds. The main disadvantage of this test is the possible generation of micro-cracks in the surrounding concrete during drilling. This may not represent the actual quality of covercrete. Furthermore, it cannot be used to differentiate the effect of different surface treatments and the effect of permeable formwork.

4) The field permeability test (FPT):

A test method developed by Meletiou, Tia and Bloomquist [2.14], at the University of Florida, USA, was called the field permeability test (FPT). In order to measure water absorption, first a hole of 23 mm in diameter and 152 mm deep is drilled into the concrete as shown in Fig.2.5. Then a probe is inserted in the hole and tightened by a nut to seal off the central chamber with the help of expanding neoprene packers. Before inserting water a vacuum is applied for 5 to 10 min. Water is inserted by pressure from the nitrogen bottle. Pressure applied to push the water is from 1000 to 3500 kPa, normally, the average value is 1700 kPa.

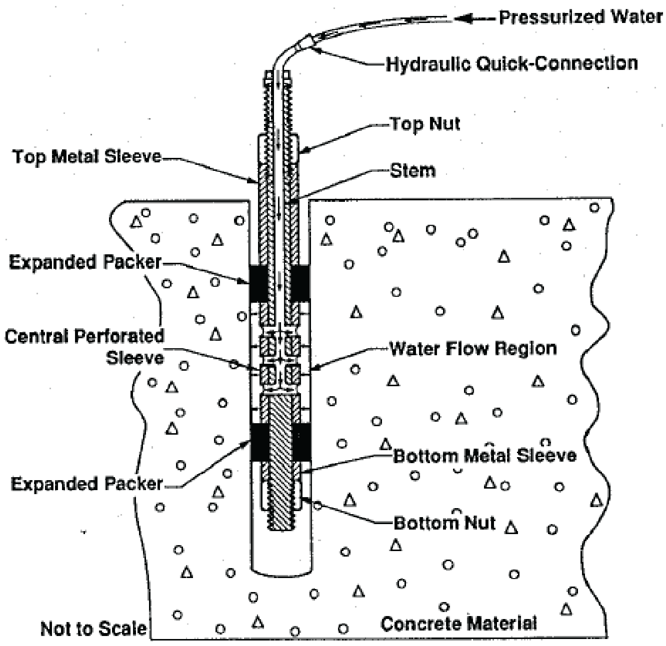

Fig.2.5 Schematic diagram of the field permeability test [2.10]

When the steady flow is achieved, usually after 30 minutes, the rate of flow is recorded from 5 to 15 minutes intervals for about 2 hours with the help of capillary flow meter. From the pressure and flow rate, coefficient of permeability is calculated according to Darcy's law [2.14] in units of cm/s. It takes approximately 3 hours to complete one test. Main disadvantages of this test are same as that of the Figg water absorption test. Furthermore, this method requires long duration to determine the quality of covercrete.

2.6.2 Tests Based on Air Permeability

1) Schönlin air permeability test:

This test method was invented at the Technical University of Karlsruhe, Germany [2.15]. It is shown in Fig.2.6. The pressure less than 99 kPa below atmospheric pressure is created in the cell with the help of a vacuum pump. In order to keep the apparatus against the concrete surface, it is necessary to provide external atmospheric pressure. Once the pressure reaches below 99 kPa, valve is closed. The time is noted when the pressure in the chamber reaches 95 kPa. The time required for the pressure to reach 70 kPa is again recorded. From the known volume of the cell and the time, air permeability index is calculated in units of m^2/s.

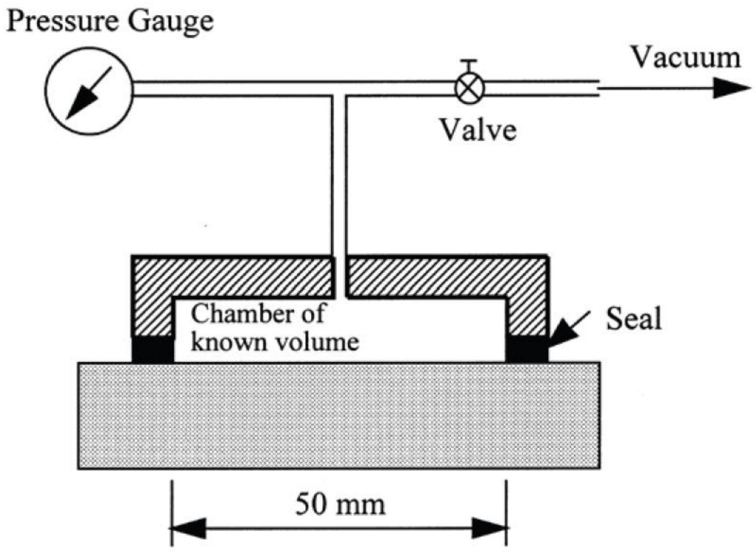

Fig.2.6 Schematic diagram of Schönlin air permeability test

2) Autoclam air permeability test:

The apparatus is almost the same as that of Autoclam water permeability test (Fig.2.7). Gas Permeability tests can be carried out on most building materials for which the coefficient of permeability is less than 10^{-10} m/s. Both the Water Permeability and Sorptivity (water absorption) tests can be carried out on impermeable materials to those in which the maximum rate of flow of water is 1 ml/minute. The resolution in these tests is one microliter.

Fig.2.7 Schematic diagram of Autoclam air permeability test [2.12]

3) Figg air permeability test:

The apparatus is the same as that of Figg water permeability test. In this case, instead of attaching the hypodermic needle to the capillary tube, it is attached to a hand vacuum pump to produce a vacuum inside the hole (Fig.2.8). Using the hand pump, the pressure is reduced in the hole to 55 kPa below atmospheric pressure. Then the valve is closed and the pressure inside the hole starts increasing. The time required to increase the pressure by 5 kPa is recorded that will give the total pressure of 50 kPa inside the hole. The required time is reported as the air permeability index.

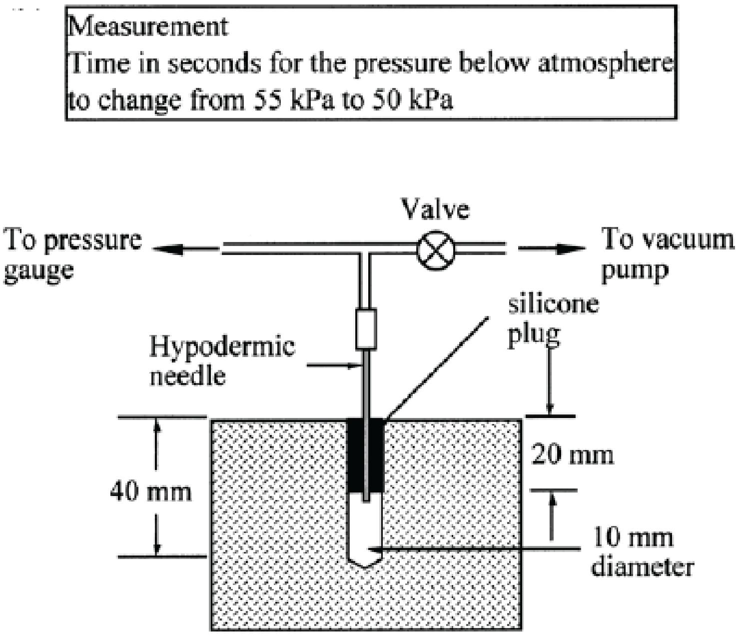

Fig.2.8 Schematic diagram of Figg air permeability test [2.12]

4) Torrent permeability tester:

Torrent permeability tester was developed at "Holderban Management and Consulting Ltd." in Switzerland [2.16]. This test consists of a two-chamber cell and a regulator to balance the pressure in the inner and outer chamber (Fig.2.9). Regarding the operation of this test device, the two chamber cell is attached to the concrete surface by creating a vacuum in the inner and outer cells using the vacuum pump. The external atmospheric pressure provides the necessary force to hold the chamber against the concrete surface. The stop-cock 1 is shut and the chamber is attached to the surface through suction. Then the stop-cock 2 is shut at 30 seconds and opened at 35 seconds; and again it is shut at 1 min. The pressure in the inside cylinder starts increasing due to the air is drawn from the subject concrete. The rate of increase in pressure is recorded which is directly related to its permeability. The results of this test are expressed in terms of the coefficient of permeability *kT* in m^2 units [2.16]. Furthermore, the depth of concrete L (mm) is a function of *kT* [2.17]. The duration of the test is also included in the test results. The qualitative rating criteria are shown in Table 2.1.

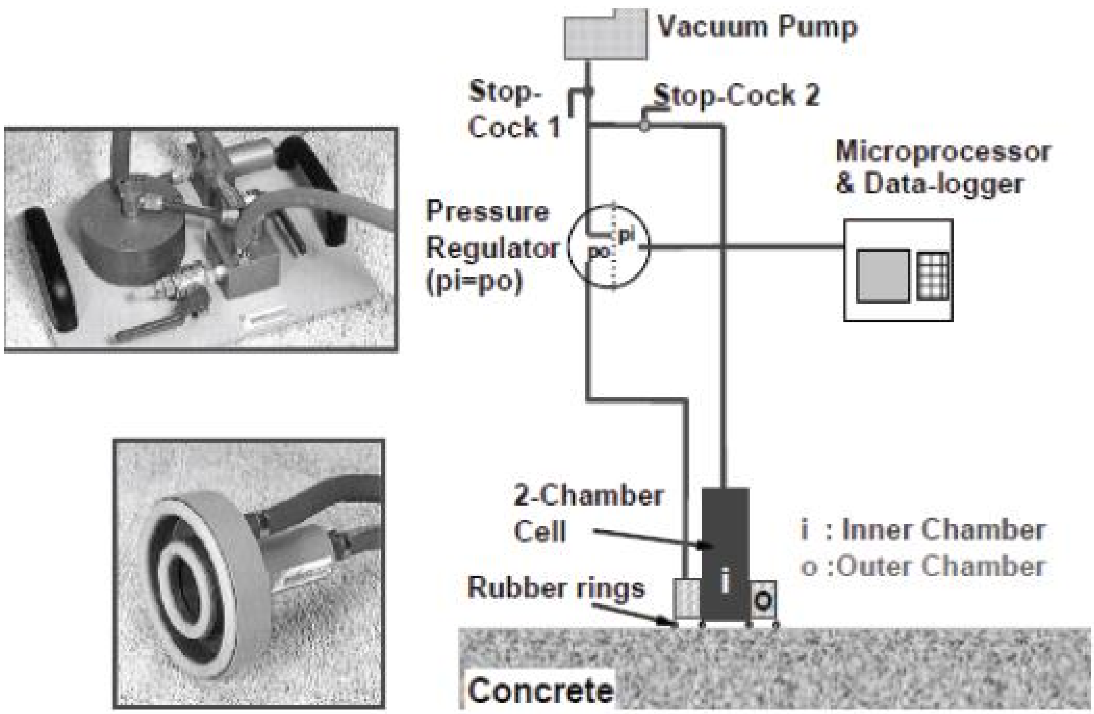

Fig.2.9 Torrent permeability tester [2.8]

Table 2.1 Classification of the quality of the "covercrete" based on the Coefficient of Air-Permeability *kT* [2.18]

Covercrete Grade	A	B	C	D	E
Quality	Excellent	Very Good	Fair	Poor	Very Poor
Coefficient of Air-Permeability *kT* (10^{-16} m^2)	<0.01	0.01-0.1	0.1-1	1-10	>10

2.7 Initial surface absorption test (ISAT)

The Initial Surface Absorption Test (ISAT) was first conducted by Glanville in 1931 at the Building Research Establishment in the UK [2.18] and modified by Levitt [2.19-2.21] in the early 1970s.

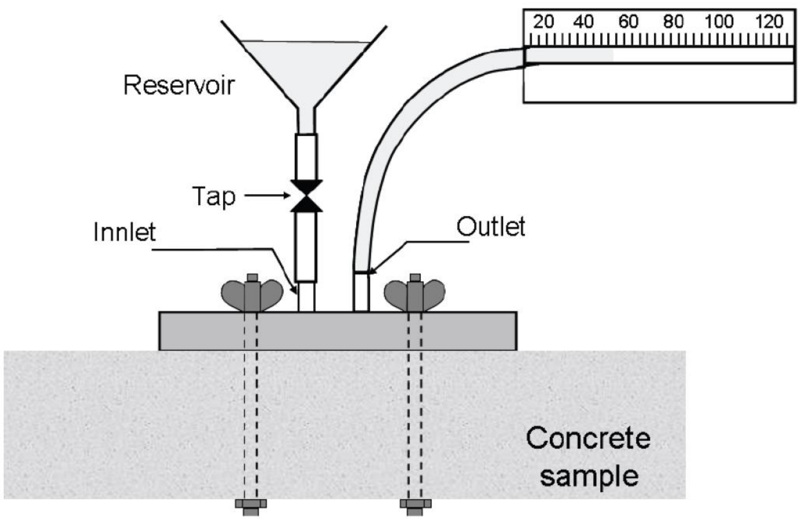

Fig.2.10 Schematic diagram of ISAT

2.7.1 Description of test apparatus and procedure

The method consists of a plate sealed onto the concrete surface and making it water-tight by clamping it. A pressure head of 200 mm (~0.02 bar) is set up by means of a water reservoir (Fig.2.10). When the inlet tap is opened, water flows from the reservoir to fill the cap and then through the outlet it climbs into the calibrated horizontal capillary tube. After 10 min, the tap is closed and the rate of water suction by the concrete is monitored by following the retraction of the meniscus in the capillary tube. This provides the initial surface absorption at 10 minutes. The absorption values are determined in this manner at 30, 60 and 120 min from the start of the test. The inlet tap is opened after taking each measurement and water in the reservoir topped up in order to allow the head of water to be maintained at 200mm. The minimum water-concrete contact area is 5000 mm^2.

2.7.2 Utilization of ISAT

The method is entirely non-destructive unless flanges have to be clamped to the surface in order to fix the cap. The method cannot be applied to the underside of slabs and beams, except very close to the edges. According to Dhir, et. al. [2.22] only the surface layer up to 10 to 15 mm of covercrete can be measured by surface water absorption test. However, this depth can be sufficient to distinguish the materials and curing condition which affects the absorption of concrete. Dhir et al [2.22] also investigated the effect of the water by cement ratio and the duration of moist curing on the ISA-Value. Their results, as shown in Fig.2.11, indicated that the ISAT can distinguish the effects of both these variables.

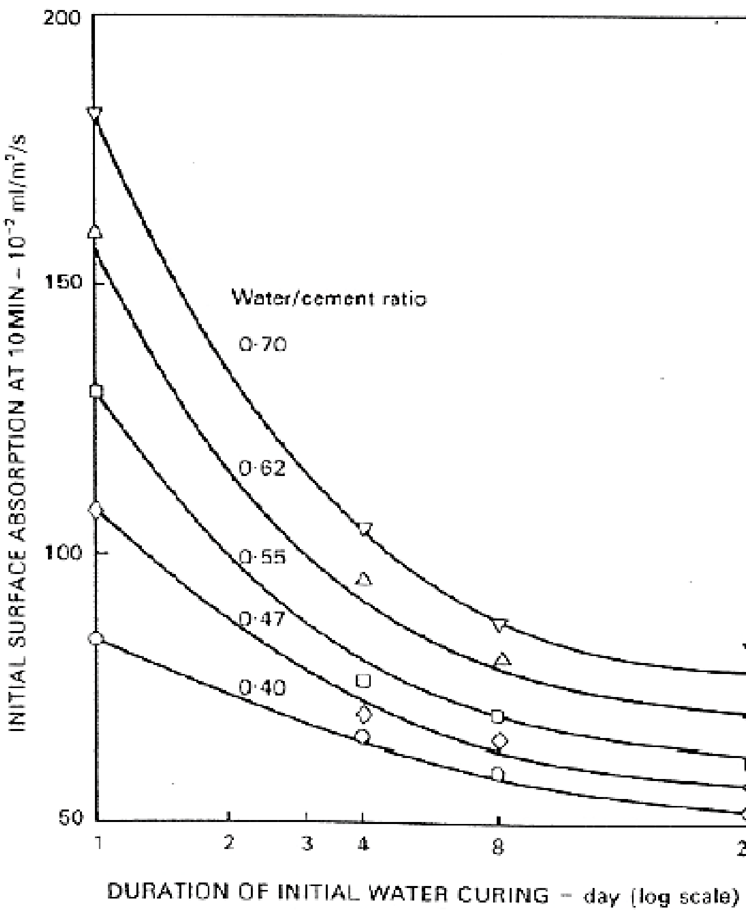

Fig.2.11 Effect of W/C ratio and curing on the ISA - Value after 10 min

2.7.3 The relationship between ISA and duration of drying

A minimum air drying period of 7 days preferably 14 days, before conducting ISAT tests on site is recommended so that the results are not influenced by the variations of moisture content into concrete as seen in Fig.2.12. Dhir et al [2.22] said that even with this drying regime, some variations due to the moisture content in concrete were indicated, making the test not capable of reflecting the true quality of the concrete.

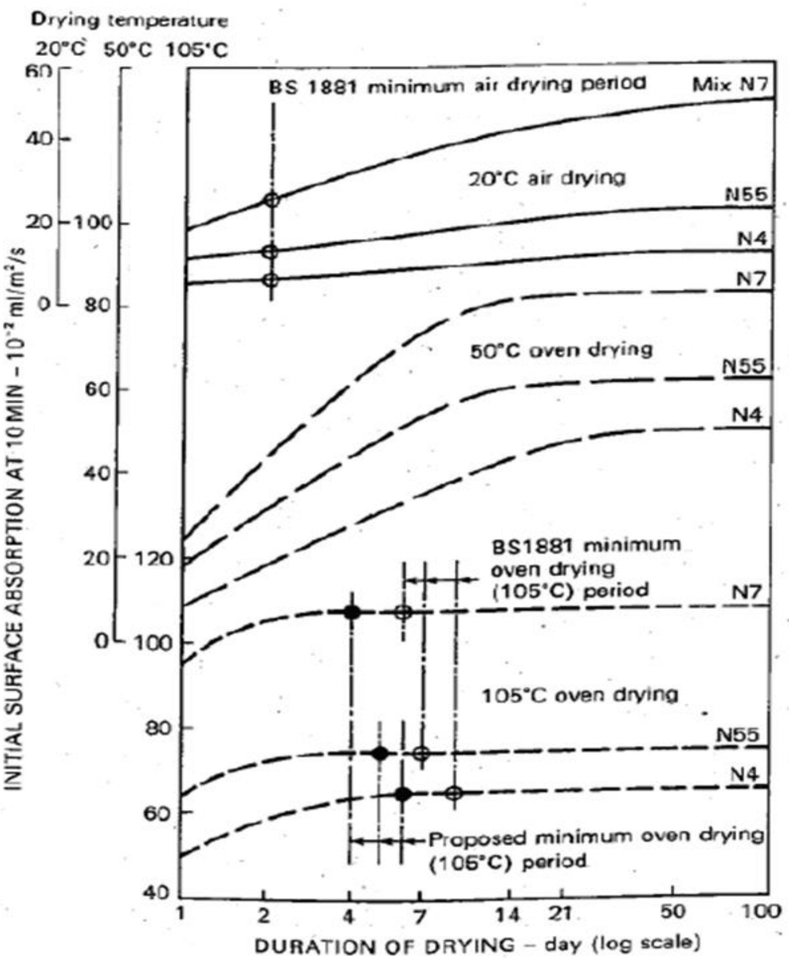

Fig.2.12 Relationship between ISA and duration of drying [2.24]

2.7.4 Qualitative rating of ISAT

A proposed criterion of the water absorption in covercrete is given in Table 2.2., which was based on the ISA-Values [2.23].

Table 2.2 Classification of covercrete's absorption based on ISA values [2.25]

Concrete Absorption	ISAT results ml/m²/s			
	Time after starting test (min)			
	10	30	60	120
High	>0.50	>0.35	>0.20	>0.15
Medium	0.25-0.50	0.17-0.35	0.10-0.20	0.07-0.15
Low	<0.25	<0.17	<0.10	<0.07

2.7.5 Theoretical derivation for ISAT

The theoretical derivation for initial surface absorption (ISA) obtained by Levitt [2.23] is,

$$ISA = at^{-n} \quad (2.1)$$

Where “t” is time, “a” is constant and “n” is another constant showing the decay of rate of water absorption having theoretical value of 0.5. Levitt [2.23] also found a variation of ±0.2 about a theoretical “n” value of 0.5, and suggested that high rate of decay (n = 0.7) is due to the silting up of pores in concretes with high cement contents or containing fillers, whilst the low rate of decay (n = 0.3) is due to capillary flushing may occur in mortar mixes especially with single sized sand.

The main limitation of this method is that it cannot be applied to the underneath of slabs and beams, except very close to the edges. Furthermore, it is difficult to keep the cap water-tight onto the concrete surface. The method takes more than 2 hours to be completed.

2.8 GWT method [2.24]

German’s Water permeation Test (GWT) has been recently introduced in EU exhibit the same function as ISAT and Autoclam, used in many European countries for evaluation of concrete ability to resist water penetration under pressure. The testing methodology proposed in this standard is based on the determination of the depth of water penetration under pressure in hardened concrete. This standard specifies procedure of applying water under controlled conditions of pressure to the surface of the concrete. As an evaluation parameter the depth of penetration of the waterfront, which is measured after splitting the specimen, is recommended. Fig.2.13 shows a view of the GWT instrument.

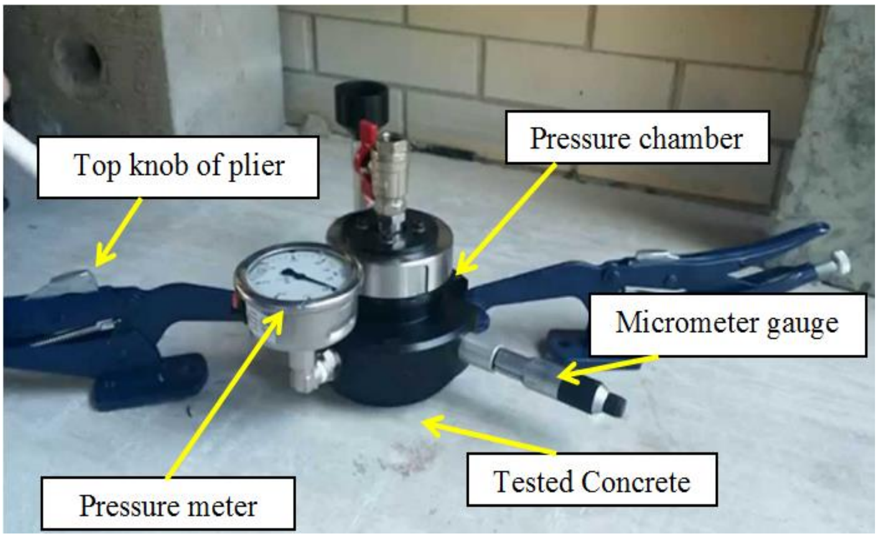

Fig.2.13 View of GWT-4000 instrument (Tam et al., 2012)

As can be seen from Fig.2.14 the chamber of the device is sealed to the covercrete by 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 by 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.

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 one hour. The cumulative amount of absorbed water can be calculated as follow:

$$i = \frac{B.(g_1 - g_2)}{A} \tag{2.2}$$

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 mm^2 for the 10mm of pin diameter,

g_1 and g_2: Micrometer gauge readings at the start of the test and after the reading time (mm), and

A: water contact surface area which is 3018 mm^2 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.

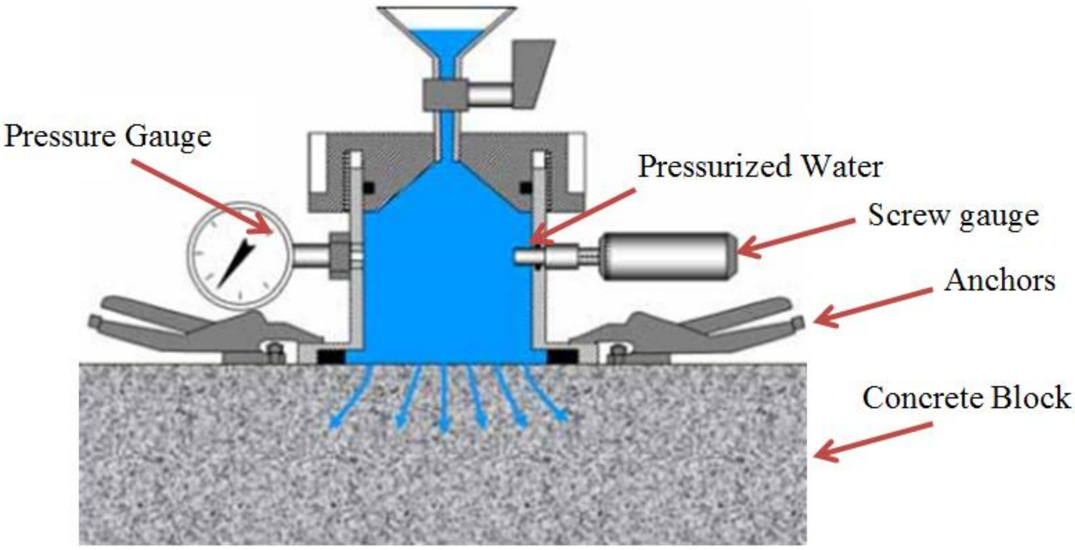

Fig.2.14 Schematic of GWT concrete test device (GWT-4000 Manual, 2010)

In practice GWT can be successfully applied for:

1) Evaluation of water permeation of the skin-concrete in finished structure
2) Testing of the water tightness of construction joints and sealed control joints, *f*
3) Testing of the surface before and after application of protective water-proofing membranes to estimate the effectiveness of them
4) Evaluation of the water permeation of masonry structures

The most important disadvantage of such measurements is their time-consuming laboratory investigation which excludes the possibility of quick evaluation of water permeability of the actual concrete structures in site.

2.9 ASTM C1585 [2.25]

This test method is used to determine the rate of absorption (sorptivity) of water as a function of the time in hydraulic cement concrete by measuring the increase in the mass of a specimen due to the absorption of water when only one surface of the specimen is exposed to water. The specimen is conditioned in an environment at a standard relative humidity to induce a consistent moisture condition in the capillary pore system. The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete is dominated by capillary suction during initial contact with water.

According to the ASTM C1585 Standard, the test was conducted by using disc concrete specimens of 100 ± 6 mm diameter with the 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 the temperature of 50±2°C and R.H of 80±3% for three days. This preconditioning result is providing samples with 50 to 70% of internal relative humidity which is found to be the typical R.H. in covercrete zone of some infield structures (DeSouza et al., 1997, DeSouza et al., 1998). Then, 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 is 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 a pan which filled with water as is shown in Fig.2.15.

The specimens are removed from the pan and their mass recorded at intervals up to 7 to 9 days. Equation 2.3 presents the calculation of the absorption, I, which is the change in specimen's mass divided by the product the cross-sectional area of the sample and the density of water which is considered as 0.001 g/mm^3.

$$I = \frac{m_t}{a.d} \tag{2.3}$$

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).

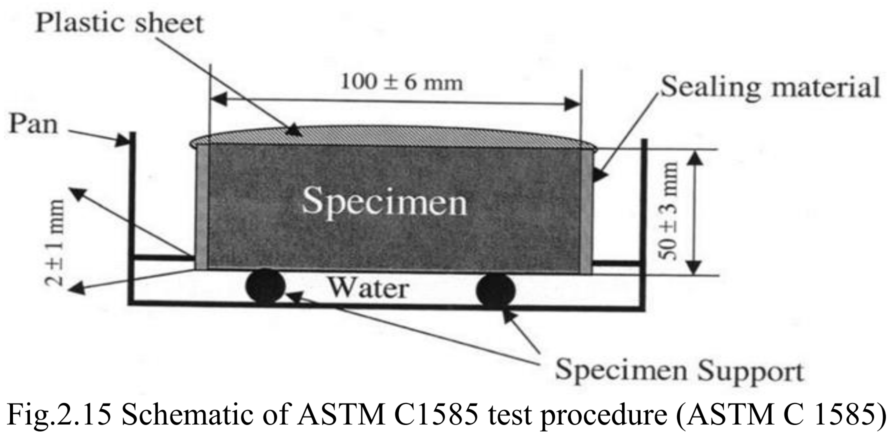

Fig.2.15 Schematic of ASTM C1585 test procedure (ASTM C 1585)

The calculated absorption value at each time will be plotted against the square root of time ($\sqrt{s}$) to investigate the slope of its linear trend, sortivity. This index is determined in two stages; initial and secondary absorption due to the absorption time (Fig.2.16). Most commonly, the initial sortivity is reported in the literature.

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 R.H. for concrete samples, it is not the R.H. of field concrete elements in all environmental conditions (Parrott, 1994, Basheer and Nolan, 2001).

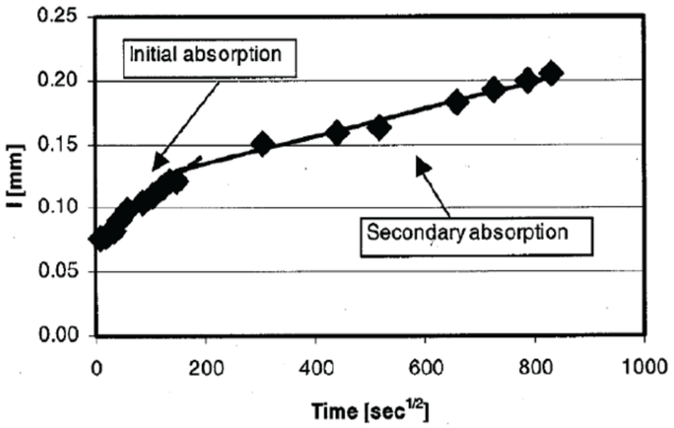

Fig.2.16 Absorption test data points in ASTM C1585 method (ASTM C1585)

2.10 Test method for water penetration rate coefficient of concrete subjected to water in short term (JSCE-G 582-2018) [2.26]

1) Equation: The principle of the method is that a concrete specimen has one surface in contact with water while all others are sealed, to allow a direct and accurate assessment of it sorptivity. The water penetration depth is measured as the following equation:

$$L=A.t^{1/2}+B \tag{2.4}$$

Where, L: moisture permeability (mm), A: Moisture penetration rate coefficient, t: immerse time (hour), B: constant

2) Water permeation test: Concrete is immersed in water, and then the moisture penetration rate coefficient is determined.

3) Specimen: Specimen used has 100mm in diameter and 200 mm in height. After casting, they are stored in curing room at temperature 20 ± 2°C and RH 60 ± 5%

in 91days and confirmed that the mass change in 24 hours is 0.1% or less. In order to shorten the drying period, drying may be ended by giving 28 days in an environment at a temperature of 40 ± 2°C and a relative humidity of 30 ± 5% and confirming that the mass change of 24 hours is 0.1% or less. When drying at 40°C, It is left in room temperature for more than 1 hour from drying to immersion in order to return the temperature of the specimen to room temperature. In order to prevent the specimen from absorbing moisture in the air, it is kept in a sealed container. If the 24-hour mass change exceeds 0.1%, drying is continued until it is below 0.1%. According to this criterion, the scale used for measuring the mass of the specimen is 0.1g or less. After the drying is completed, the surface will be immersed in water and the other surfaces are to be sealed. The purpose of sealing is to suppress penetration and dissipation of moisture from the side of the specimen during the water penetration test. In order to make the water ratio as homogeneous as possible, the sealed condition is decided to be carried out after drying. Epoxy resin, polyurethane resin, aluminum tape, or waterproof material such as vinyl tape can be used. When the epoxy resin is used, it is to be confirmed that fully cured in minutes before immersing.

4) Test methods: The bottom of the specimen is cut apart before immersing in the water. The bottom is always soaked in the water around 10±1mm from the water surface during the experiment time. Tap water is kept in a container at 20 ± 2°C for immersion. The water taken from the tap has a large amount of dissolved air that affects the test result. In order to stabilize the water is left at room temperature of 20 ± 2°C for more than 24 hours. The distance between the bottom of the specimen and the bottom of the container is 5 mm or more. The contact area between the spacer and the specimen shall not exceed 10% of the cross-section of the specimen. The immersion time in water shall be 48 hours.

The measurement method of water penetration depth of concrete is as follows:

The measurement time of moisture penetration depth is 5 hours after immersion start. Standard 24 hours and 48 hours later measurement time is recorded in minutes. The criterion assumes the short-term water retention such as rainfall and temporary water action. In Japan it is very rare for rain to continue for more than 3 days. Therefore, a 48-hour immersion period is marked. The number of specimens measured per time should be three or more. The specimen lifted from the immersion water is split immediately at the center of the specimen in the vertical direction. After splitting in two halves, the water penetration depth is determined by spraying the solution to change the color of the specimens. Then, the depth from the immersion surface of each part is measured and recorded in units of 0.5 mm by using a caliper defined in JIS B 7507. Further, a metal straight line specified in JIS B 7516 is used to measure and keep record in 0.5 mm increments, in different locations relative to the width (100 to 150 mm) of the specimen. The distance from the sealed surface parallel to the moisture infiltration direction of the split face to the measurement position is set to 20 mm or more. In case there are coarse aggregates or a hollow at the measurement position of the boundary of discoloration, it is on the straight line connecting both ends of the coarse aggregate or the hollow has escaped. When the boundary of discoloration is difficult to understand, the distance from the boundary furthest to the immersion surface in the discoloration area is measured. Since, long duration is required to measure the penetration depth of water; the measurement result may be influenced. Hence, the measurement of the depth of penetration of water can be performed immediately after splitting of specimens.

The water penetration rate coefficient A is obtained by the following equation by using the moisture penetration depth and the square root of the immersion time obtained mainly during the period from 5 hours to 48 hours of immersion.

$$A = \frac{\sum_{n=1}^{n}(\sqrt{t_i}-\overline{\sqrt{t}}).(L_i-\overline{L})}{\sum_{n=1}^{n}(\sqrt{t_i}-\overline{\sqrt{t}})^2} \tag{2.5}$$

Where, A: Moisture penetration rate coefficient (mm /$\sqrt{hr}$)

n: Number of data

$\sqrt{t_i}$: The square root of the immersion time of the i_{th} data ($\sqrt{hr}$)

$\overline{\sqrt{t}}$: The average value of the square root of immersion time ($\sqrt{hr}$)

L_i : The penetration depth of the i_{th} data (mm)

$\overline{L}$: Average penetration depth (mm)

B: Constant

The constant B which is an intercept of the approximate straight line is obtained by the following equation.

$$B=\overline{L}-A.\overline{\sqrt{t}} \tag{2.6}$$

5) Disadvantages: This method is to measure short-term absorption by splitting specimens, so it requires long time to conduct and to collect the results.

2.11 Surface Water Absorption Test (SWAT)

SWAT is a fully non-destructive test manufactured and developed by Hayashi and HOSODA [2.27], [2.28]. It has a water cup with a graduated tube, and a sensor to count reduced water amount, as can be seen in Fig.2.17. The rate of water absorption at 10 minutes (600 seconds) is defined as water absorption resistance of concrete, called p_{600}. The unit is calculated in ml/m^2/s. In order to evaluate covercrete quality the authors have proposed the criterion as shown in Table 1 [2.27], [2.28].

The limitation of SWAT device is the change of p_{600} values when moisture content changes. Recently, attempts have been made to reduce the measurement time of SWAT shorter than 10 minutes depending on the purpose and conditions of measuring by SWAT.

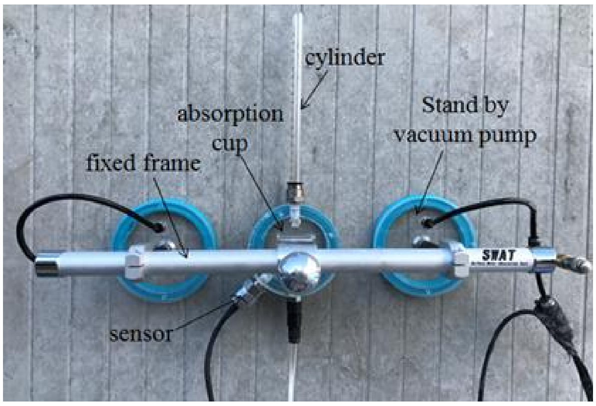

Fig.2.17 SWAT device

1) The comparison of ISAT and SWAT

Compared with ISAT method, SWAT test developed by Hayashi and Hosoda [2.27] had more significant advantages which are given in Table 2.3.

Table 2.3 Comparison of SWAT and ISAT

Sr. No.	SWAT	ISAT
01	A variable head test method with initial water head of 300 mm.	A constant head test method with a water head of 200 mm.
02	Due to fully non-destructive test, SWAT does not require and any destructive setup arrangement.	Requires some destructive arrangement such as adhesives pastes and resins to hold the test apparatus against the concrete surface.
03	SWAT is easily applicable on the site.	Setup is complex and is bit difficult in application to the site.

Sr. No.	SWAT	ISAT
04	As SWAT is simple in nature, so, more tests can be conducted in the given time.	Due to more time required to setup and complex apparatus lesser number of tests could be performed in the given time.
05	SWAT is being developed as no pre-conditioning would be required for the testing in lab as well as at site.	Lab specimens are always pre-conditioned to constant moisture condition at 105°C in the oven.

2) Effect of water head on the results of SWAT

In SWAT device, a 300 mm water height is used to simulate the rain and wind pressure considering the weather condition of Japan developed by Hayashi and Hosoda [2.27] to measure the quality of covercrete for the wide range of concrete. While Levitt [2.19-2.21] had selected a constant head of 200 mm for initial surface water absorption test (ISAT). According to Levitt [2.19-2.21], a pressure head of 100 mm is equivalent to a combined wind and rain pressure of 130 km/h. Therefore, using a 200 mm pressure head during any test procedure gives a twofold safety factor. According to A.M. Neville [2.1], this head is slightly greater than that would be caused by driving rain.

In Eq.2.1 for Levitt model, he proposed a constant water head of 200mm. While from the data analysis of SWAT it was seen that the model proposed by Levitt was also good in variable water head method of SWAT device. Therefore, it is decided to determine the effect of water head in detail on the results of SWAT by applying the higher water heads. Study results showed that up to 500mm water head had insignificant effect on the results of SWAT.

3) Effect of wetting on the results of SWAT

It is true that results of SWAT vary as the boundary conditions of the concrete changes either due to rain or due to change in humidity. BS 1881 [2.23] and Dhir, et al. [2.22] recommended that for site investigation, the surface shall be tested after a period of at least 48 hours during which no water has fallen onto the test surface. Furthermore, according to Dhir, et al. [2.22] minimum air-drying period of 7 days, preferably 14 days, should be secured for reading taken on the site, and even then some variations in the results can still be expected. Hence, it is important to know in detail the effect of moisture condition on SWAT results. This objective will be studied deeply in chapter four, and five.

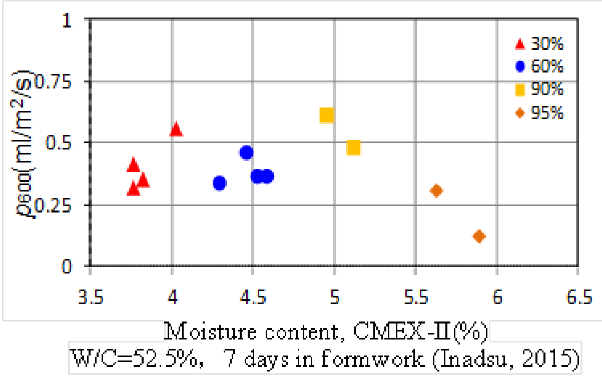

Fig.2.18 Relationship between water absorption and moisture content

In 2015, Inadsu (2015) [2.29] investigated on effects of moisture content on water absorption of SWAT. Inadsu found that when moisture content detected by the AC impedance method was higher than 5.5%, water absorption results in ten minutes (p_{600}) conducted by SWAT were apparently small as shown in Fig.2.18. However, the number of specimens and moisture profiles in her research is limited. Therefore, this content should be investigated deeply.

4) Effects of plateau zone and threshold values of moisture content on SWAT results

According to Shirakawa et al. (1999) [2.30], there exists a plateau zone in gas diffusion coefficient at a range of moisture content as shown in Fig.2.19. When R.H. is higher than 45%, effective diffusion coefficient is apparently small. According to his investigation results (Fig.2.19) gas diffusion coefficient is very high when R.H. becomes zero.

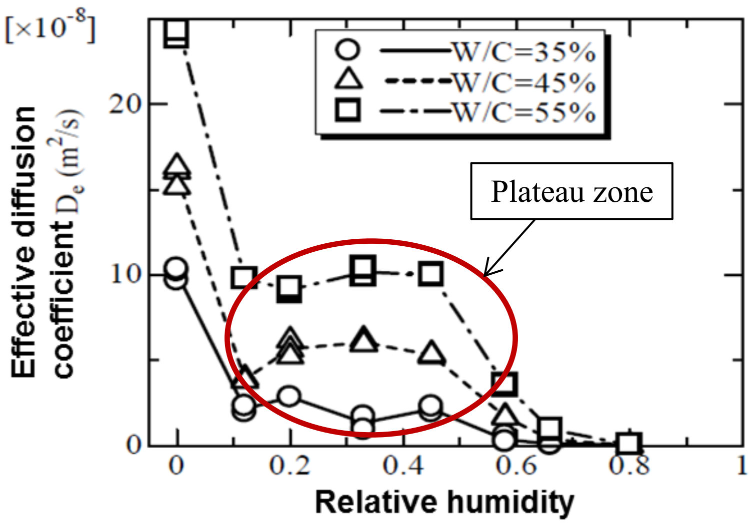

Fig.2.19 Relationship between effective diffusion coefficient and R.H

There is a same tendency with gas diffusion coefficient in water absorption results obtained by Raphael et al. in 2019, as shown in Fig.2.20. When percentage saturation degree of permeable pore voids around 20% to 60%, water absorption in covercrete belongs to plateau zone. When saturation degree is higher than 60% and lower than 20%, p600 are apparently small or high, respectively.

It is observed that when R.H. or saturation degree are higher or lower than a specific range, gas diffusion and water absorption results are changed. It indicates that, surface absorption resistance of concrete cannot be determined accurately when R.H or saturation degree are very low or very high. The value which R.H. or saturation degree makes gas diffusion coefficient or p600 apparently small is defined as the threshold value in the present research. It is important to determine the threshold value in order to make sure that effective diffusion coefficient or p600 belongs to plateau zone.

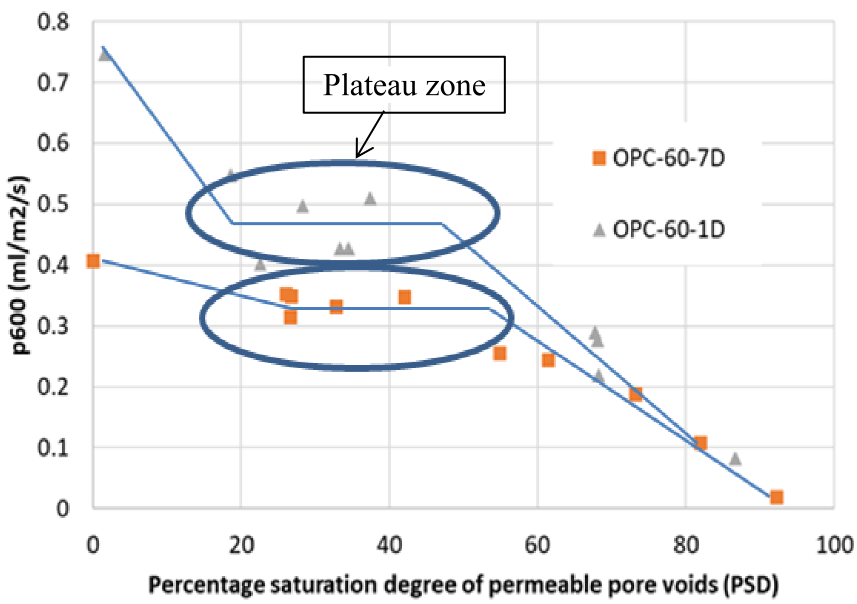

Fig.2.20 Relationship between *p600* and percentage saturation degree of permeable pore voids

Therefore, finding the threshold value of moisture content of moisture meters to apply for conducting SWAT and air permeability test is indispensable in the current research.

5) Effect of saturation degrees on the results of SWAT

There is a question that how to evaluate the water absorption resistance of covercrete when moisture content in concrete is higher than the threshold value (p_{600} is apparently small) and does not belong to plateau zone. In order to answer that question, initiatives should be undertaken related to saturation condition in covercrete. Furthermore, when moisture content in concrete is higher than the threshold value the criteria for evaluating the water absorption resistance of covercrete by SWAT should be calibrated. The targets of the investigations are:

i) To revalidate the established threshold and edge percentage saturation degrees (PSD) of permeable pore voids for correct covercrete quality evaluation by SWAT

ii) To investigate the effects of "dry to wet" and "wet to dry" paths of different covercrete PSD surface water absorption and SWAT.

iii) To investigate the influence of PSD on air permeability

iv) To investigate the relationship between the water absorption coefficient by SWAT and water penetration coefficient by JSCE method

v) To investigate the effect of concrete temperature at different PSD on SWAT

vi) To investigate the effects of environmental temperature at different PSD on SWAT.

6) Significance of the selected measurement duration range

The water absorption value of SWAT at 10 minute is selected as an index to evaluate the quality of covercrete according to the the laboratory investigations that total volume absorbed at 10 minutes has a good relationship with that of the total volume of water absorbed in the long-term as exhibited in Fig.2.11. Therefore, only from the 10 minutes records, long-term behavior of concrete regarding water permeation can be assessed.

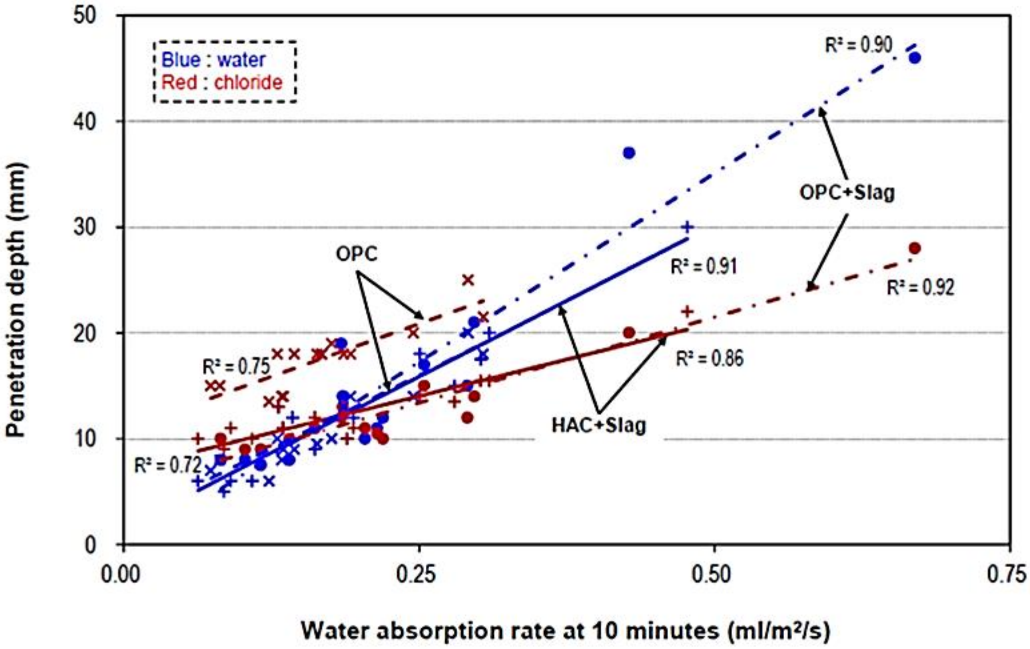

Fig.2.21 Relation between 10 minutes and long-time water absorption [2.31]

However, recently, a proposal to shorten the water absorption measurement time has been published by Igawa et al [2.32]. In his research, Igawa indentified that when the measurement time is between 1 minute and 10 minutes, the surface water absorption amount is proportional to the surface water absorption rate. Hence, it is possible to evaluate the surface layer quality only by grasping the surface water absorption amount, thus simplifying the current measurement method was suggested.

Table 2.4 Proposal of evaluation standard value (boundary value) according to measurement time

tm	*p*m	Qm	*p*m	Qm
60	1.22	0.45	2.24	0.83
120	0.76	0.61	1.43	1.16
180	0.57	0.74	1.09	1.41
240	0.47	0.84	0.90	1.62
300	0.4	0.93	0.78	1.80
360	0.35	1.00	0.70	1.97
420	0.32	1.07	0.63	2.11
480	0.29	1.13	0.58	2.25
540	0.27	1.19	0.54	2.38
600	0.25	1.25	0.50	2.50

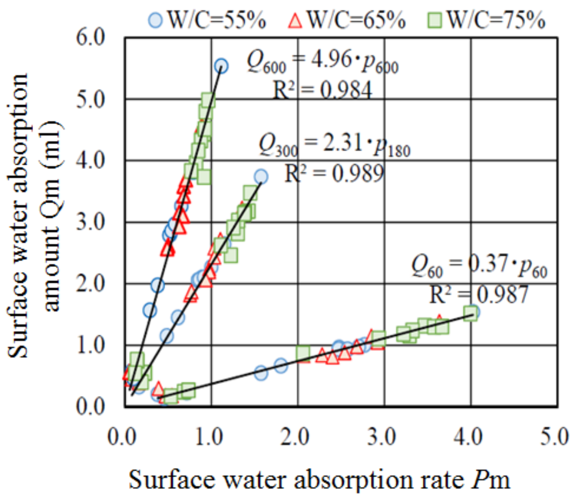

Fig.2.22 Relationship between surface water absorption Qm and surface water absorption rate *p*m

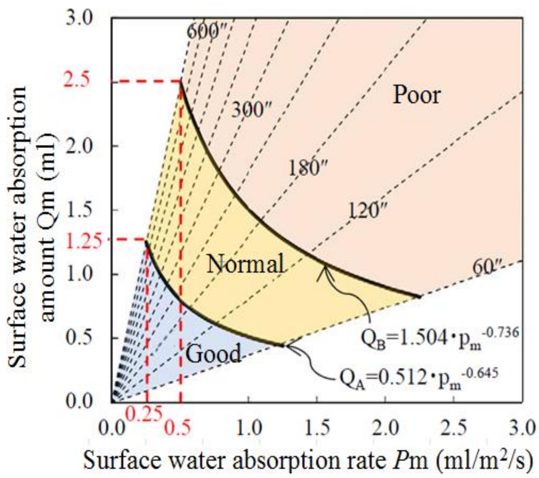

Fig.2.23 Determination criterion range of surface layer quality according to measurement time

Fig.2.22 shows the good relationship between the surface water absorption rate and the surface water absorption amount at measurement time from 1 to 10 minutes. Fig.2.23 and Table 2.4 illustrate the determination criterion range according to the measurement time of the surface water absorption rate and surface water absorption amount.

Shortening the SWAT conducting time has some advantages. First, in case of evaluation quality of slab using of SWAT, it was found that the amount of water absorption of concrete slabs is often smaller than that of pier, abutment and lining concrete. This may be due to the high moisture content of concrete slabs. Thus, there is a possibility that the quality of the upper surface of concrete slabs may be misjudged when p600 is used. This research was conducted on sufficiently dried concrete only. In real structures, concrete is usually in humid condition. Therefore, it should be investigated when concrete is dried for some days after a long time in wet condition.

2.12 Summary

The covercrete plays an essential role regarding durability of concrete structures. Therefore, quality of covercrete must be investigated to determine and improve its resistance against the permeation of aggressive substances into the concrete structures. Until now, many test methods have been proposed to check the covercrete of concrete structures depending on different working principles. However, every method that is currently available is either not representing the actual phenomenon with reference to the driving force caused by the natural environment inducing the ingress of aggressive substances into the concrete or due to the difficulties to apply to in-situ concrete. Furthermore, some methods require certain destructive arrangements in order to install the test apparatus. Therefore, reducing the disadvantages of methods which affect water absorption is indispensable. SWAT device and relative moisture meters are investigated deeply in this study to improve the effect of moisture content to SWAT results. Furthermore, a new index to evaluate water absorption resistance in an appropriate time of covercrete conducted by SWAT is proposed.

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Chapter 3

IMPROVEMENT OF SURFACE WATER ABSORPTION TEST APPARATUS

3.1 Introduction

This section is aimed for describing the general outline of Surface Water Absorption Test (SWAT) and the improvement in the testing apparatus. It depicts test device details, setup details, test procedure, analysis of test data, mechanism of water absorption and the SWAT and ISAT comparison in the initial part of the chapter. Improvement, test procedure, calibration method and advantages of auto measure SWAT system are also described. In the final part of the section, the impact of water head and that of the transient wetting, as well as a comparison of new and old gadgets on the test consequences of SWAT are incorporated.

3.2 Objectives

In order to improve and develop the SWAT device, several researches have been conducted recently. The objective of the current chapter is to compare the difference between new and old SWAT devices in terms of design and accuracy of two devices.

3.3 Why Water Absorption Test is needed?

It is believed that water and fluid are as the main thrust for the forceful aggressive substances which causes the most deterioration processes into the concrete (Fig.3.1).

Air permeability tests are normally conducted at high pressures which is not the actual phenomenon. In surface water absorption test method, a water head is inferred almost at the same pressure as that of the driving force of rain and wind representing the actual phenomenon. The evaluation quality of concrete by visual observation method like leakage through micro-cracks is only possible in case of water absorption, it is impossible in case of air permeability test due to air is not visible.

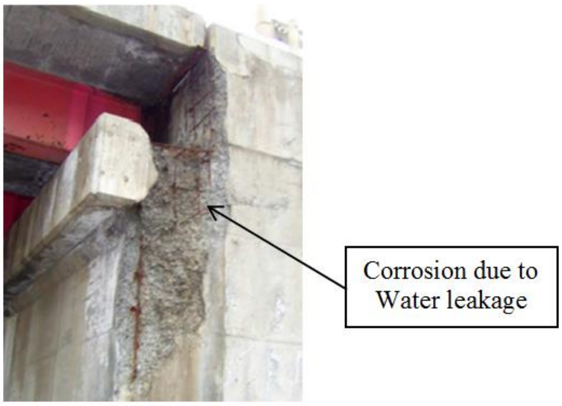


Fig.3.1 Corrosion of steel grid [3.1]

3.4 Surface Water Absorption Test (SWAT)

Surface Water Absorption Test (SWAT) is a device to evaluate the durability of RC structures in terms of absorption resistance. It is a simple, quick and completely non-destructive test method with variable water head, which has been developed by Hayashi and HOSODA [3.2].

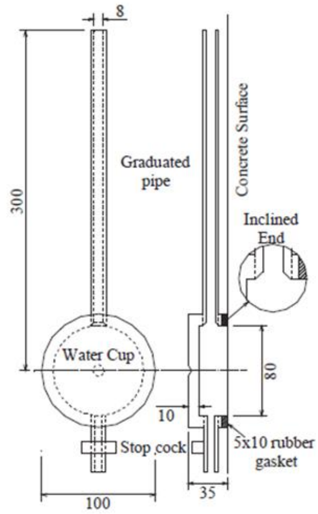
3.4.1 SWAT devices

The original test device consists of a water cup with the graduated pipe as shown in Fig.3.2.

The diameter of the water cup is 100mm, the inside diameter of the water cup is 80 mm and the height of the tube from the center of the cup is 300 mm. According to the minimum area surface, water absorption test by ISAT, the area inside of the water cup is 5000 mm^2. A stopcock is attached at the bottom of the cup to fill and remove water from the apparatus. A sensor attached next to the stopcock is linked with the PC to measure the changes in water head level as be seen in Fig.3.3. The water cup and the tube are made by transparent plastic in order to observe the air bubbles during the test. Other dimensions regarding the overall thickness and the wall thickness of the water cup are also shown in the Fig.3.2b.

A 5 mm thick sponge is attached in front of the water cup in order to fill the minor uneven spaces between the water cup and concrete surface, to avoid water leakage during the test. An inclination is provided at the junction of the tube and the water cup to avoid the accumulation of air bubbles at the junction as was observed in the apparatus without this particular measure.

(a)



(b)

Fig.3.2 Surface water absorption test device

3.4.3 Testing procedure [3.3]

Following procedure is adopted for the test to record the data visually;

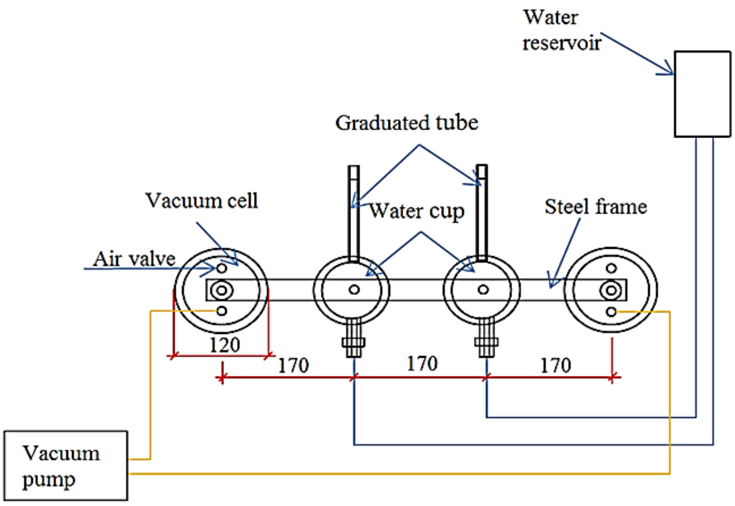


Fig.3.3 Test setup details: Assembly of components

1) First of all, choose measurement location and clean the covercrete surface with the help of scrubber to remove any loose particles or dust
2) Record the moisture conditions (temperature and moisture content) by using concrete and mortar moisture meters such as HI-520, HI-100, CMEX-II and infrared thermometer (Fig.3.5 (a), (b), and (c)), and also record boundary conditions by using temperature and humidity meter (Fig.3.5 (d))
3) Prepare the stand of the steel frame by attaching on the two vacuum cells
4) Link the air pump and the vacuum cells by air tubes

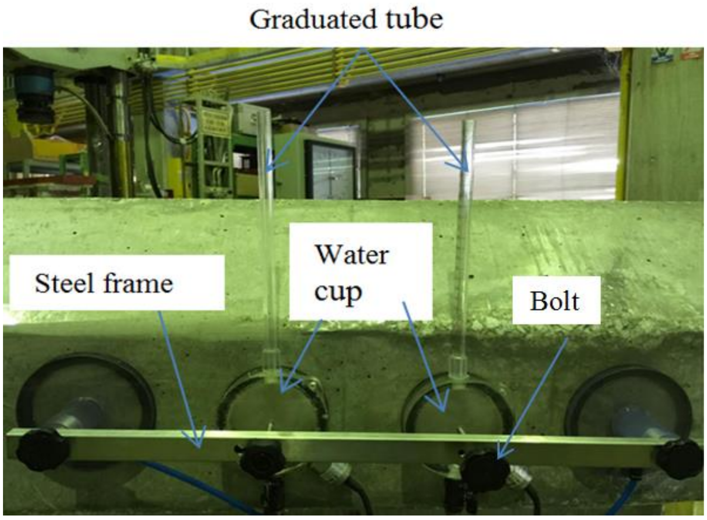


Fig.3.4 Setup at site

5) Fix the frame on the concrete surface by vacuum generated through the vacuum pump

6) Link the water reservoir to the water cup through flexible polyurethane water tubes. If some air is present in the tubes remove it by opening the stopcock because it may generate the air bubbles at the time of filling water to water cup as shown schematically in Fig.3.6

7) Wet the sponge of the water cup with water before attaching the water cups on the concrete surface

8) Fix the water cups by tightening the bolts on the steel frame. Also, make ensure the verticality of the devices visually

9) Fill up water from the reservoir to graduated tube on the top of water cups about 200 to 300 mm above

10) Record the starting time, finishing time, and information about measuring location as well as boundary conditions in the recording sheet as seen in Fig.3.7

11) Record the reading after one minute is completed after the initial reading

12) Start filling water for the second water cup after the first measuring point finishing

13) Similarly, the time to fill and the order to acts for the second point are the same with the first point

14) Now keep on recording the water levels from the graduated tube at intervals of 1 minute until 10 minutes and 30 seconds from start conducting

15) After finishing, leaving the reservoir lower than the water cup and open the stopcocks to remove the water

16) Remove the water cups by opening the bolts

17) Remove the standby opening the air valve on the vacuum cell

18) Conduct the other test place and follow the above procedure

19) After finishing the testing data are analyzed to calculate the SWAT values

(a) Kett concrete and mortar moisture tester HI-520

(b) Infrared thermometer assembly

(c) Moisture meter CMEX-II

(d) Temperature and humidity meter

Fig.3.5 Moisture, temperature and humidity measuring devices

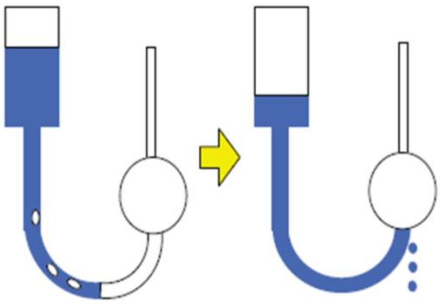


Fig.3.6 Air removal from the assembly

Theoretical data and interpretation method are explained in the next section.

3.3.4 Tackle the test document

This method is to measure water absorption in a short time. Furthermore, the mechanism of water transport is capillary absorption under the application of a water head. Therefore, Eq.3.1 can be applied (Levitt [3.4-3.6]) for the Initial Surface Absorption Test (ISAT) to determine the rate of water absorption.

$$p = at^{-n} \tag{3.1}$$

Where:

p = instantaneous rate of water absorption at any time in (ml/m^2/s)

t = time (seconds)

a = rate of water absorption at 1 second (ml/m^2/s)

n = coefficient regarding the reduction of rate of water absorption with passage of time.

Eq.3.1 is derived from the Poiseuille empirical equation for viscous flow through a fine capillary that is given as

Flow rate $$\frac{dv}{dt} = \frac{\pi H r^4}{8LS} \tag{3.2}$$

Where:

H = Pressure head

r = Capillary radius

L = Capillary length

S = Viscosity of the permeating fluid

Considering "r" as the average pore radius and "H" is constant during the test, we can take all H, r and S as constants. The Eq.3.2 can be written as

$$\frac{dv}{dt} = \frac{A}{L} \text{ where } A = \frac{\pi H r^4}{8S} \tag{3.3}$$

Since "L" is proportional to the volume of the capillary "V" therefore, Eq.3.3 becomes

$$\frac{dv}{dt} = \frac{A}{V} \tag{3.4}$$

Integrating Eq. 3.4

$$v^2 = 2At \quad (3.5)$$

Substituting the value of "v" from Eq. 3.5 to Eq. 3.4

$$\frac{dv}{dt} = 0.5\sqrt{2At}^{-0.5} \quad (3.6)$$

$$\frac{dv}{dt} = at^{-0.5} \quad (3.7)$$

Where "a" is a constant

Total 11 readings are recorded in one test from initial reading at 10 seconds after starting filling water to last reading at 670 seconds after starting filling water at an interval of 60 seconds. At any time cumulative absorption can be represented by Eq.3.8.

$$w_i = \frac{10^3(h_{0-h_1})A_{cyl}}{A_{con}} \quad (3.8)$$

Where:

i = 0 to 10.

w_i = Cumulative water absorption by concrete per unit area at i^{th} reading (ml/m^2).

h_0 = Water level at the initial reading (mm).

h_i = Water level at the i^{th} reading (mm).

A_{cyl} = Area of the graduated tube (mm^2).

A_{con} = Area of the water cup (mm^2).

Here it is important to note that the cumulative amount of water absorption that is calculated from the observed data contains error. This is due to the expected variation of 0.5mm during the recording of the water levels from the graduated tube.

At any i^{th} reading, the rate of water absorption is calculated by Eq.3.9.

$$P_i = \frac{w_{i-}w_{i-1}}{t_i-t_{i-1}} \quad (3.9)$$

Where:

t_i = time at i^{th} reading (seconds)

For a very small interval of recording time the rate of water absorption can be given according to the Eq.3.10.

$$p_i = \frac{dw_i}{dt} \tag{3.10}$$

Incorporating the Levitt model for rate of water absorption from Eq.3.1 to Eq.3.10, rearranging and integrating Eq.3.10 time adjusted cumulative volume is calculated by Eq.3.11.

$$w_i = \int p_i dt = \frac{a}{-n+1} t^{-n+1} \tag{3.11}$$

From the observed visual data, average rate of water absorption can be calculated by using Eq.3.12.

$$V_i = \frac{w_i}{t_i} = \frac{10^3 (h_{0-h_1}) A_{cyl}}{A_{con} t_i} \tag{3.12}$$

The average rate of water absorption is selected to process the data instead of adjusted cumulative rate as the R2 value in case of the average rate of water absorption is more than that in case of adjusted cumulative rate of water absorption.

Putting the value of the adjusted cumulative volume from Eq.3.11 to Eq.3.12 adjusted average rate of water absorption can be calculated by Eq. 3.13.

$$V_i = \frac{\frac{a}{-n+1} t^{-n+1}}{t} = \frac{a}{-n+1} t^{-n} \tag{3.13}$$

Using least square method, curve fitting was performed for the observed values of average rate of water absorption from Eq.3.12. The equation of the fitted curve can be represented by Eq.3.14.

$$V_i = kt^m \tag{3.14}$$

Comparing Eq. 3.13 and Eq. 3.14 values of constants a and n are calculated and are given in the Eq. 3.15 and Eq. 3.16 respectively.

$$a = k(m+1) \tag{3.15}$$

$$n = -m \tag{3.16}$$

The above-prescribed method is suitable for the accumulated rate of water absorption values obtained from the Eq.3.12. In this case, the effect of the reading error will be averaged as compared with the direct rate of water absorption values obtained by following Eq.3.9.

The direct rate of water absorption of test data is compared with that of the adjusted rate of water absorption after calculating the values of “a” and “n” in Fig.3.8.

Sueface Water Absorption Test & Torrent Test

Measurer (　　　　　　)

Date	/ /	Temp. (°C)		Weather	
Time		Humidity (%)		Water Temp. (°C)	
構造物名		部位		リフト名	

SWAT Measurement			
Point Name			
Date File Name	.csv		
Record Start Time	:		
Surface Temp. (°C)			
Surface Moisture Content (%) [Kett HI-520-2]	1		Average
	2		
	3		
Surface Moisture Content (%) [CMEX Ⅱ]	1		Average
	2		
	3		
Surface Moisture Content (%) [Kett HI-100]	1		Average
	2		
	3		
カウント値 [Kett HI-100]	1		Average
	2		
	3		
water head (mm)	0sec		
	5sec		
	10sec		
	600sec		
a			
n			
p_{600}			

概略図
コメント
写真ファイル名

Torrent Measurement			
Point Name			
Surface Temp. (°C)			
Surface Moisture Content (%) [Kett HI-520-2]	1		Average
	2		
	3		
Surface Moisture Content (%) [CMEX Ⅱ]	1		Average
	2		
	3		
Surface Moisture Content (%) [Kett HI-100]	1		Average
	2		
	3		
カウント値 [Kett HI-100]	1		Average
	2		
	3		
kT ($10^{-16}m^2$)			
Measured Depth (mm)			

Fig.3.7 Data recording sheet

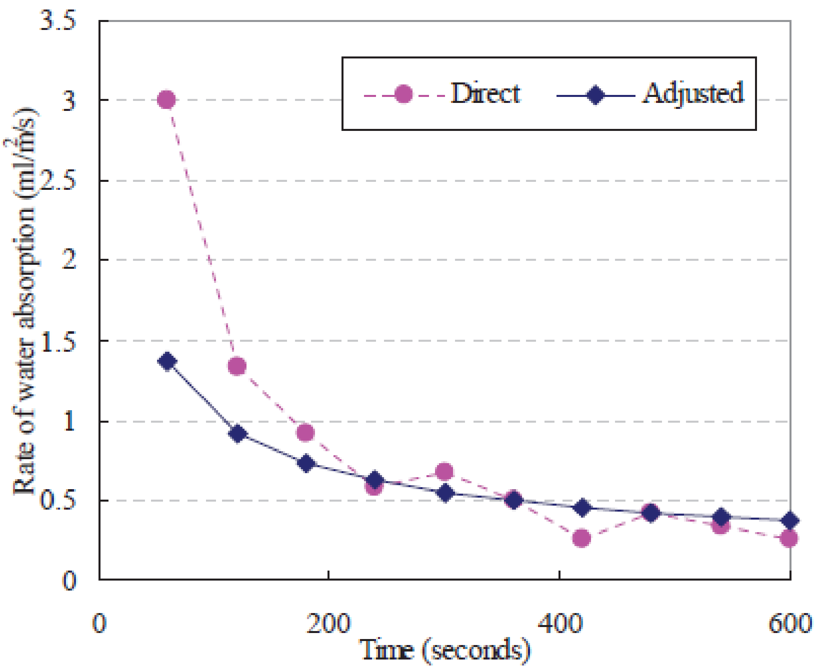


Fig.3.8 Test data analysis

In some cases, during the investigation of relatively good quality concrete, it might be possible that two successive values are same. Calculation of values of "a" and "n" using this data will not represent actual behavior. So, in such cases, discard the 2nd successive reading and consider the next value that will be different from the 1st one. Calculate the values of "a" and "n" by following the calculation procedure given above from the remaining values for adjusting the rate of water absorption.

3.5 Auto measurement SWAT system

An improvement in the SWAT to record the test data automatically was proposed by Hayashi et al. [3.7]. For this purpose, the pressure sensor was attached to the water cup in order to record the changes of water ahead as shown in Fig.3.9. Schematic diagram of the whole SWAT system is shown in Fig.3.10. The sensors not only record the decrease of water level automatically but also minimize the chance of some error due to readings up to 0.1 mm accuracy could be recorded.

Following are the specifications of the pressure sensors used in auto measurement SWAT system;

Voltage range	0.1-4.1 V
Pressure range	0-20 kPa (0-2039 mm of water head pressure)
Power supply	12-28 VDC

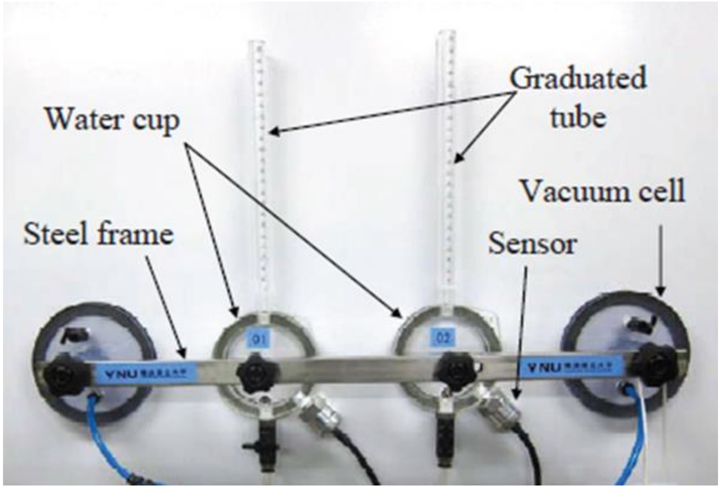


Fig. 3.9 SWAT system with pressure sensors

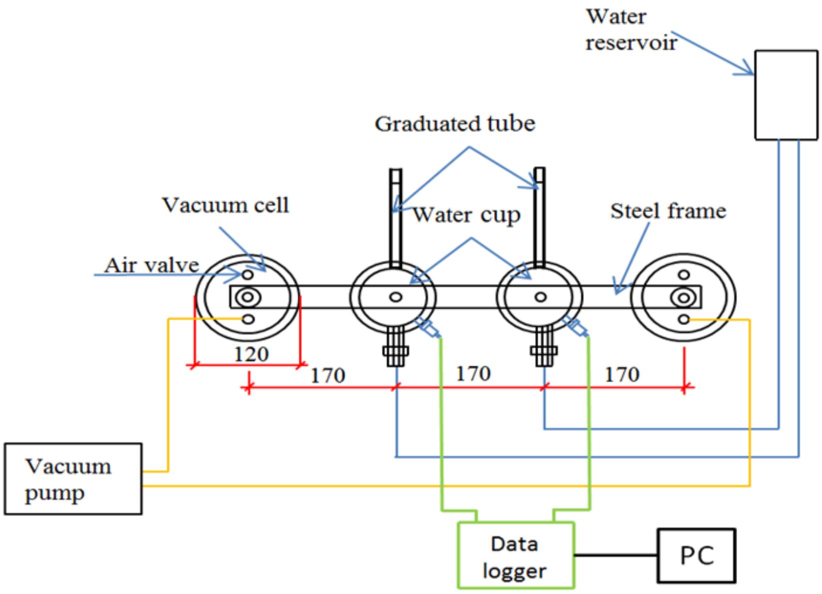


Fig.3.10 Auto measure SWAT assembly

Data are acquired by using the software SWAT on a laptop. Data are recorded in terms of voltage. After that, it is converted to the depth of water in the tube to calculate the rate of water absorption. For this purpose, calibration is required to convert the voltage values to the depth of water.

When comparing one test data between visual and auto measurement, the result is presented in Fig.3.11. It was seen that as the interval will be smaller more realistic behavior as compared with the large interval will be observed at the start. From 60 sec interval, both visual and auto measure showed the same results.

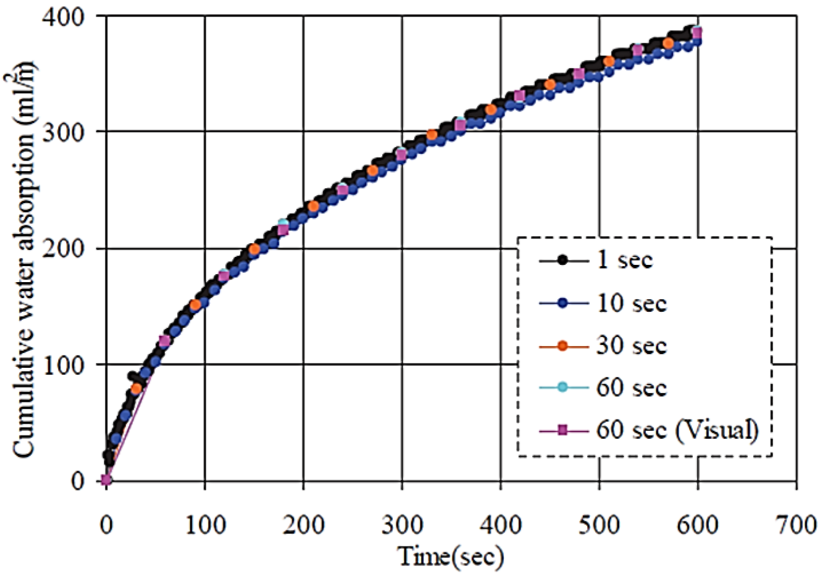


Fig.3.11 Comparison of auto measure and visual test data

3.5.1 Advantages

It is sure that using the pressure sensors and automatic data recording system will have many advantages than using visual observations method. Advantages of this automatic measurement include:

1) Amount of water absorption will be recorded with more precision
2) Eliminating the chances of data tampering
3) Increase in the number of measurement as the observer can prepare the other points for investigation during the data recording time
4) Long-term water absorption measurement is possible for other research purposes

3.5.2 Testing procedure

Following procedure is adopted for the auto measure SWAT system:

1) First of all, calibrate the auto measuring SWAT. The detailed procedure of calibration is given in the next section

2) Choose to measure the location and clean the concrete surface with the help of scrubber to remove any loose particles or dust

3) Record the surface conditions (temperature and moisture content) and boundary conditions (air temperature and R.H.)

4) Prepare the standby attaching the steel frame with the two vacuum cells

5) Link the air tubes between the vacuum pump and vacuum cells

6) Fix the stand against the concrete surface by vacuum generated through the vacuum pump

7) Link the water reservoir with water cup through flexible polyurethane water tubes. If some air is present in the tubes remove it by opening the stopcock due to it may generate the air bubbles at the time of filling to the water cup

8) Wet the sponge by water before attaching the water cup into the concrete surface

9) Fix the water cups by tightening the bolts on the steel frame. Also, ensure the verticality of the devices visually

10) Raise the water reservoir about 200 to 300 mm above the top of the graduated tube of the test device

11) Set up the PC and data logger. Connect the data cables of pressure sensors to the data logger and open the setup file on the PC to record the data. Start the logging of the data

12) Open the stopcock of the left water cup then close the stopcock after the device is filled with water and record the initial time. After that, doing the same order with the right water cup was done

13) Due to the automatic measurement method, the observer can prepare the other test locations, while the data is being acquired by the data logger

14) Stop the data recording by the data logger. Save the file on PC with the appropriate name to be used later for data analysis

15) Remove water from the water cups after 10 minutes measurement

16) Remove the test devices by opening the bolts

17) Remove the standby opening the air valve on the vacuum cell

18) Move the device to the other test place and follow the above procedure

After finishing the testing data are analyzed to calculate the SWAT results.

3.6 Comparison of the effect of old and new devices on the results of SWAT

Recently, Hachiyo consultants Co. has been created a new version of SWAT device with more many advantages than the old one. However, water absorption results given from new version are absolutely different with that from old SWAT device.

Hence, it is important to know in detail the effect of devices on SWAT results. A comparison about design and working of two devices is conducted on concrete specimens in Laboratory.

3.6.1. Comparison of designs between the old and new version of SWAT device

Both the old and the new versions of SWAT device consists of the water cup with the graduated pipe as shown in Fig.3.12 and 3.13. A stopcock is attached to the bottom of the water cup to add and remove water from the water reservoir. A stand consists of a steel frame and two vacuum cells support the SWAT device to be attached with the concrete surface. The stand is fixed on the concrete surface by vacuum pressure created inside the vacuum cells by air pump through air tubes. Water is added to (or removed from) the SWAT device from (or to) the water reservoir using the flexible water tubes. The p_{600} data is recorded automatically by a PC through pressure sensors attached under the water cup.

There are some significant differences between the old and the new version of SWAT. Firstly, the old versions have two different frame types, i.e., short and long frames. The short frame entails single water cup (Fig.3.14) while the long frame comprises two water cups (Fig.3.15). The stiffness of the long frame is lower than the stiffness of short frame due to the differences in their cross-sections. On the other hand, both of those frames of the old SWAT device have rectangular cross-section whereas the new SWAT device comprises the frame with a circular cross-section.

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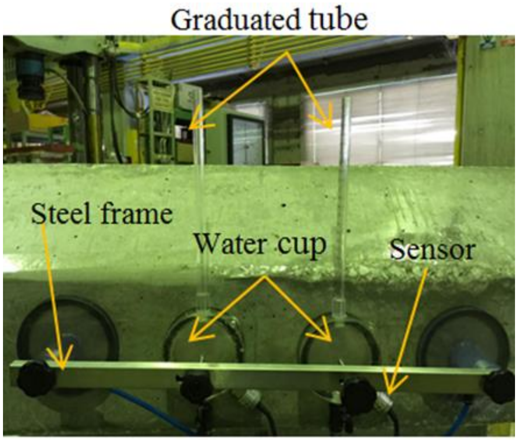

Fig.3.12 Old frame

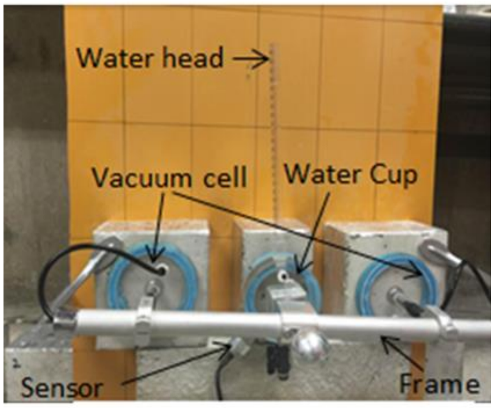

Fig.3.13 New frame

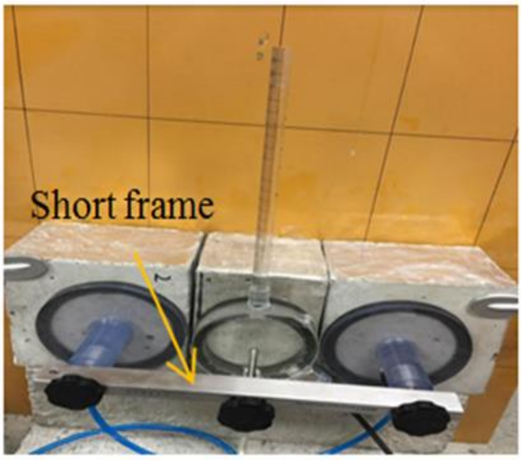

Fig.3.14 Old short frame

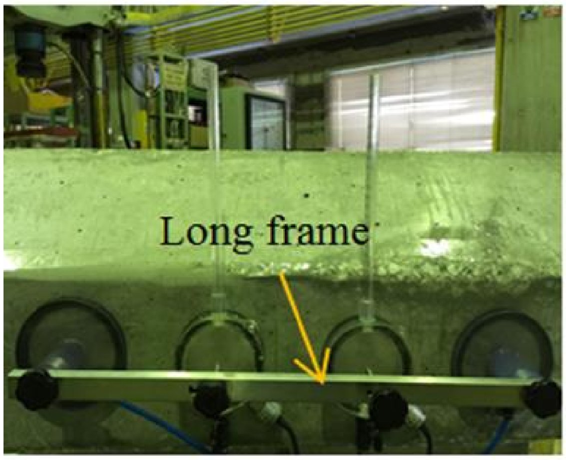

Fig.3.15 Old long frame

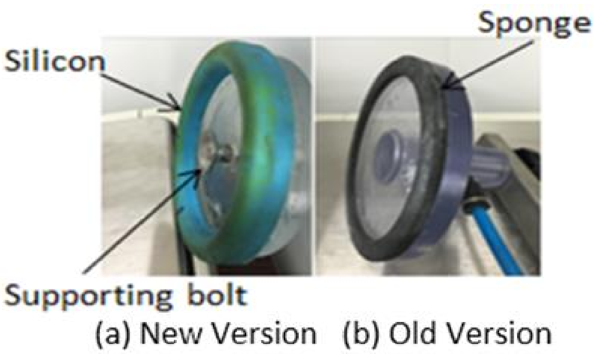

Fig.3.16 Vacuum cells

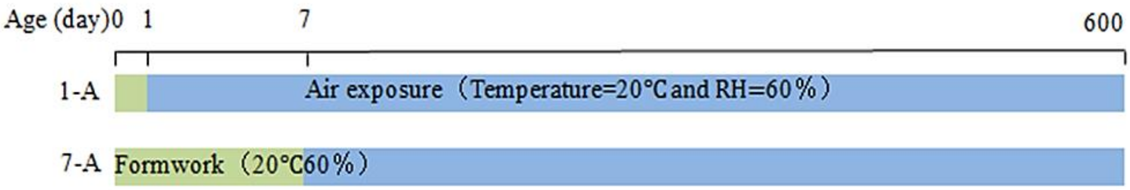

Fig.3.17 Curing conditions

Fig.3.18 Specimen 40-7 and specimen 52.5-1

Table 3.1 Mix proportions for the specimens

Type	W/C (%)	The maximum aggregate size(mm)	Amount of air (%)	Unit amount(kg/m^3)					
				Cement	Water	Fine aggregate	Coarse aggregate	AE water reducing agent	AE agent
BB	40	20	4.5	413	165	731	1013	2.48	3.30
	52.5	20	4.5	322	169	814	996	2.58	2.58

3.6.2. Experimental program

1) Materials and Curing Conditions:

The effect of old and new SWAT devices on the measured water permeability results of cover concrete was investigated considering two specimens of different mix proportions (summarized in Table 3.1) as well as under different curing conditions (Fig.3.17). The first specimen with 40% of W/C ratio was kept under sealed condition into the formwork for seven days. After the formwork removal, the specimen was exposed to 20^{o}C room temperature along with 60% relative humidity (R.H.) for further 600 days. The specimen was considered to be obtained good concrete quality and termed as 40-7. Another specimen with W/C ratio of 52.5% was kept undersealed with formwork only for one day and then exposed to the same condition as specimen

40-7 for 600 days. It was considered to possess poor concrete quality and was termed as 52.5-1. Specimens are seen in Fig.3.18.

2) Experimental Methods:

In the present study, the influences of the old and the new SWAT devices on the corresponding recorded permeability results considering both good and poor quality of concrete was investigated following the permeable and the impermeable measurement methods.

Impermeable Measurement Method:

In the impermeable measurement method, the specimens were sealed with plastic sheets preventing water absorption by the concrete. Each specimen was measured with the short and long framed old SWAT devices as well as with the new SWAT device. At the same time, these specimens were measured considering sealed and unsealed vacuum cells location. Then, they were measured with vacuum cells without sponge regarding old frame and without supporting bolt corresponding to a new frame. The measured results were shown as Fig.3.19, 3.20 and 3.21.

Permeable Measurement Method:

In the permeable measurement method, specimens 40-7 and 52.5-1 (Fig.3.18) have been sliced (into a smaller size) to control moisture more easily and the five surfaces of each specimen were sealed with alumina tape ensuring an exposed surface for each specimen for SWAT. Thereafter, the specimens were placed into the oven for drying at 60ºC temperature for five hours. Next, they were kept into the curing room at 20ºC temperature along with 60% R.H. for 48 hours. Thus the specimens were prepared for SWAT. The weight of the specimens was recorded consistently before and after drying, along with curing process and at the time of SWAT. It is to be noted that the weight of the specimens before measuring SWAT has to be the same to ensure that the pore structure of concrete is similar for each measurement stage. The weights of the specimens were summarized in Table 3.2 and SWAT results were depicted in Fig.3.18.

3.6.3 Results and Discussions

1) Results obtained from the impermeable measurement:

First, it is observed from Fig.3.20 and 3.21 that there is the same trend in results obtained from both long and short framed old SWAT devices. It reveals that the differences in stiffness and length of frames regarding old SWAT device do not affect water permeability results of cover concrete.

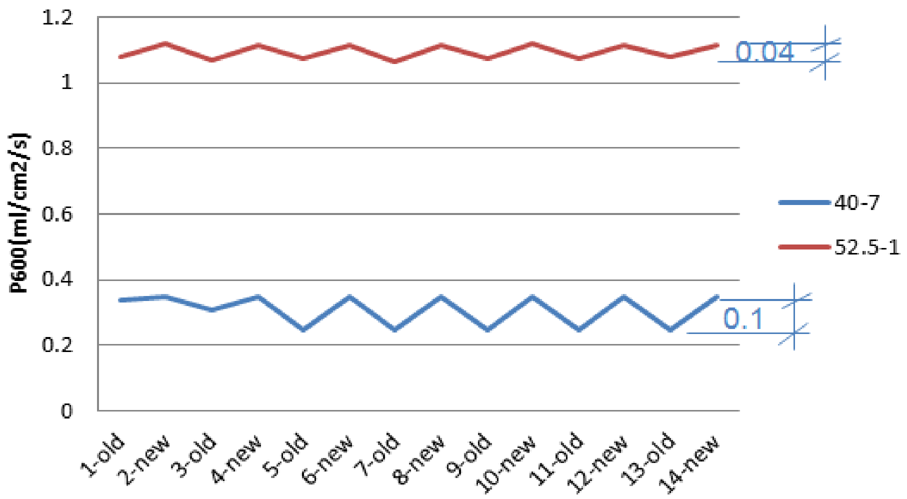

Fig.3.19 Permeability Results from the Permeable Measurement Method Recorded by the Old and the New SWAT Devices

Table 3.2 The weight of specimens before and after SWAT measuring

Specimens	40-7A		52.5-1A	
Number of measurements	Weight (g) before measurement	Weight (g) after measurement	Weight (g) before measurement	Weight (g) after measurement
1-old	3473.88	3476.48	3496.98	3502.4
2-new	3473.89	3476.16	3496.63	3503.24
3-old	3473.88	3476.18	3496.69	3502.33
4-new	3473.83	3476.04	3496.7	3502.16
5-old	3473.84	3476.24	3496.71	3502.22
6-new	3473.91	3475.98	3496.87	3502.29
7-old	3473.92	3476.27	3496.86	3502.25
8-new	3473.95	3476.2	3496.87	3502.08
9-old	3473.98	3476.23	3496.88	3502.36
10-new	3473.89	3476.1	3496.7	3502.02
11-old	3473.88	3476.15	3496.88	3502.42
12-new	3473.87	3475.74	3496.84	3502.24
13-old	3473.86	3476.09	3496.79	3502.32
14-new	3473.88	3475.98	3496.86	3502.08

Second, despite the sealed condition, there was a rapid increase in the water height of the old device with sealed vacuum cups corresponding to a good quality concrete (specimen 40-7) (Fig.3.20 and 3.21). During the measuring process, the vacuum cells of the old SWAT device comprising of soft sponge are sucked forward to the specimen surface under the action of air pressure pump. As a result, the contained water inside the water cup is elevated and filled up the water head. This phenomenon occurred dramatically in case of a good quality concrete surface with very fine pores or sealed surface with no pores as the existing air inside the vacuum cells is sucked out instantly by the air pump. It is also noticeable that using an old frame without sponges in front of vacuum cups provides accurate results.

Alternatively, in case of poor cover concrete having large pore-size with complex pore-distribution, the absorbed air inside the concrete is sucked out leisurely over the concrete surface of attached vacuum cells. Consequently, the applied air pressure by the pump is reduced and the water cup is attached to surface concrete unhurriedly. As a result, the water head increased a little in case of poor quality concrete.

Third, when the impermeable measurement is done without any sponges in front of water cells, the water head was unchanged explaining the contribution of sponges on the absorption results of cover concrete, as shown in Fig.3.20 and 3.21.

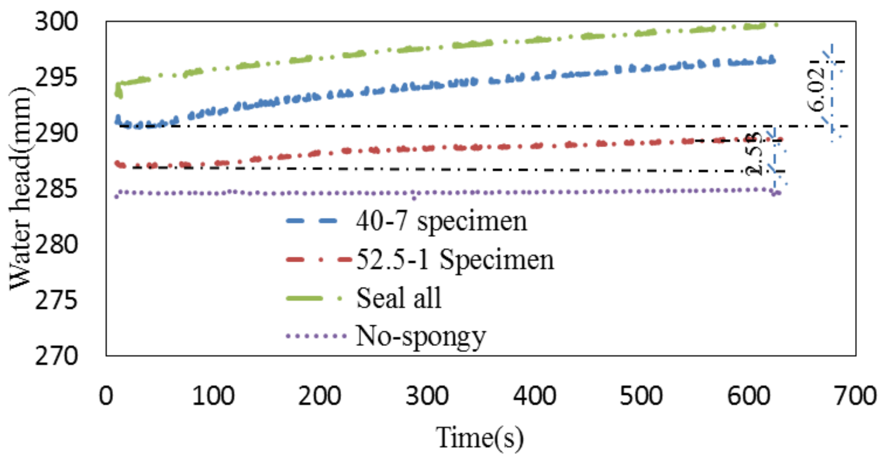

Fig.3.20 Impermeable measurement results with short and old frame

Fourth, the water head increased rapidly when the supporting bolt is removed from the water cups for the new SWAT device (Fig.3.22). The constant water head is observed when supporting bolt exists. It is supposed that the supporting bolt in the new SWAT device is a useful tool to resist the frame from moving forward the specimen surface.

Finally, it was observed that the water permeability results provided by the old SWAT device are always less than those obtained from new SWAT device (Fig.3.20 and Fig.3.21).

2) Results obtained from permeable measurement:

The permeable measurement results are shown in Fig.3.19 confirming that the water-permeable result of cover concrete detected by an old SWAT device is always lower than that measured by the new version of SWAT device, and lower than the real permeable result. Water head was constant in new device results. This is proof that new device always gives real absorption results. The difference between the p_{600} values measured by old and new device regarding poor concrete is 0.04 (3.64%), while the difference corresponding to good quality concrete is much higher, about 0.1 (28.57%) as observed in Fig.3.19.

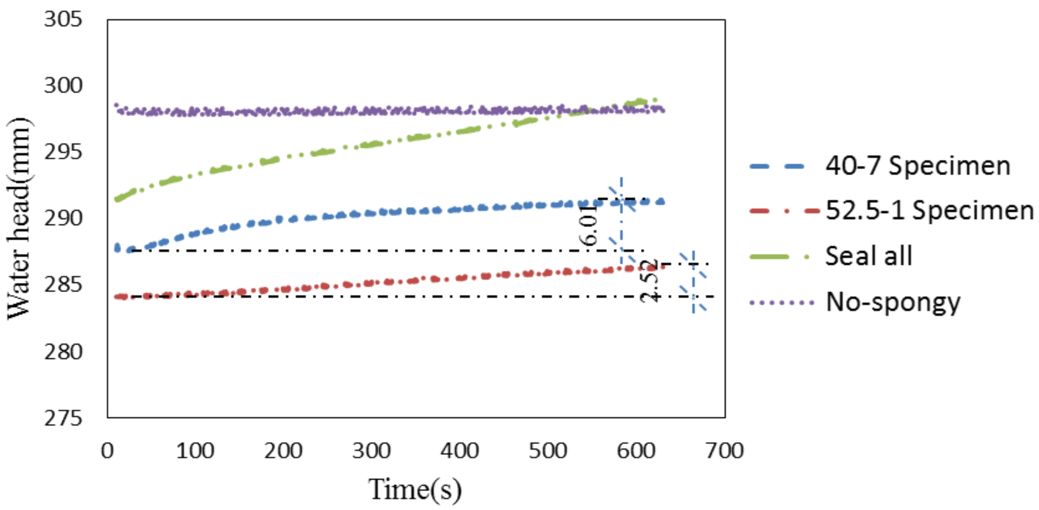

Fig.3.21 Impermeable measurement results with long and old frame

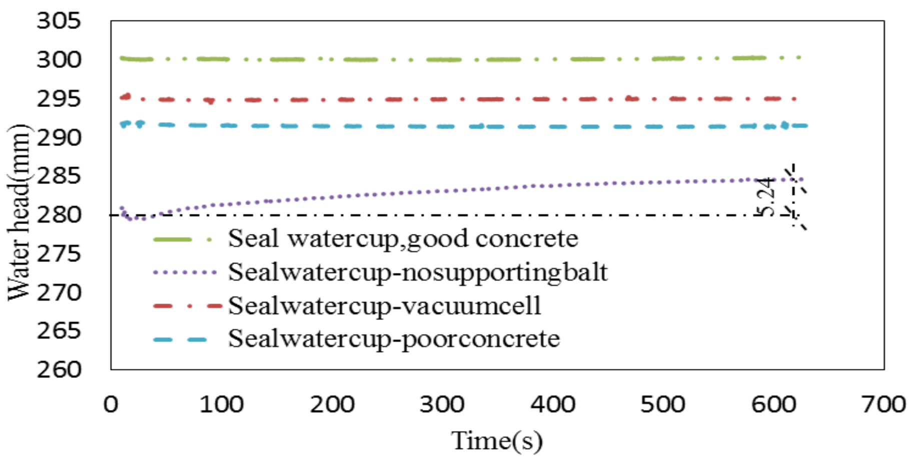

Fig.3.22 Impermeable measurement result recorded by the new SWAT device

3) Effect of the stiffness of the frames on the measured permeability results:

In case of the impermeable measurement method, the bias of water height is almost same around 6.01mm and 2.51mm corresponding to good and poor quality concrete irrespective of the differential stiffness of long and short frame in the old

SWAT device. That proves that the stiffness of SWAT frames does not affect permeability results. Similarly, the results provided by high stiffness frame were constant due to the existence of supporting bolts, while the measured result without supporting bolts shows a dramatically increase water height by 5.24mm.

3.7 Summary and Conclusions

A simple, fully non-destructive, rapid and variable surface water absorption test (SWAT) has been presented in this chapter. Also, introduction to the auto measure SWAT system has been described. The force induced by the test device to the concrete surfaces is representing actual behavior as that of driving force of rain and wind to move the aggressive substances into the concrete.

1) Unlike another test method like ISAT, SWAT is equally and effectively applied at the laboratory and to actual RC structures. Also, SWAT does not require any destructive arrangement for installation as is required in case of ISAT.

2) Due to its easy and quick installation, 10 to 12 points can be tested by SWAT in 1 hour by two water cups on the given structural member.

3) Auto measure SWAT system requires no observer for visually recording the data during the test time and in this way, time can be saved as the observers can prepare the other test points during the data accusation system. Hence, the number of observations can be increased and the testing can be completed quickly as compared with the visual observation method. Furthermore, by utilizing the auto measure SWAT system chances of tempering of test data are minimized.

4) It is seen that the differences in stiffness and length of frames regarding old SWAT device do not affect water permeability results of cover concrete.

5) The rapid increase of water head occurs in the old SWAT device with sealed vacuum cups corresponding to good quality concrete due to the soft sponge attached to the vacuum cups along with very fine pores of the good quality cover concrete influencing the instant suction of the existing air from the vacuum cup by the air pressure pump and causes consequent filled up water head.

6) The water head increases slowly in the old SWAT device for poor quality concrete having large pore-size with complex pore-distribution since the absorbed air inside

the concrete is sucked out leisurely over the concrete surface of attached vacuum cells.

7) When the impermeable measurement is done without any sponges in front of water cells, the water head was unchanged explaining the contribution of sponges on the absorption results of cover concrete.

8) The water head increases rapidly when the supporting bolt is removed from the water cups for the new SWAT device. The constant water height is observed when supporting bolt exists proving the supporting bolt as a useful tool in the new SWAT device to resist the frame from moving forward the specimen surface.

9) The water absorption results provided by the old SWAT device are always less than those obtained from new SWAT device. Conversely, the old SWAT device without sponges in front of vacuum cups can provide accurate results.

10) The water permeability value of cover concrete detected by old SWAT device is lower than that measured by the new version of SWAT device.

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Chapter 4

THE EFFECTS OF MOISTURE CONTENT ON SURFACE WATER ABSORPTION TEST AND AIR PERMEABILITY TEST

4.1 Introduction

The SWAT results will change when the moisture condition of concrete changes due to either rain or humidity changes. As a result, absorption measuring at different moisture content receives different absorption results at the same location. Therefore, it is necessary to find out the threshold of moisture content which always receives stable results when SWAT conducted. It has been pointed out in previous studies that when the surface moisture of covercrete measured by CMEX-II is over 5.5%, the results of air permeability become apparently smaller which will cause overestimating of air permeability resistance [4.1]. However, the number of research works related to the effects of the moisture content on water absorption and gas permeability is limited. The present chapter investigates the effects of moisture content of covercrete on water absorption and air permeability and find out the threshold of moisture content to conduct SWAT and double chamber air permeability test.

4.2 Objectives

In this chapter, water absorption and air permeability tests are conducted for wet concrete after one or two days curing in high relative humidity. This can be true in site when SWAT and double chamber air permeability measurement of concrete structures are done in a humid environment. It is called dry to wet process. This chapter has some objectives as below:

1) To investigate the effects of the moisture content of covercrete on water absorption and air permeability.
2) To define the rational threshold of moisture content measured by two moisture meters (CMEX-II and HI-520-2) when conducting SWAT and double chamber air permeability test
3) To investigate the effect of curing condition and water to cement ratios on surface absorption and air permeability.

4.3 Experimental Program

There were 27 prism specimens 300x300x150 mm made with three kinds of water to cement ratios (W/C) such as 40%, 50%, and 60%. They were cured in three different patterns. After the age of 60 days from casting day, these specimens were stored in three relative humidity conditions at 60% (curing room), 80% and 99.9%, and temperature at 20°C. After 1 to 2 days, SWAT and double chamber air permeability tests were conducted. The flow of experiment is shown in Fig.4.1

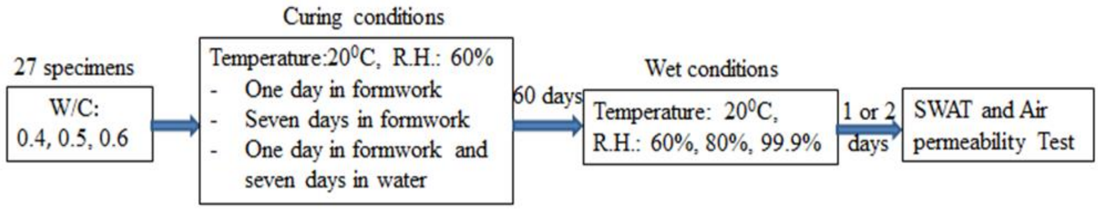

Fig.4.1 Flow of Experiment

4.3.1 Dimension Details of Specimens

The front view, the side view, and the measurement locations in specimens are shown as Fig.4.2. Dimensions are 300x300x150mm

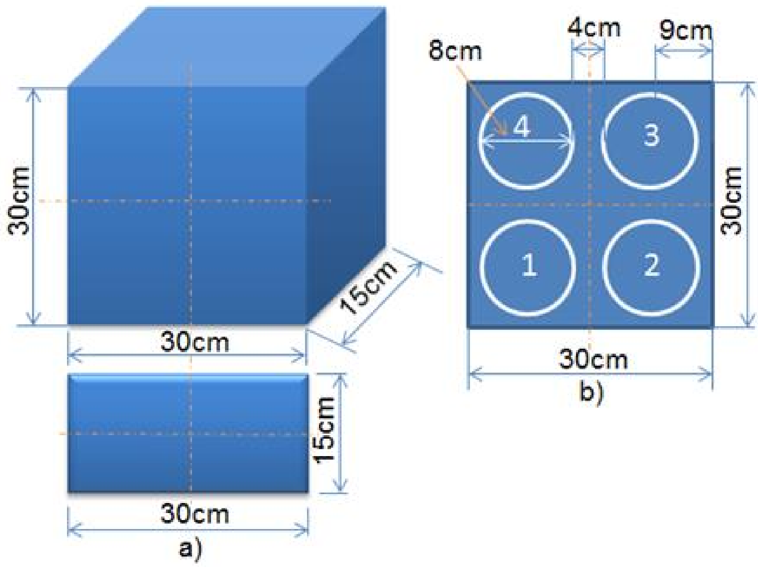

Fig.4.2 Shape of specimens

4.3.2 Materials and Mix Proportions of Specimens

The materials used for concrete mixes in this experiment are shown in Table 4.2. Cement is ordinary Portland cement made by Taiheiyo Cement Co., Ltd. Water to cement ratio was set to three kinds of 40%, 50%, and 60%.

Table 4.1 Materials used for Concrete

Materials name	Types and Characteristic values
Cement	Ordinary Portland cement (OPC) (density: 3.16g/cm^3)
Fine aggregate	Provided by Hachiyo consultant (density: 2.58g/cm^3)
Course aggregate	Provided by Hachiyo consultant (density: 2.62 g/cm^3)
Admixture	AE water reducing agent Floric SF 500S AE agent Floric AE-4

Table 4.2 Mix proportions

Max. Agg. (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Mix compositions(kg/m^3)					
					W	C	Fine aggregate	Coarse aggregate	Admixture	
									[1]Ad	[2]AE
20	12	4.5	40	45	160	400	776	687	4.4	0.8
20	12	4.5	50	47	160	320	841	688	3.2	0.64
20	12	4.5	60	48.5	160	267	890	684	2.67	0.53

[1]Ad: Water reducing admixture, [2]AE: Air entraining agent

4.3.3 Curing Conditions

27 specimens were created and cured in the curing room at temperature 20^{o}C, and relative humidity (R.H.) at 60%. There were nine specimens for each kind of W/C ratio. In which, three specimens of each kind of W/C ratio were removed from formwork after one day of casting, three specimens were removed from formwork after seven days of casting, and remaining specimens were removed from formwork after one day and immersed in water for six days before all of them were exposed in curing room. The curing process is shown in Fig.4.3.

At the age more than 60 days, Series-1 consisting 27 specimens divided into nine groups were started to be measured. In each group, three same types of specimens were moved into three different environmental conditions for one or two days. The first specimen was kept in the curing room at (20±1)^{o}C and (60±2)% relative humidity (R.H.). The second specimen was moved to a room where R.H. was 80±2% and the temperature was (20±1)^{o}C. The last one was moved to a room where R.H. was 99.9% and the temperature was (20±1)^{o}C. The moisture content of specimens was measured by two moisture meters CMEX-II, and HI-520-2 devices. CMEX-II and HI-250-2 devices are shown as Fig.4.4.

4.3.4 Moisture Meters

In this experiment, two devices (CMEX-II and HI-520-2) are utilized to measure the moisture content of concrete at the surface of the specimens.

CMEX-II is a low-frequency device to detect and evaluate the moisture content in concrete by measuring the electrical impedance. A low frequency electronic signal is transmitted into the material under test device. The strength of this signal varies in proportion to the amount of moisture present in the material. The CMEX-II determines the strength of the current and converts this to a moisture content value for concrete.

HI-520-2 is a handy high-frequency capacitive moisture tester with an integrated main unit and sensor section. When water content in concrete is high, the conductivity will increase. HI-520-2 can determine the moisture content by determining the relationship between moisture content and conductivity. The value obtained in this way is displayed as the measured moisture content.

4.4 Results and Discussion

After one or two days in curing room for each level of R.H. in high relative humidity room, Specimens were measured using SWAT and double chamber air permeability test. First, moisture contents were measured by CMEX-II and HI-520-2 devices. Then, double chamber air permeability test was conducted. SWAT was measured at least 20 minutes after double chamber air permeability measurement. Each specimen was measured at two opposite sides; each side has four measurement locations. Measurement locations are shown in Fig.4.2. Results were determined as depicted in Fig.4.6 to 4.11.

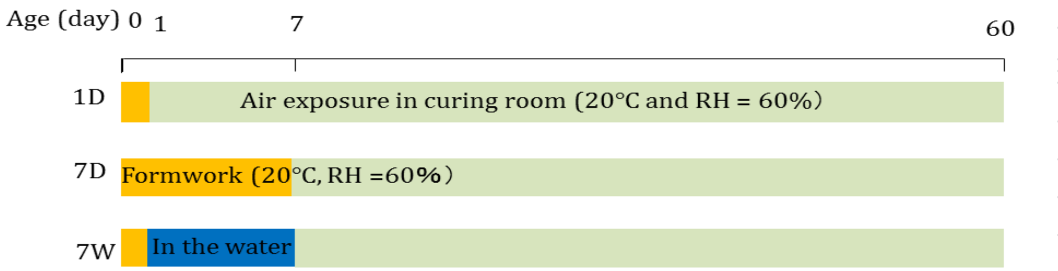

Fig.4.3 Curing conditions

Fig.4.4 Moisture Meters

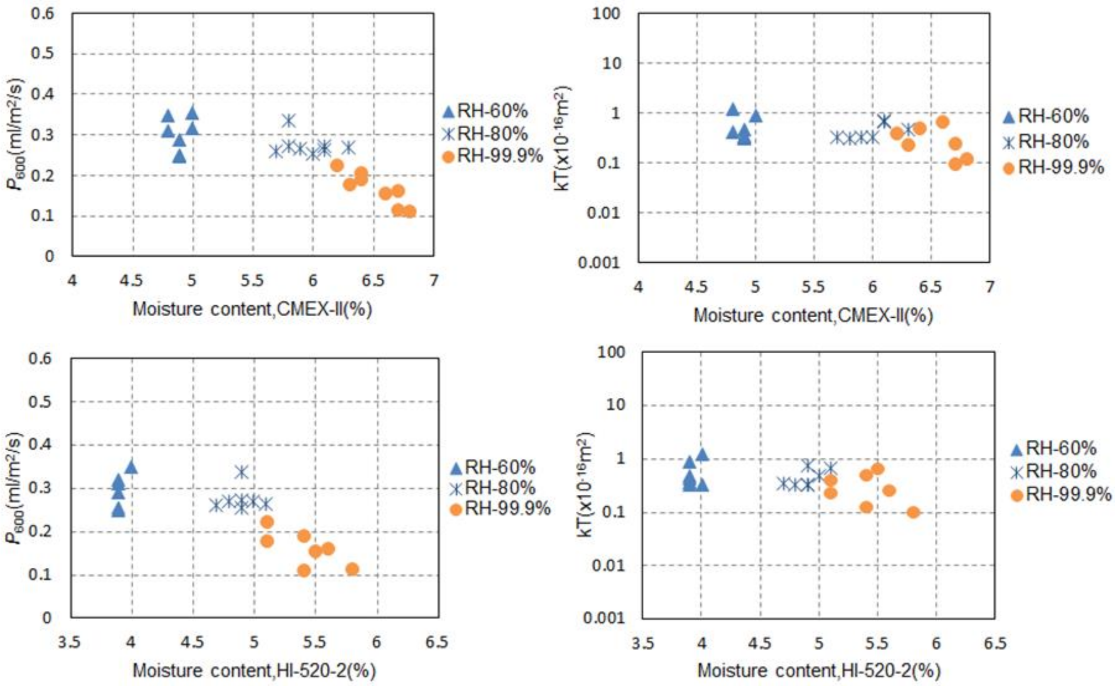

Fig.4.5 Water absorption and air permeability results (W/C=40%, one day sealing in formwork)

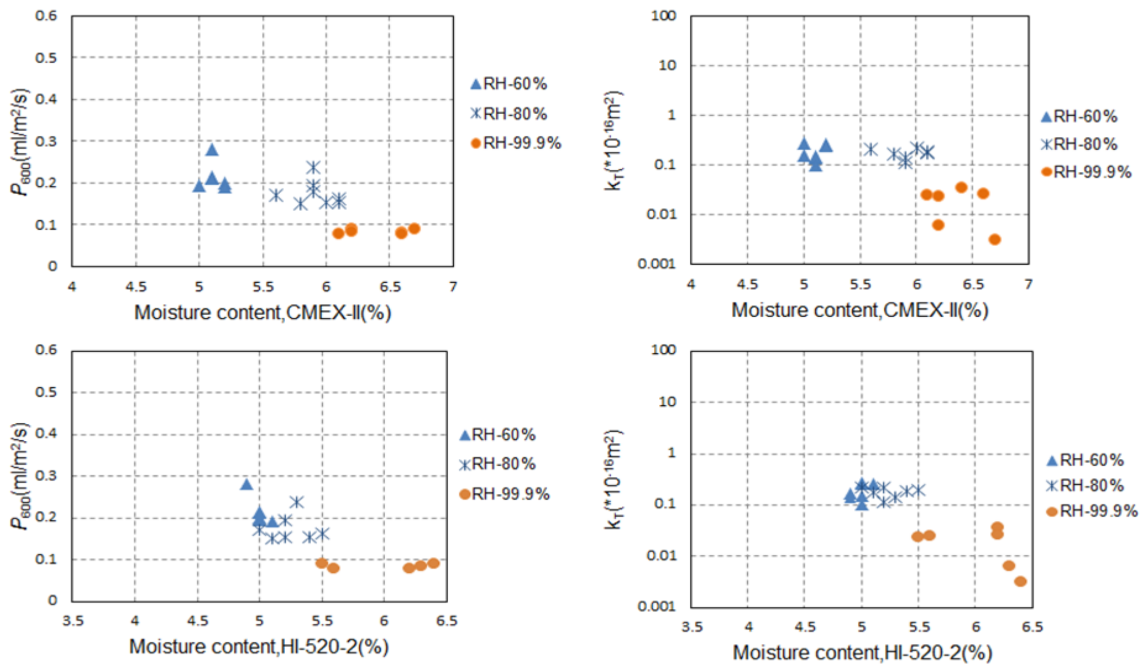

Fig.4.6 Water absorption and air permeability results (W/C=40%, one day sealing in formwork and six days water curing)

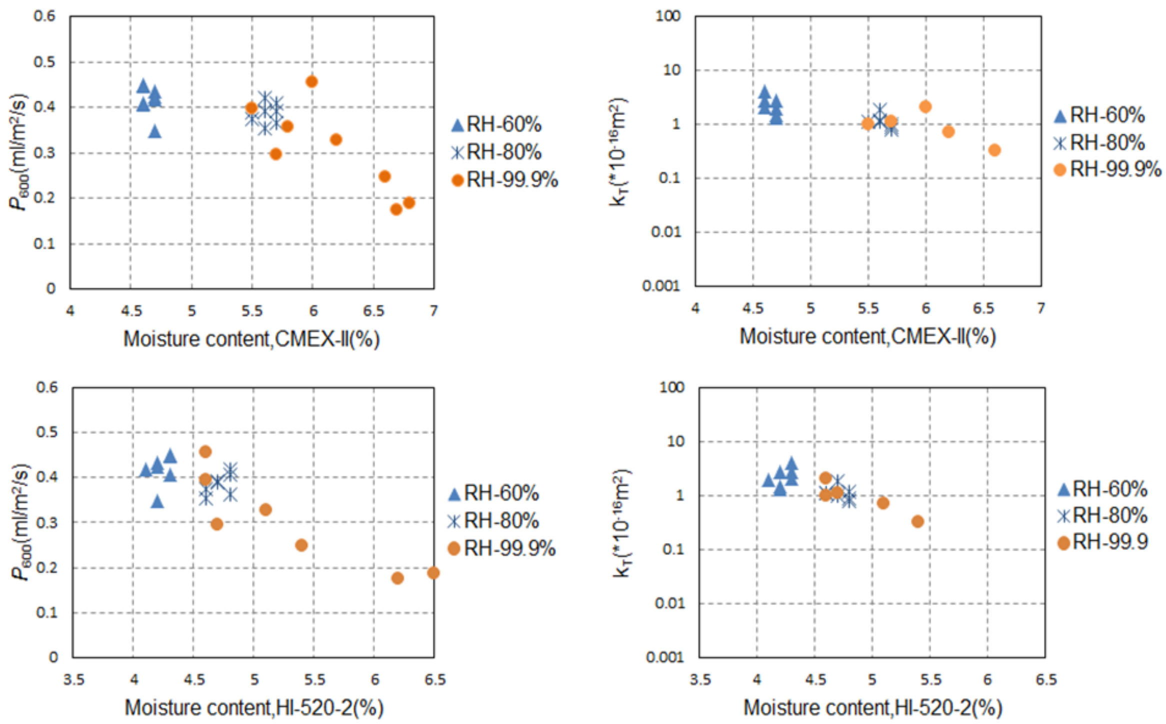

Fig.4.7 SWAT absorption and air permeability results (W/C=50%, one day sealing in formwork)

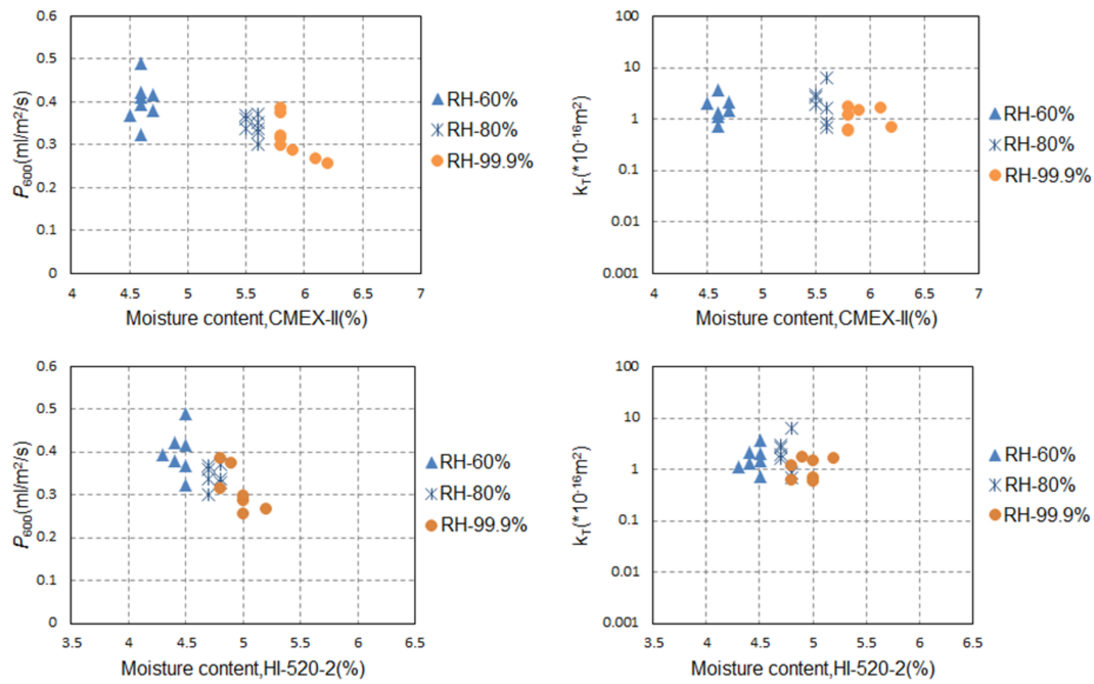

Fig.4.8 SWAT results and air permeability (W/C=50%, one day sealing, and six day in water)

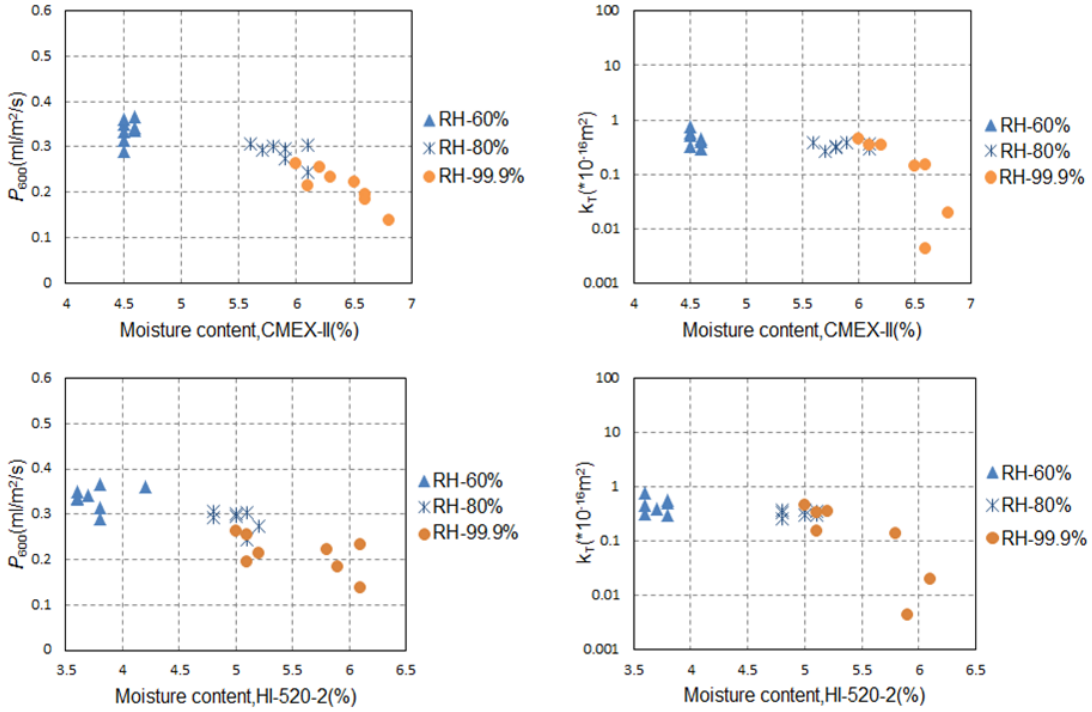

Fig.4.9 SWAT results and air permeability (W/C=60%, seven day sealing)

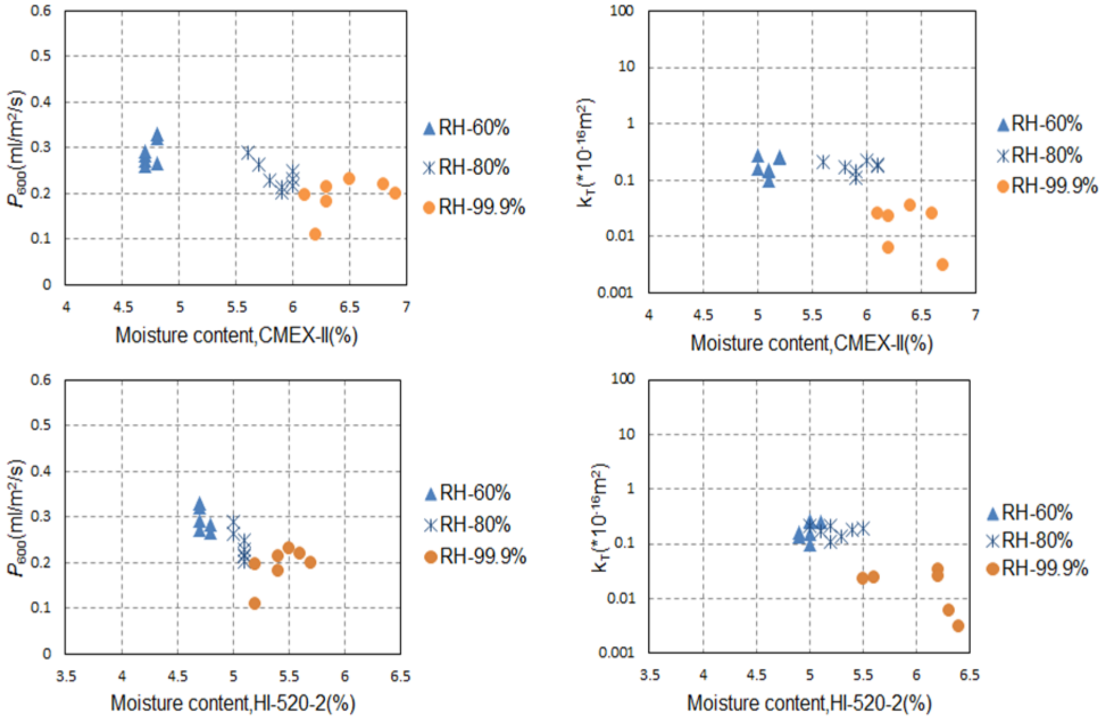

Fig.4.10 SWAT results and air permeability (W/C =60%, one day sealing and six days in water curing)

4.4.1 The Rational Threshold of Moisture Meters [4.4]

As can be seen in Fig.4.5-4.10, a general trend is observed that higher the moisture content, smaller the water absorption and the air permeability (p_{600} and kT). It is observed in all figures that p_{600} and kT are almost constant values when the moisture content (measured by CMEX-II and HI-520-2) is lower than a threshold value. The moisture meter CMEX-II seems to show larger variation in measured moisture content than HI-520-2.

It can be seen from figures that p_{600} seems apparently smaller when the moisture content measured by the AC impedance method was higher than about 6.0%. Meanwhile, when the moisture content measured by handy high-frequency moisture meter (HI-520-2) was higher than approximately 5.0%, p_{600} showed apparently smaller values.

From Fig.4.5 to 4.10, it is observed that at the value of about 6.0% in moisture content detected by CMEX-II, kT showed smaller values. At present, the value of 5.5% in moisture content measured by the AC impedance device is utilized as a threshold value to judge whether appropriate measurement can be done, however, this value seems conservative, so it can be increased according to further investigation. When HI-520-2 was used, the threshold value of moisture content was around 5-5.5%.

In the present investigation, two moisture meters were used. The authors have not clarified the characteristics or effective measurement depths (in concrete) of these moisture meters. The environmental conditions for specimens are limited in this chapter. Therefore, the authors will not propose here a kind of threshold value of surface moisture content for appropriate measurement of SWAT and double chamber air permeability test.

4.4.2 The Effect of Curing Condition on Surface Absorption

Fig.4.11 and 4.12 show the effects of curing condition on SWAT results of W/C 60%, and 40% specimens, respectively. It can be seen that the specimens with poor curing condition absorbed more water than the specimens with good curing condition, while the specimens with good curing stored in the highly humid condition of 99.9% showed very high moisture content. As a result, it is confirmed that the specimens with good curing are easy to get wet in a humid condition (Fig.4.11). The Fig.4.12 shows the results of W/C 40% specimen which reveals the same kind of tendency with the Fig.4.11, but the effects of curing conditions are not clear, because the original moisture content of concrete is high and p_{600} is small due to low W/C.

Fig.4.13 and 4.14 show the effects of curing condition on air permeability results. The tendency is similar to that of water absorption shown in Fig.4.11 and 4.12.

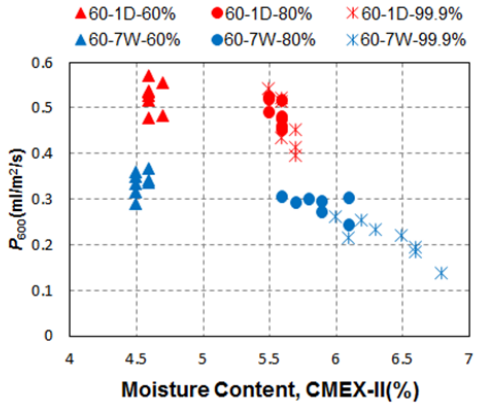

Fig.4.11 SWAT result (W/C=60%)

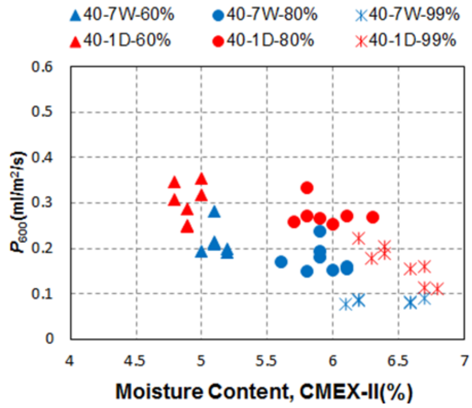

Fig 4.12 SWAT result (W/C=40%)

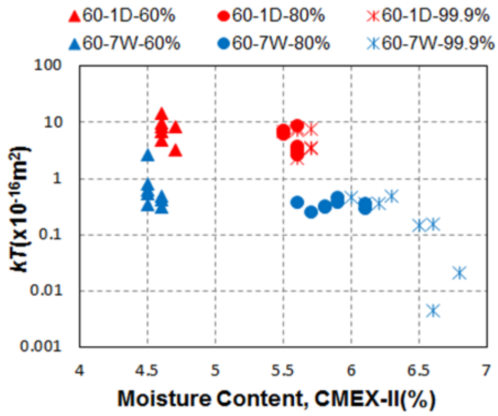

Fig.4.13 air permeability result (W/C=60%)

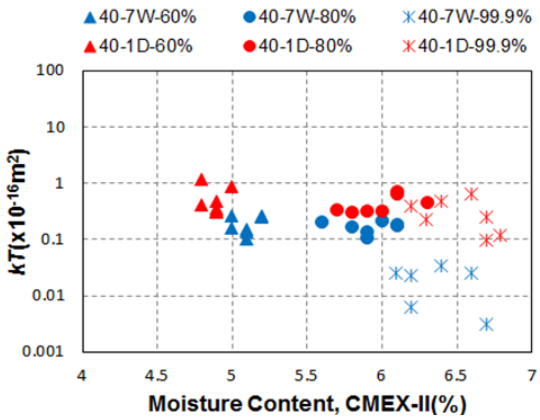

Fig.4.14 air permeability result (W/C=40%)

4.4.3 The Effect of Water to Cement Ratio on Surface Absorption

Fig.4.15 and 4.16 show the effect of W/C ratio on water absorption. The results of 40% and 60% W/C of specimens with poor curing condition are shown in Fig.4.15. It can be seen that the specimens with 40% W/C absorbed less water. Furthermore, the specimens with 40% W/C showed higher moisture content. Therefore, we can say that for lower W/C ratio, the water absorption rate is smaller and covercrete gets wet easily in high R.H. In Fig.4.16, the results of specimens with good curing are shown. The effects of W/C ratio can be observed but not very clear, because both specimens originally possessed high quality and high moisture content.

The effects of W/C ratio on air permeability are shown in the Fig.4.17 and 4.18. The tendency is similar to that explained in the Fig.4.15 and 4.16.

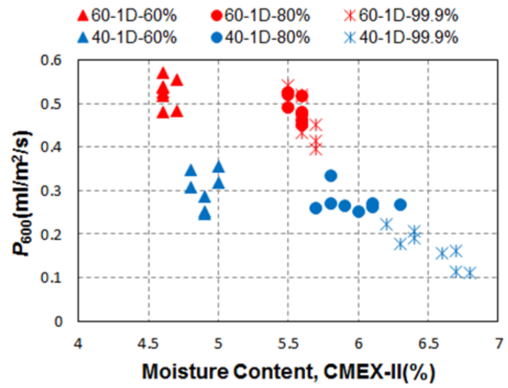

Fig.4.15 SWAT results (sealed for one day)

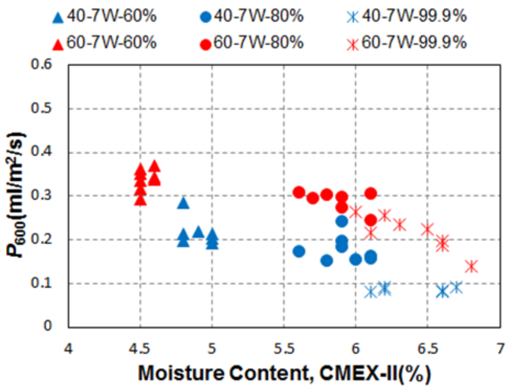

Fig.4.16 SWAT results (one day sealing and six days water curing)

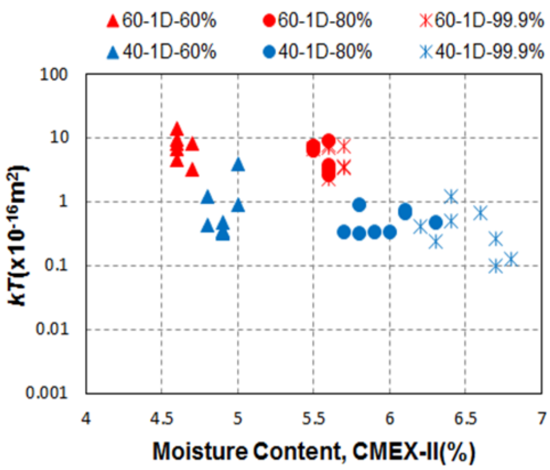

Fig.4.17 Air permeability results (sealed for one day)

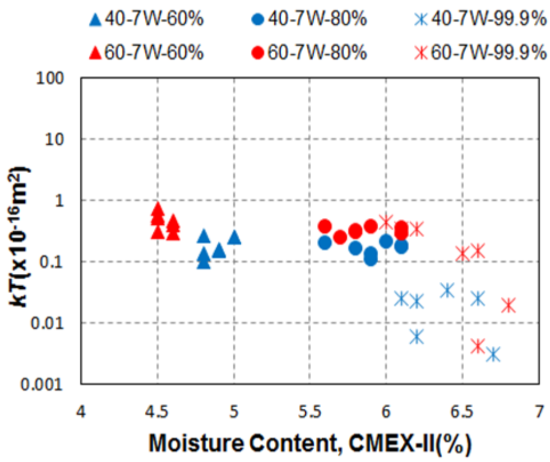

Fig.4.18 Air permeability results (one day sealing and six days water curing)

4.5 Summary and Conclusions

Two devices (CMEX-II and HI-520-2) are used to measure the moisture content of concrete before conducting SWAT and double chamber air permeability test in case of concrete specimens stored in wet conditions for one or two days after long term air dry condition. The results are summarized as below.

1) It has been seen that moisture content of covercrete affected the water absorption resistance (p_{600}). When the moisture content measured by CMEX-II was higher than about 6.0%, p_{600} was apparently smaller. When the moisture content was

measured by HI-520-2, p_{600} showed apparently smaller values when the moisture content was higher than around 5.0%.

2) It has also been found that moisture content of covercrete influenced the air permeability (*kT*). If moisture content measured by CMEX-II was higher than 6.0%, *kT* showed smaller values. When HI-520-2 was used, the threshold value of moisture content was around 5-5.5%.

References

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[4.4] Toan, VN. Hosoda, A. Komatsu, S. and Ikawa, M., "Effects of Moisture Content on Surface Water Absorption Test and Air Permeability Test" Proceedings of the JCI, Vol. 40, No.1, pp 1725-1730, 2018.

Chapter 5

EFFECTS OF LONGTERM WETTING ON MOISTURE PROFILE OF COVERCRETE AND ON SURFACE WATER ABSORPTION TEST

5.1 Introduction

In chapter 4, water absorption of concrete affected by higher moisture content obtained in humid environment was investigated. At actual sites, water absorption test can be conducted any time, for example in sunny days after long time wetting due to rain, where the surface of covercrete may be dry but inner concrete is still wet. As a result, this may cause overestimation of water absorption and air permeability resistance. Therefore, current chapter presents the investigations regarding the effects of l long-term wetting on moisture profiles of covercrete and on SWAT results.

5.2 Objectives

Water absorption and air permeability of concrete specimens were measured with various kinds of moisture profiles after their moisture content were detected by moisture meters, and by count values of sensors embedded into concrete. Each kind of moisture meter can be used to measure moisture content at different depths in concrete and they have different relationships with SWAT and double chamber air permeability values. The aim of this chapter is to investigate the effects of long-term wetting on moisture profiles in covercrete and the effects on SWAT results and air permeability results. In this chapter, the author will confirm that some moisture meters cannot detect whether concrete at the depth of 5mm is sufficiently dry for appropriate SWAT measurement. Furthermore, through numerical simulation results, the author will check the effect of rehydration on water absorption and air permeability of covercrete stored in high relative humidity for seven days.

5.3 Investigating the Effects of Moisture Profiles on SWAT and Air Permeability Test Results in Two Processes of Curing

5.3.1 Outline of Experiment

54 specimens were provided of 300x300x150mm size with three kinds of water to cement (W/C) ratio, 40%, 50% and 60%. In order to detect moisture profiles of

covercrete, 5 sensors are embedded in each specimen at 5mm, 10mm, 20mm, 30mm and 50mm depth as shown in Fig.5.1 (c). After casting, these specimens are cured in three different conditions.

First one-third of 54 specimens (18 specimens) are removed from formwork after one day, second one-third of specimens are removed from formwork after 7 days of casting. Remaining 18 specimens are soaked in water for six days after removing the formwork at one day. At the age of 8 days these specimens are cured in a curing room at temperature of 20°C and relative humidity (R.H.) of 60%. After 60 days of material age, they were divided into two series, such as Series-1 and Series-2. Each series consists of 27 specimens.

The specimens in Series-1 were kept at different R.H., 60%, 80%, 99.9%, at the same 20°C room temperature in one to two days before conducting SWAT and double chamber air permeability test. This curing process is defined as dry to wet process. The specimens in Series-2 were stored in a high R.H. room of 99.9% and temperature of 20°C for seven days. Then, they were exposed in the air in the curing room (RH=60%) for 3 days, 7 days and 14 days before conducting SWAT and double chamber air permeability test.

The shape and dimensions: The front view, the side view, measurement locations and dimensions are shown as Fig.5.1.

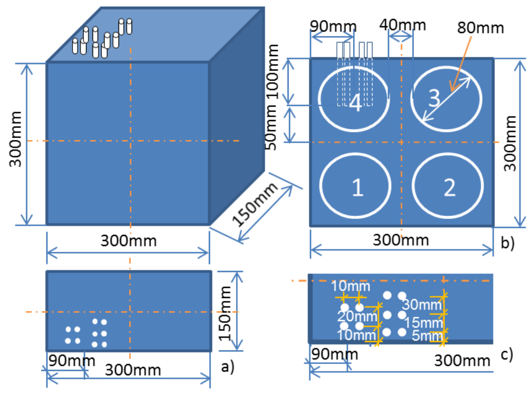

Fig.5.1 Dimensions of Specimen

Materials and proportion: The materials used for concretes in this experiment are provided and the specimens were placed at Hachiyo consultant. Mix proportions are shown in Table 5.1.

Table 5.1 Mix proportions

Max. aggregate (mm)	Slump (cm)	Air (%)	W/C (%)	s/a (%)	Mix compositions(kg/m^3)					
					W	C	Fine aggregate	Coarse aggregate	Admixture	
									[1]Ad	[2]AE
20	12	4.5	40	45	160	400	776	687	4.4	0.8
20	12	4.5	50	47	160	320	841	688	3.2	0.64
20	12	4.5	60	48.5	160	267	890	684	2.67	0.53

[1]Ad: Water reducing admixture, [2]AE: Air entraining agent

Preparation of electrical resistance sensors: Sensors were embedded into covercrete. Each sensor was made by using two M4 threaded bars. The vertical depth of the sensors from the top of the horizontal surface was 100 ± 0.5 mm. However, the total length of the sensors was 144 ± 5 mm as shown in Fig.5.1. The distance between two M4 threaded rods was kept constant using 10 mm thick wooden plates arranged outside the specimens and fixed to the formwork. Each M4 threaded bar was covered by a rubber tube in order to prevent contact with water. The only length of 5 mm of M4 bars inside concrete is not covered by rubber and used for measuring the electric resistance of concrete.

Implementing process: At the material age of more than 60 days, testing of 27 specimens was started for Series-1. The process of testing is as follows:

Nine groups of specimens were provided (three mix proportions, three curing conditions). In each group, three same specimens were moved into three different environmental conditions for one or two days. The first specimen was kept in the curing room at (20±1)^{o}C and (60±2)% R.H. The second was moved to a room where R.H. was 80±2% and the temperature was (20±1)^{o}C. The third specimen was stored in a room where R.H. was 99.9% and the temperature was (20±1)^{o}C. The experimental procedures for Series-1 can be seen in Fig.5.2.

After one or two days, moisture content in covercrete was changed. Moisture distribution in covercrete was measured through sensors by moisture meter named HI-800 before conducting air permeability test and SWAT. HI-800 is an electrical resistance type with an integrated main unit and sensor section. Electric sensors are used to evaluate electric resistance related to moisture content of concrete in depth direction from the surface. The change in electric resistance between the coupled embedded electrode bars termed as ‘count value’ is measured by HI-800. It is true that the higher count value measured by HI-800, the lower electric resistance (higher moisture content. The moisture content of specimens was also measured by surface moisture meters such HI-520 and CMEX-II shown in Fig.5.3.

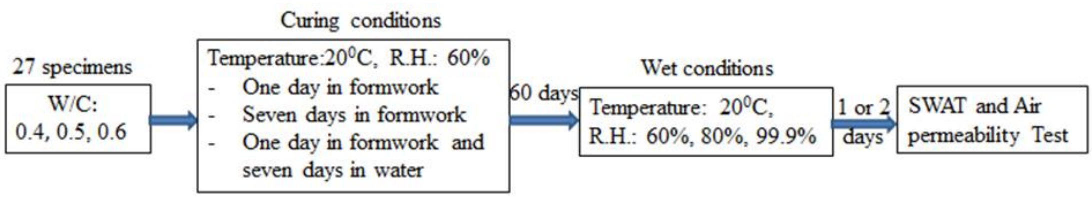

Fig.5.2 Experimental procedure of Series 1 (Dry to wet process)

(a) HI-800 (b) HI-520-2 (c) CMEX-II

Fig.5.3 Moisture meters

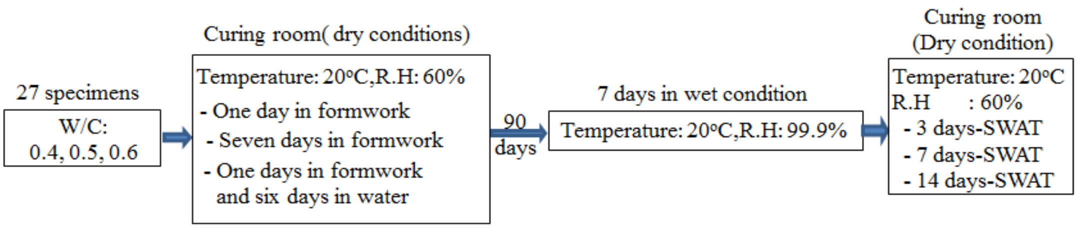

Fig.5.4 Experimental procedure of Series 2 (Wet to dry process)

For Series-2 experiment, remaining 27 specimens were used. The specimens were placed in the curing room until around the age of 90 days and after that they were moved from the curing room and stored for 7 days in a humid room of high R.H. of 99.9% and temperature of 20°C. Then, they were moved back to the curing room for 3 days, 7 days and 14 days respectively before conducting double chamber air permeability test and SWAT. Moisture distributions of those specimens stored in high R.H. were measured. The experimental procedure of Series-2 is shown in Fig.5.4.

5.3.2 Results and Discussion

The water absorption in two series is compared in figures below:

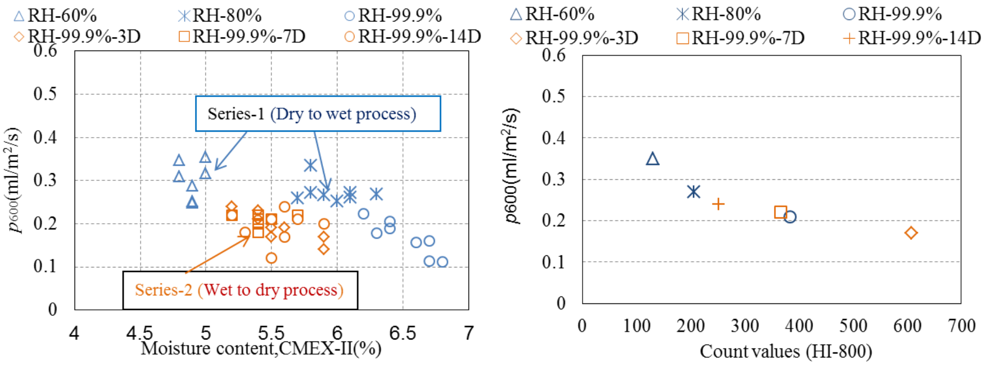

Fig.5.5 Water absorption results and count values (W/C= 40%, one day sealing)

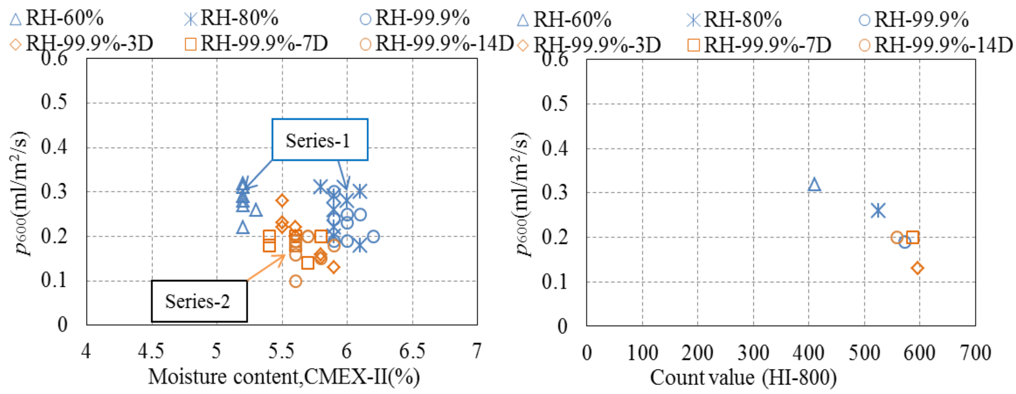

Fig.5.6 Water absorption results and count values (W/C= 40%, seven day sealing)

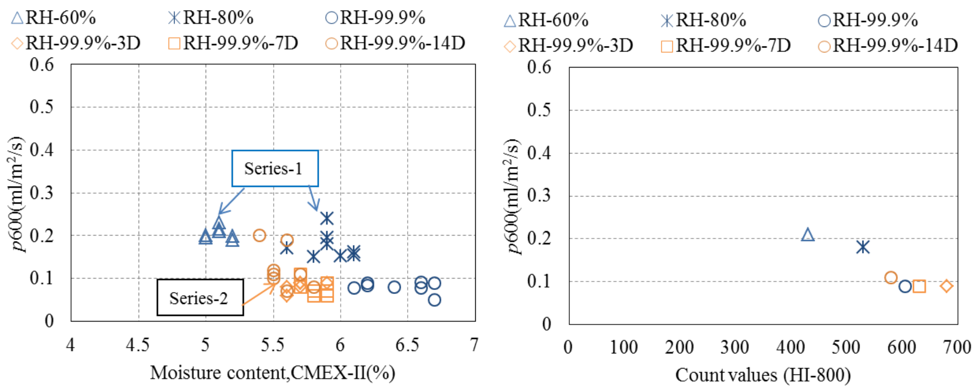

Fig.5.7 Water absorption results and count values (W/C= 40%, one day sealing and 6 day immersing in water)

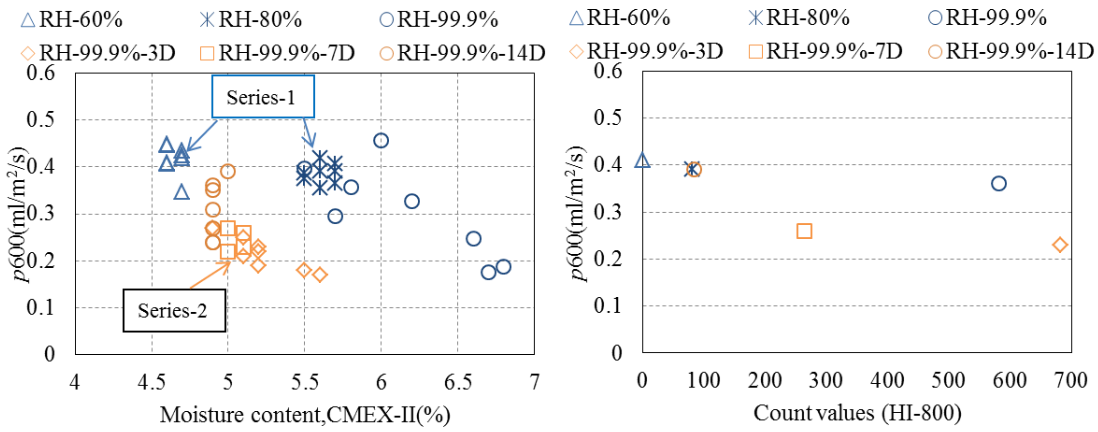

Fig.5.8 Water absorption results and count values (W/C= 50%, one day sealing)

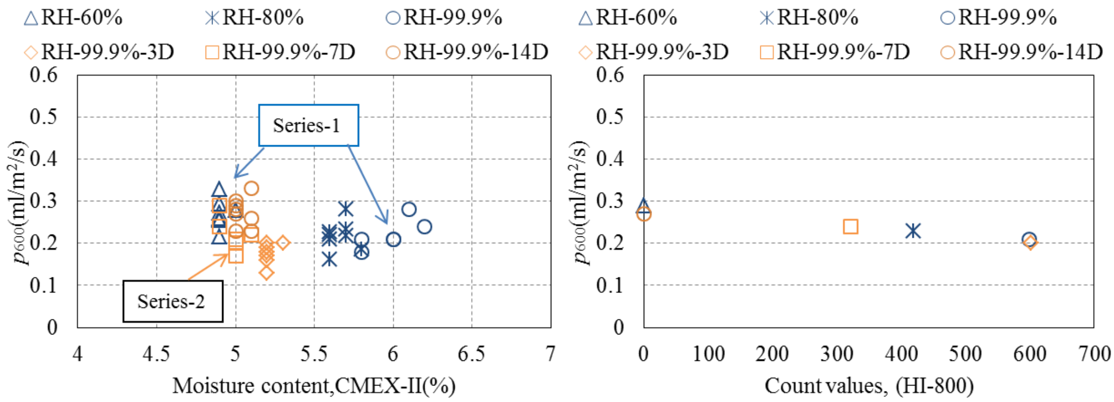

Fig.5.9 Water absorption results and count values (W/C= 50%, seven day sealing)

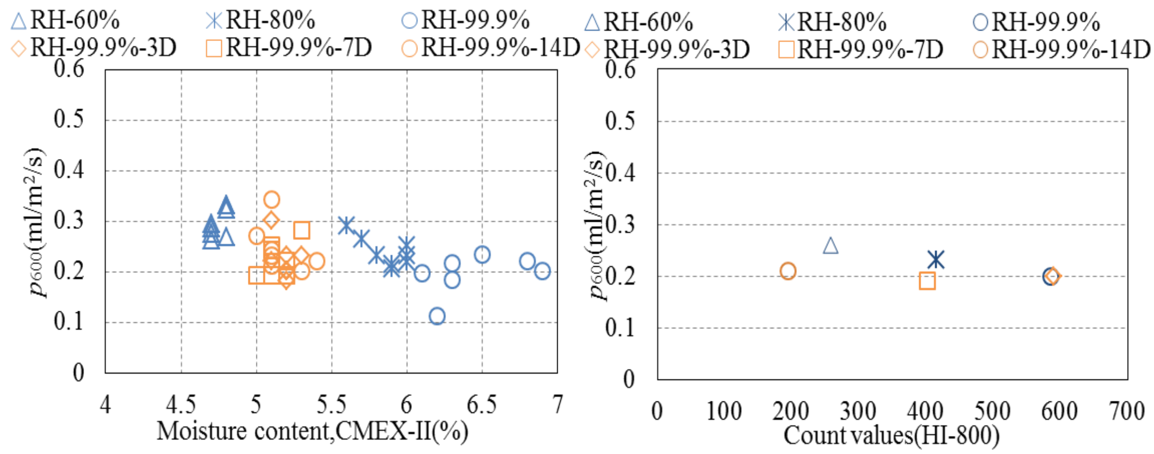

Fig.5.10 Water absorption results and count values (W/C= 50%, one day sealing and 6 day immersing in water)

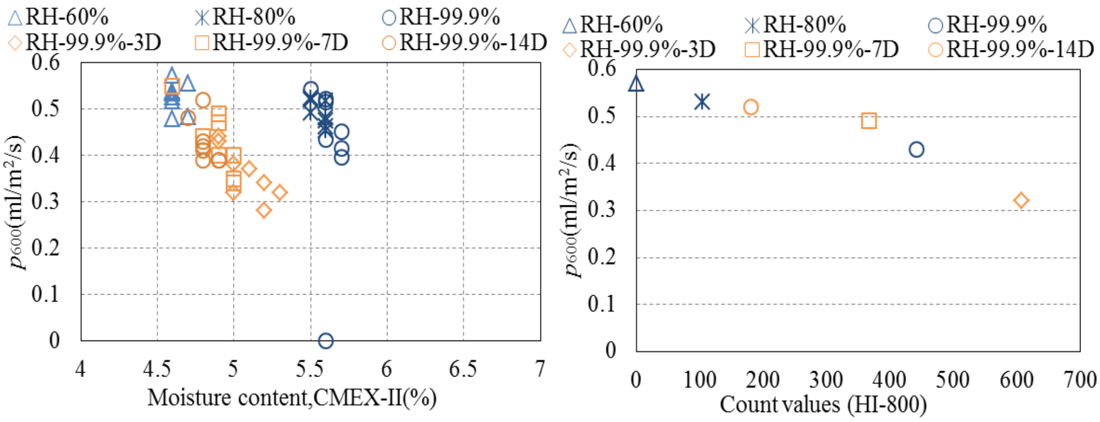

Fig.5.11 Water absorption results and count values (W/C= 60%, one day sealing)

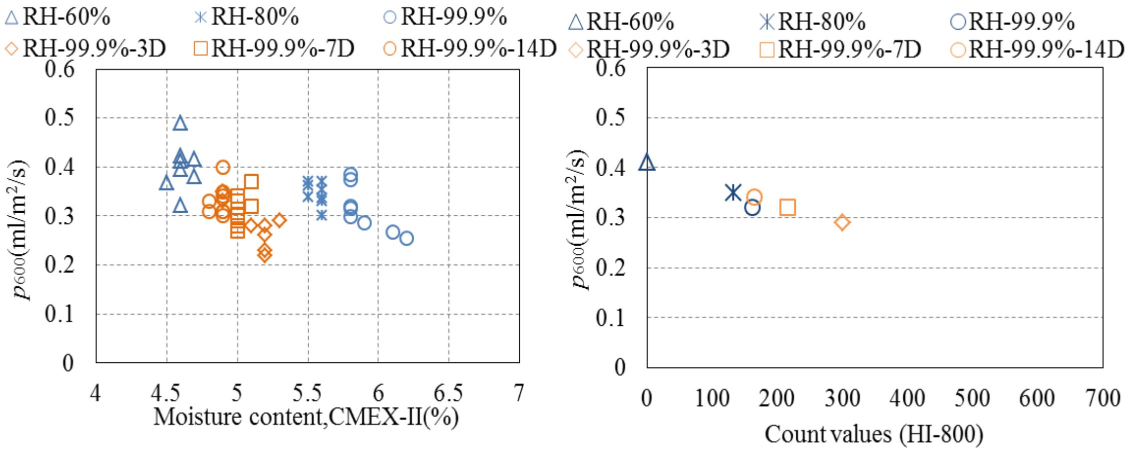

Fig.5.12 Water absorption results and count values (W/C= 60%, seven day sealing)

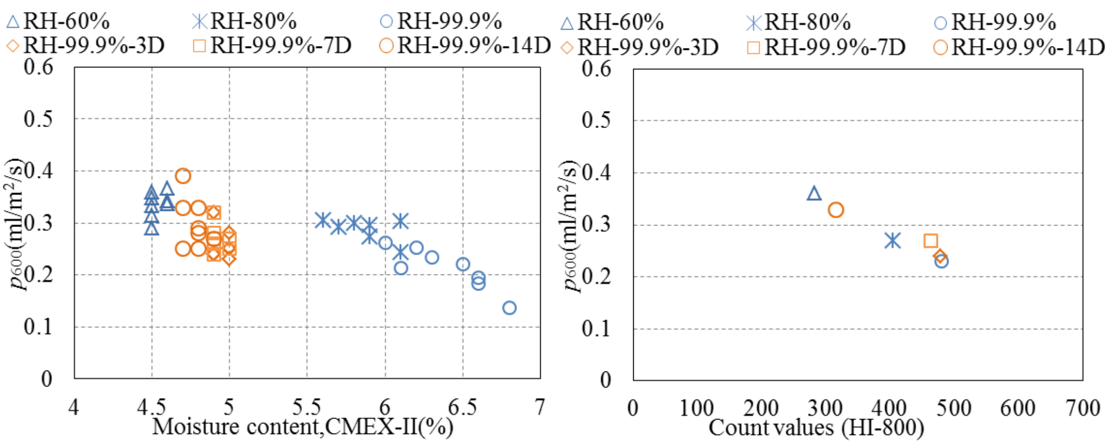

Fig.5.13 Water absorption results and count values (W/C= 60%, one day sealing and 6 day immersing in water)

In figures 5.5-5.13, the left-side figure shows the relationship between p_{600} values and moisture content. The vertical axis is the value of water absorption (p_{600}), and the horizontal axis shows moisture content measured by CMEX-II. Both the results of Series-1 and Series-2 are shown in the figures. The right hand figures show the relationship between the results of p_{600} measured at the locations where electric sensors are embedded and the electric resistance (given as "count values" by HI-800) measured by the sensors at the depth of 5mm. Relationships of p_{600} and moisture content measured by HI-520-2 showed the same tendency with that of CMEX-II.

According to previous researches, covercrete having high moisture content will absorb less water. In figures 5.5-5.13, however, although moisture content values in Series-1 specimens measured by CMEX-II are higher than that in Series-2, p_{600} values (water absorption rate at 10 minutes) in Series-2 are apparently lower than those of Series-1 in some cases.

While it can be seen from right side figures that, values of p_{600} are relatively low with high count values at 5mm depth probably because of high moisture content of concrete which cannot be detected by the two moisture meters (CMEX-II and HI-520-2) used in the present investigation. Therefore, water absorption values of the specimen in Series-2 are lower than those of specimens in Series-1 although moisture content measured by CMEX-II and HI-520-2 are the same.

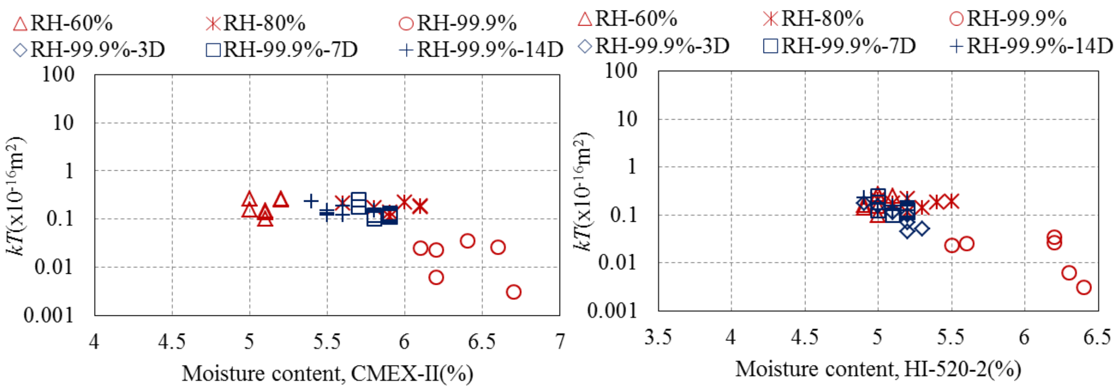

Fig.5.14 Air permeability results and moisture content measured by CMEX-II and HI-520-2 (W/C=40%, one day sealing and 6 day immersing in water)

It is seen in Fig.5.14 that air permeability results were not significantly affected by moisture content when the moisture content measured by two moisture meters were smaller than values of 6.0% for CMEX-II and smaller than around 5.5% for HI-520-2. Furthermore, in Fig.5.8 and Fig.5.11, a big gap is observed in results of Series-1 and Series-2 regarding specimens with high W/C ratio kept in curing room for one day, because the specimens might have micro-cracks due to the bad curing condition. Moreover, the reason why the water absorption in Series-2 is less than that in Series-1 might be due the re-hydration of cement. Since the specimens in Series-2 were cured in high R.H. room for a long time, re-hydration can occur. In order to prove this hypothesis, the processes of two series were simulated utilizing Ducom software and corresponding results are shown later.

5.3.3 Findings

In each series, the relationship between moisture content measured by CMEX-II and p_{600} is suitable with water absorption theory. However, the relationship between moisture content and p_{600} corresponding to Series-1 and Series-2 is different. Moisture contents measured by CMEX-II and HI-520-2 in Series-2 are lower than or same as those values in Series-1 while p_{600} values in Series-2 are lower than p_{600} values of Series-1 in high R.H. It may be because CMEX-II and HI-520-2 are not sensitive to moisture content at 5mm depth inside the concrete. Therefore, specimens in Series-1 after one or two days in humid condition have high moisture content at near surface while the inner concrete might be dry. It was confirmed through count values measured between embedded sensors. Whereas, specimens of series 2 stored in high R.H room for a long time, moisture content in inner concrete is high, after 3 to 14 days in curing room in RH=60%, the surface of the specimens might be dry whereas internal moisture content might be wet. This is the reason why Series-1 has high moisture content values measured by CMEX-II and HI-520-2 while absorbing more water than Series-2 having lower moisture content values. Therefore, it is revealed that CMEX-II and HI-520-2 can be used to detect moisture content before conducting SWAT and air permeability test for concrete in the process of curing from dry to wet condition only. In the vice versa process, CMEX-II and HI-520-2 are not suitable to detect moisture content in concrete. On the other hand, count values related to electric resistance of concrete at 5mm depth may be helpful to evaluate whether covercrete is sufficiently dry or not for conducting SWAT and double chamber air permeability tests.

5.4 Simulation of Rehydration of Concrete in High Humidity Affecting Water Absorption of Covercrete

It can be revealed from Fig.5.5 to Fig.5.13 that although specimens in Series-2 have lower moisture content values measured by CMEX-II and HI-520-2 than the moisture content of specimens in Series-1, they had lower p_{600} results than that of

Series-2. This is an unusual result. However, it is true because in Series-2 even though moisture content at the surface is low, internal moisture content at 5mm depth is high possibly due to the long term storage of specimens in high R.H, covercrete was rehydrated. As a result, pores in covercrete became finer. These affected p_{600} results. In order to investigate whether the rehydration affects or not the water absorption of covercrete, the simulation utilizing DuCOM [5.1] was performed as below.

5.4.1 Making Models

Simulation was done considering real specimens, curing period and conditions. Up to the depth of 5mm from the surface of concrete specimen model, the thickness of each element is 1mm. The deeper the concrete, the thicker the elements. The elements near surface at high R.H are easy to rehydrate. The dimensions of elements in two other directions are divided equally as can be seen in Fig.5.15.

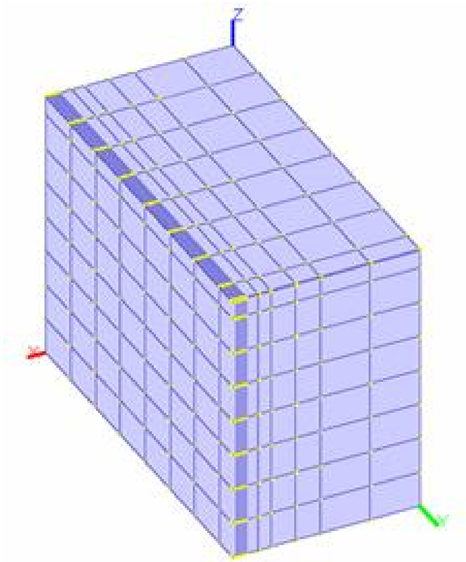

Fig.5.15 Specimen model for DuCOM simulation

5.4.2 Application Software

DuCOM and COM3D [5.1] are used to simulate these specimens because it can give accurate result about rehydration or water content in concrete. DuCOM is a micro durability platform, capable of simulating cement hydration, micropore structure formation, and mass transport in concrete ranging from nm to μm scales. Whereas COM3 is a 3D mesoscale platform to handle mechanistic actions for structural concrete ranging from mm to m scales, with in-depth considerations of time-dependent, cyclic, and fatigue behavior of uncracked and cracked concrete. In this research, we also consider the rehydration results of specimens stored in humid conditions. The results of the simulation are explained in the next section.

5.4.3 Results and Discussions

Figures 5.16-5.24 show that specimens with poor curing conditions (one day in formwork) had rehydration after 7 days storing in high R.H. However, since the effects are inconsiderable it can be ignored. Therefore, it can be concluded that water absorption and air permeability are not affected by rehydration of concrete due to 7 days curing in high R.H adopted in this research. In this research, water absorption and air permeability are influenced by the moisture content of concrete.

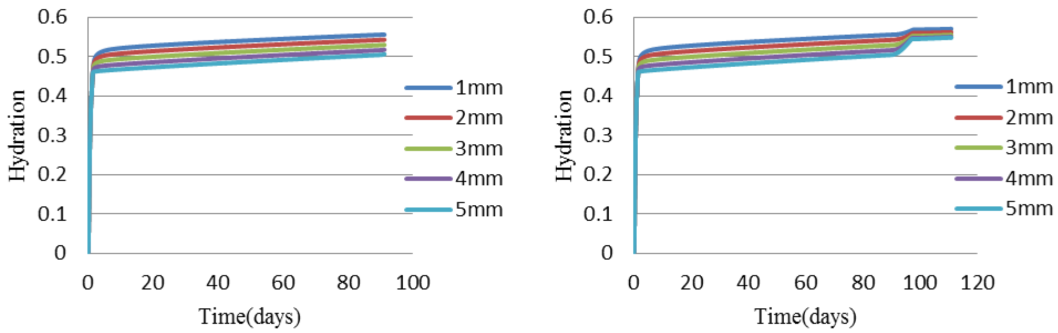

Fig.5.16 Hydration before and after storing in humid room (W/C= 40%, one day sealing)

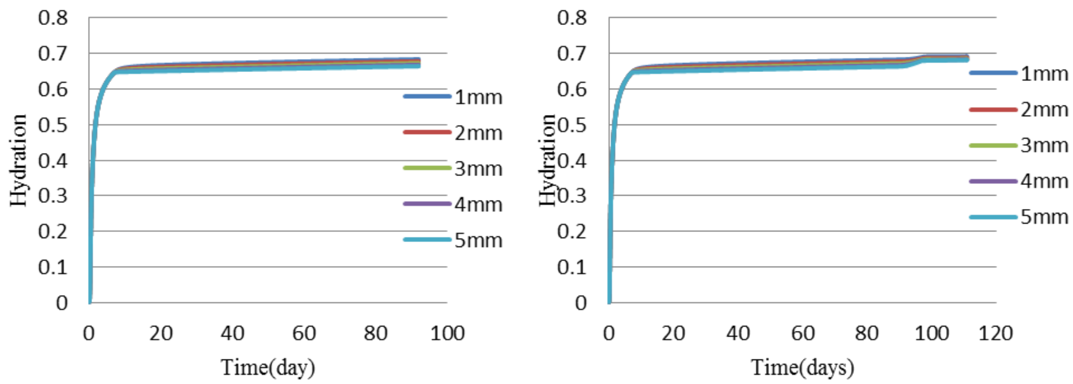

Fig.5.17 Hydration before and after storing in humid room (W/C= 40%, seven day sealing)

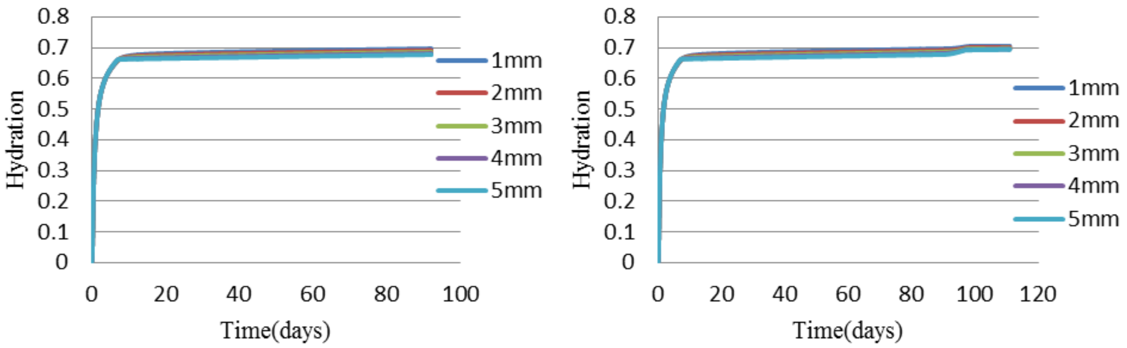

Fig.5.18 Hydration before and after storing in humid room (W/C= 40%, one day sealing and 6 day immersing in water)

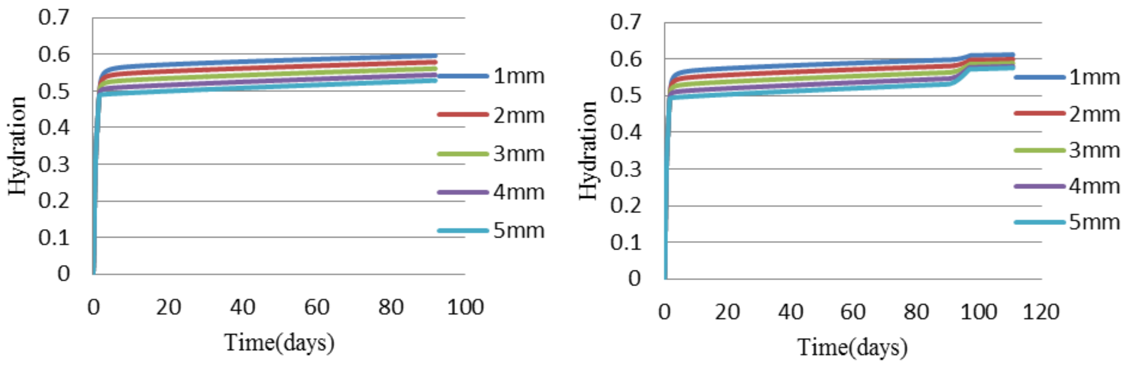

Fig.5.19 Hydration before and after storing in humid room (W/C= 50%, one day sealing)

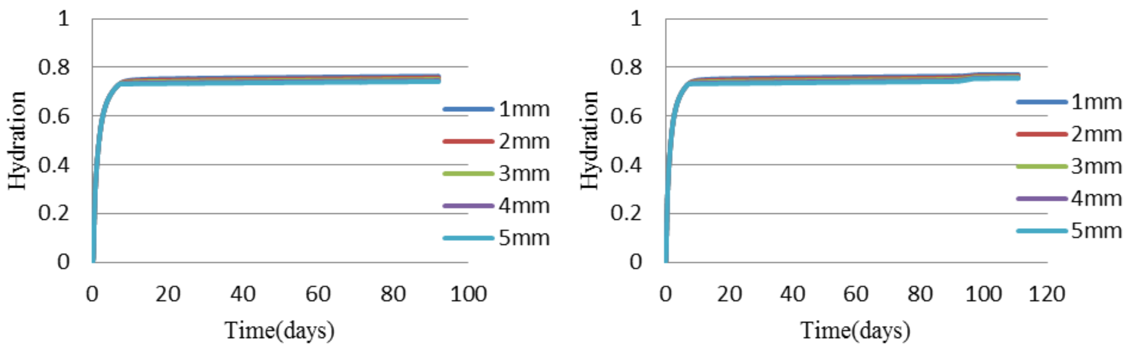

Fig.5.20 Hydration before and after storing in humid room (W/C= 50%, seven day sealing)

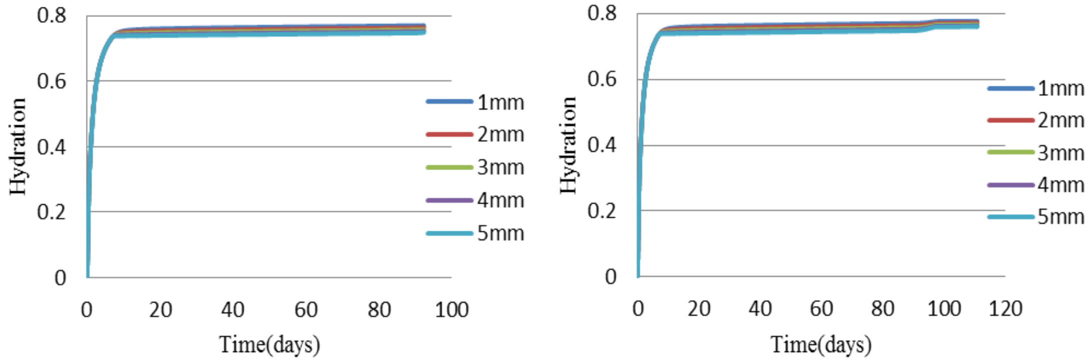

Fig.5.21 Hydration before and after storing in humid room (W/C= 50%, one day sealing and 6 day immersing in water)

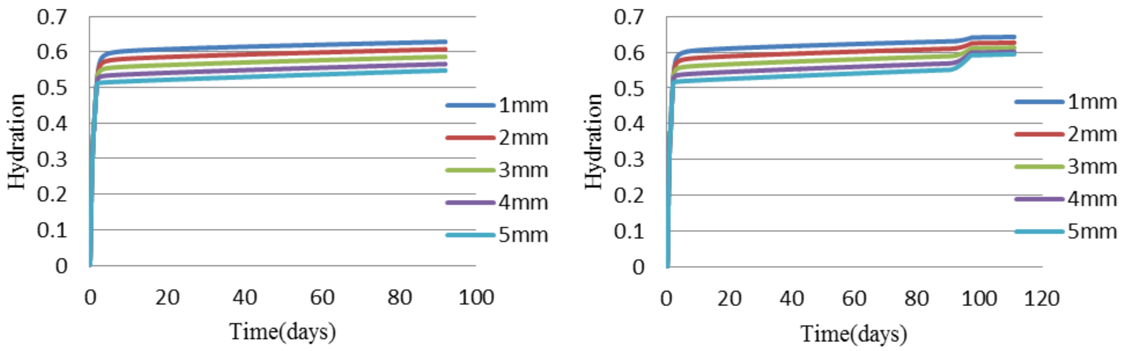

Fig.5.22 Hydration before and after storing in humid room (W/C= 60%, one day sealing)

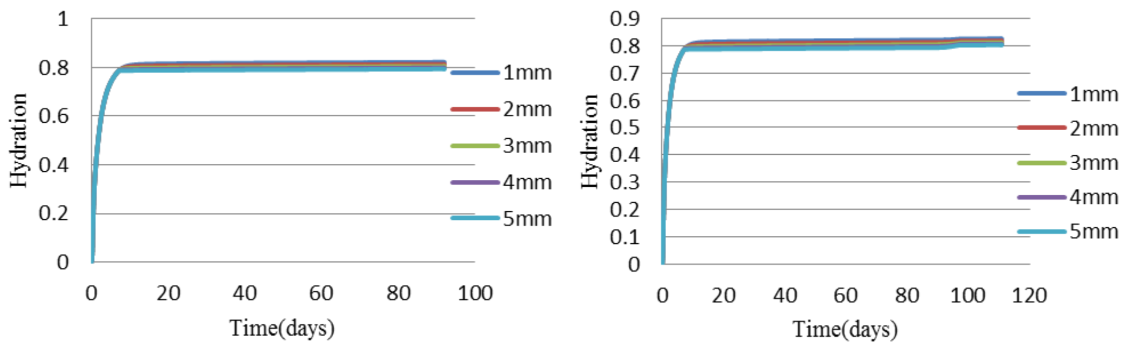

Fig.5.23 Hydration before and after storing in humid room (W/C= 60%, seven day sealing)

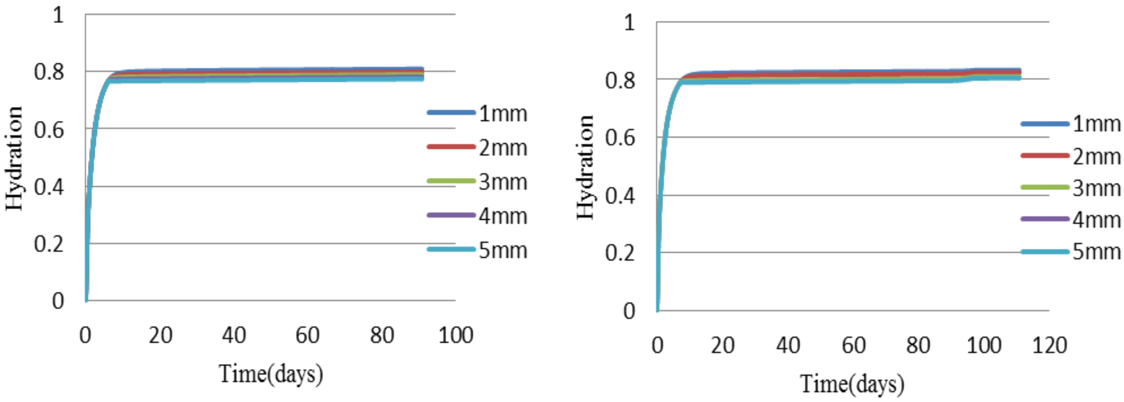

Fig.5.24 Hydration before and after storing in humid room (W/C= 60%, one day sealing and 6 day immersing in water)

5.5 Effectiveness of Moisture Meters (CMEX-II and HI-520) to Check Moisture Content before Conducting SWAT

In previous results, it was found that the amount of water absorption of specimens in the wet to dry process, as determined through the use of SWAT in 10 minutes, is often smaller than that in vice versa process although the same moisture content was measured by CMEX-II and HI-520-2 at same locations. This may be due to higher moisture content in 5mm depth of the specimen in wet to dry process. Thus, there is a possibility that moisture content measured by CMEX-II or HI-520-2 before conducting SWAT in 10 minutes may not be reliable, since in 10 minutes SWAT results will be affected by inner moisture content of concrete. Therefore, in case of wet to dry process, measuring time for SWAT should be shortened until one or two minutes since in short duration the water absorption due to SWAT only affects a shallow surface zone which may dry in 3 to 14 days. Absorption of this zone may not be affected by inner moisture content of concrete.

The objective of this part is to try to overcome the problem when concrete is dry at surface, but high moisture content is provided inside which CMEX-II and HI-250-2 cannot detect. It is investigated by conducting SWAT for a short duration for concrete specimens with three different mix proportions cured in different R.H. conditions. The resistances against water absorption were measured in 60 seconds, 100 seconds and 120 seconds.

5.5.1 Experiment

Specimens and laboratory investigation processes are shown in section 5.3.1

5.5.2 Results regarding p_{60}, p_{100} and p_{120}

It is observed that CMEX-II and HI-520-2 values in wet to dry process after 3 days, 7 days and 14 days in curing room are lower than that in case of dry to wet process. It indicates that the surface of concrete at these locations might be dried when measuring SWAT and double chamber air permeability test. However, moisture contents are still high deep inside the concrete in those locations as confirmed from the obtained count values. Therefore, the quality of covercrete at shallow depth can be evaluated. In the present study, water absorption results are analyzed at 60 seconds, 100 seconds and 120 seconds (two minutes).

5.5.3 Results and Discussions

Figures 5.25(a)-5.33(a) exhibit a slight different tendency in water absorption results at 10 minutes compared to one and two minutes.

There is no specific relationship between water absorption rate at 10 minutes and those at 1 or 2 minutes as indicated in Fig.5.25 (b) to 5.33 (b). It explains that water absorption behavior of specimens at 10 minutes compared to that of 1 or 2 minutes are different. It might be due to the dry condition of covercrete stored in curing room (RH=60%) for 3 to 14 days whereas the moisture content inside the concrete was high. Therefore, in 1 to 2 minutes, concrete surface absorbs much water and water absorption is not affected by moisture content of inner concrete. When conducting SWAT in 10 minutes, if moisture content inside concrete is high, it affects p_{600} values, hence cumulative water absorption become small. This is why; there exists no good relationship between water absorption in 10 minutes and 1 to 2 minutes for almost all the specimen. However, it is difficult to evaluate quality of covercrete in 1 to 2 minutes since it is not confirmed that specimen surface will be dry after 3 days of storing in curing room.

It is observed from figures 5.27 (b), 5.28 (b) and 5.33 (b) that specimens after 14 days in curing room, count values of sensors at 5mm depth return original values exhibiting good relationship between p_{600} and p_{60} to p_{120}. It might be due to the completely dry conditions of specimens at 5mm depth from the surface.

Figure 5.34(d) shows the relationship between surface water absorption amount (Qm) and water absorption rate (Pm) at measuring duration m (m from 60 seconds to 600 seconds) conducted by Ikawa, in 2018 [5.6]. It is shown that there is a very high R^2 (the coefficient of determination) in his research since the corresponding specimens are completely dry before conducting SWAT. On the other hand, the coefficient of determination for the present investigation is smaller than that of Ikawa's results [5.6]. It is evident that water absorption test in 10 minutes is affected by moisture content at some parts inside concrete which CMEX-II and HI-520-2 are unable to detect.

As explained above, it can be concluded that moisture meters CMEX-II and HI-520-2 are not sufficient for detecting moisture content before conducting SWAT when concrete structures are in a wet condition for a long time. It was recommended that the CMEX-II is designed to measure moisture in new concrete floor slabs which are in drying process after construction. This is calibrated on the "drying curve" which is uniform when conditions on site remain within the parameters known as "ideal conditions". In other words, it is approximately 20ºC and 40%-60% RH. The device is not designed to measure moisture content with accuracy in concrete which is rewetted; however, it can be used as a comparative/qualitative tool, giving an indication of Hi/Lo readings.

It can be said that count values related to electric resistance of concrete at 5mm depth may be useful to evaluate whether covercrete is sufficiently dry or not regarding SWAT and double chamber air permeability measurements.

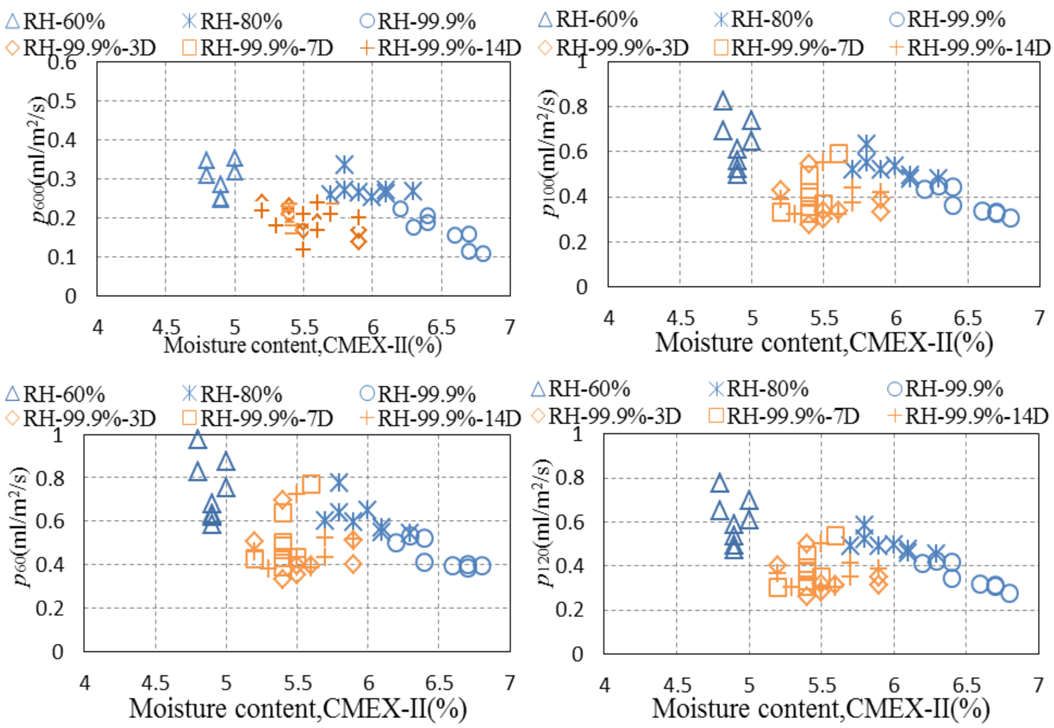

Fig.5.25 (a) SWAT absorption values (W/C=40%, 1 day in formwork)

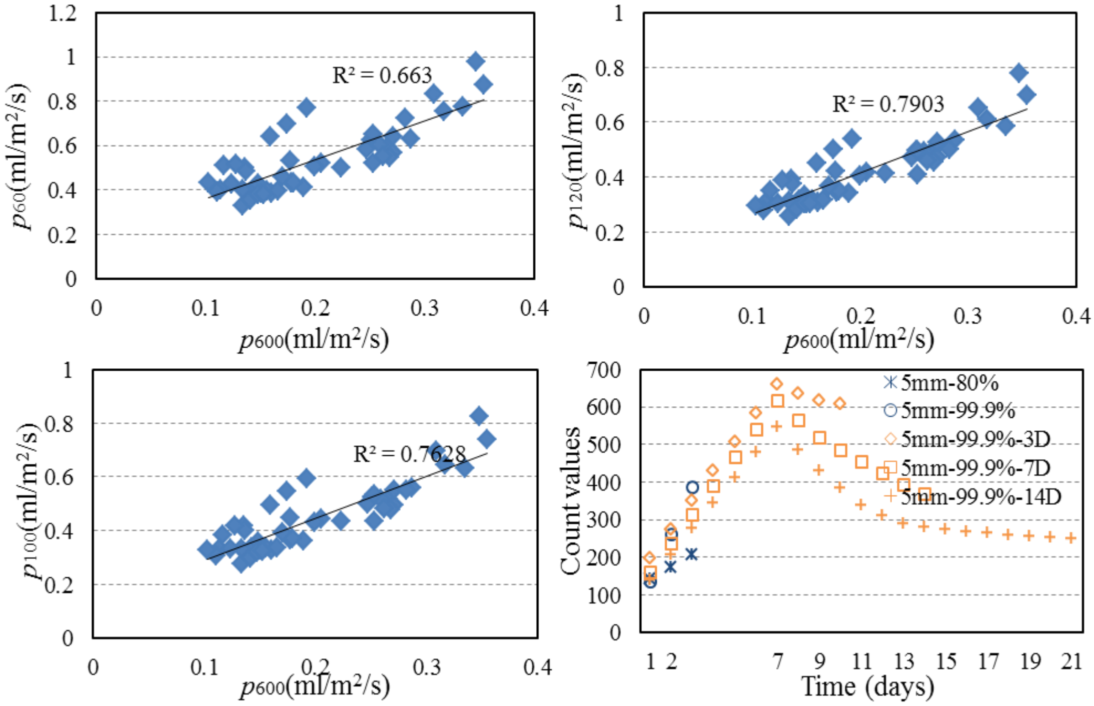

Fig.5.25 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600} and Count values (W/C=40%, 1 day in formwork)

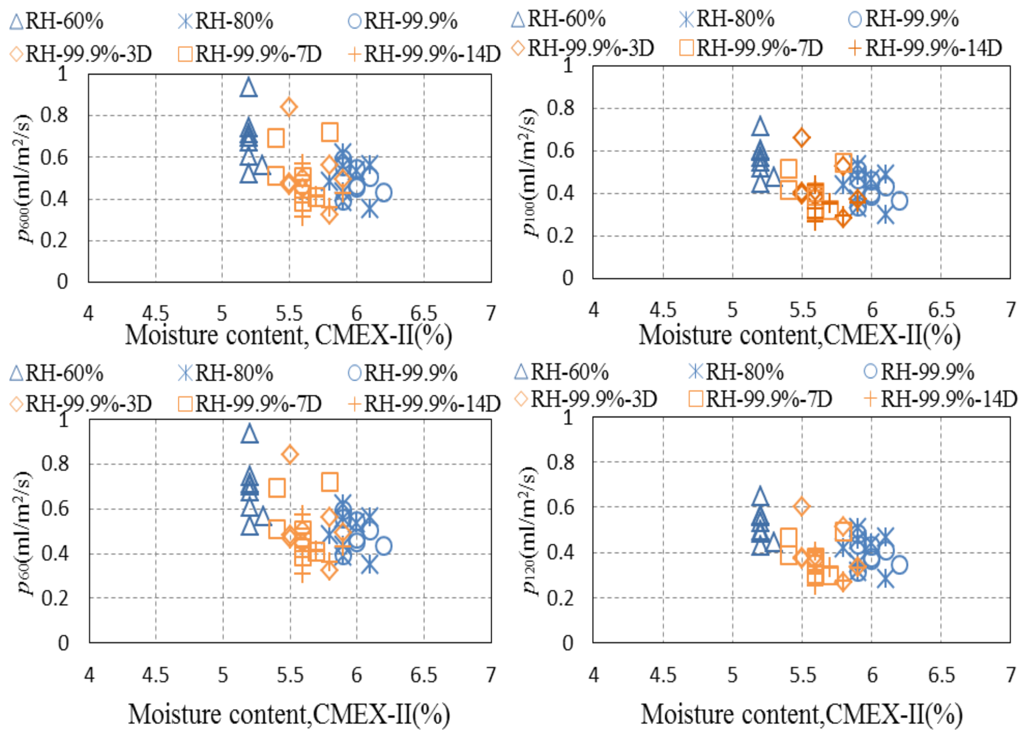

Fig.5.26 (a) Water absorption results and count values (W/C= 40%, 7 day sealing)

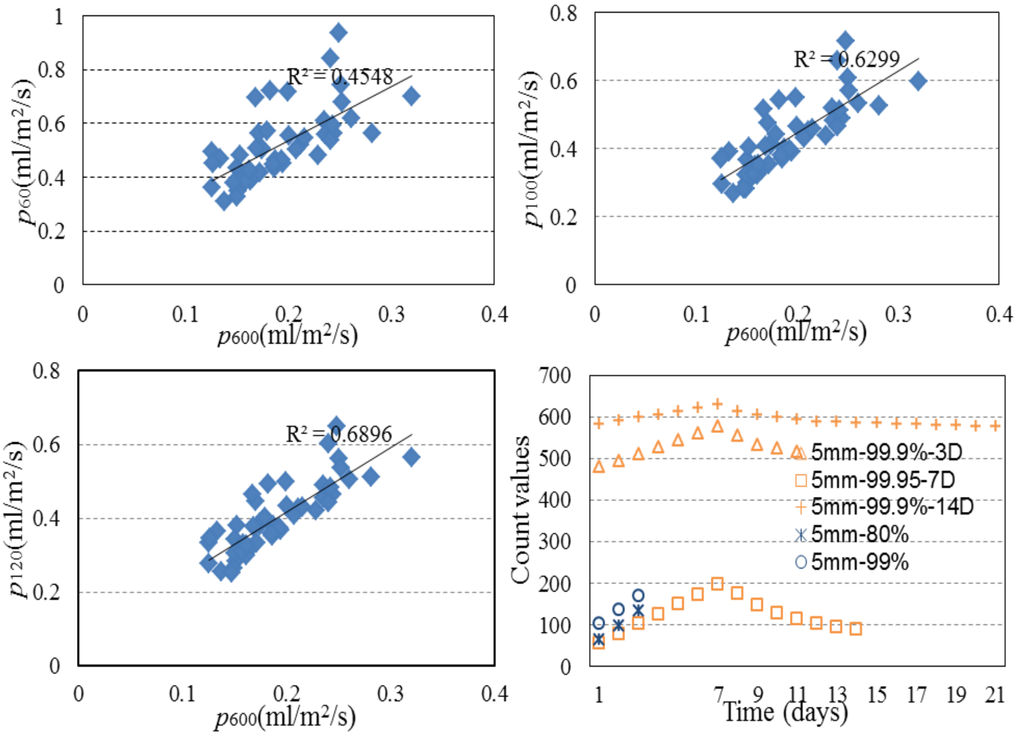

Fig.5.26 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600} and Count values (W/C=40%, 7 days in formwork)

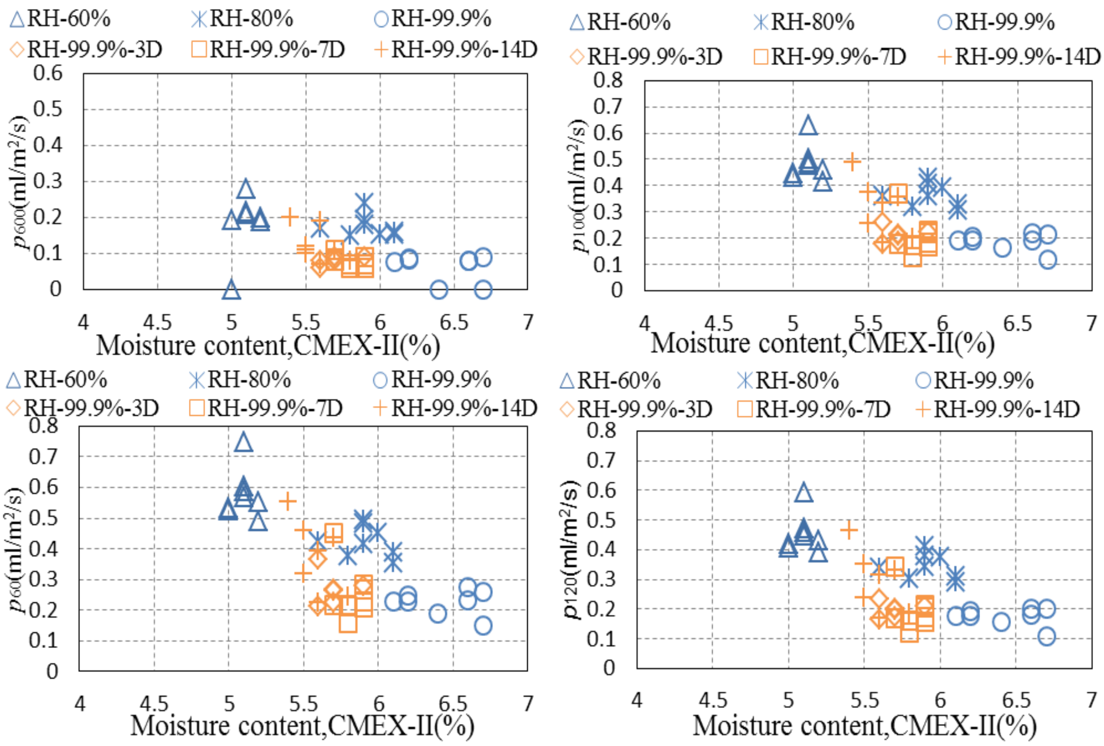

Fig.5.27 (a) Water absorption results (W/C= 40%, one day sealing and 6 day immersing in water)

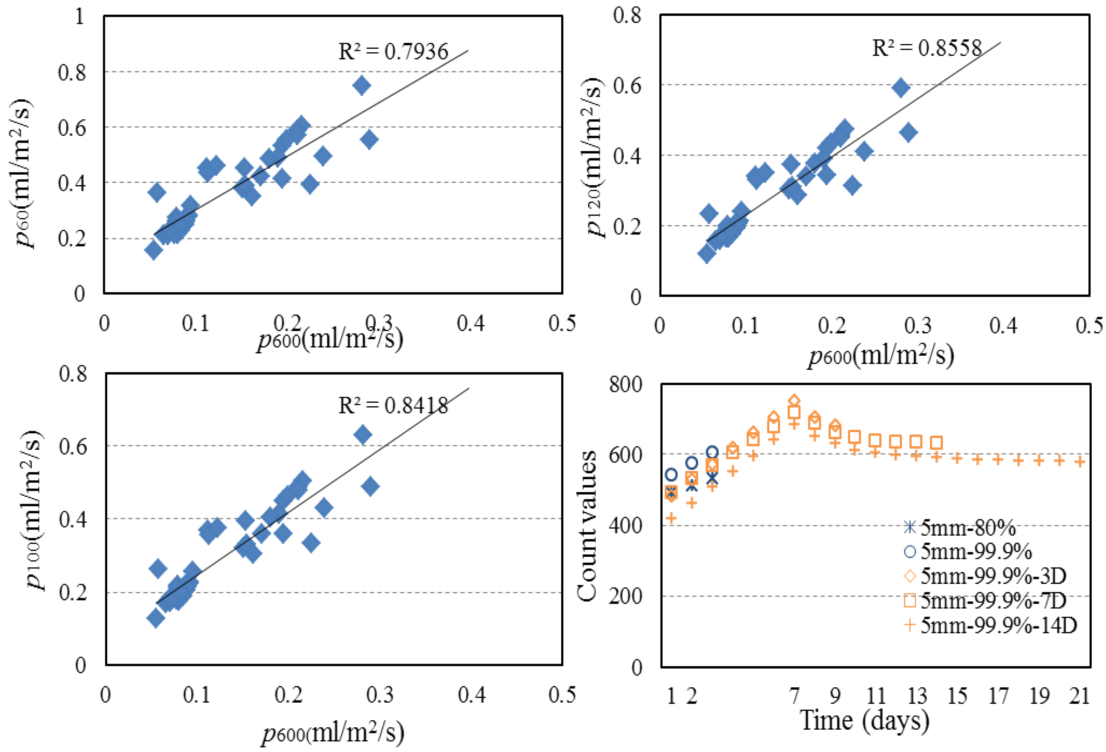

Fig.5.27 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600} and Count values

(W/C=40%, one day sealing and 6 day immersing in water)

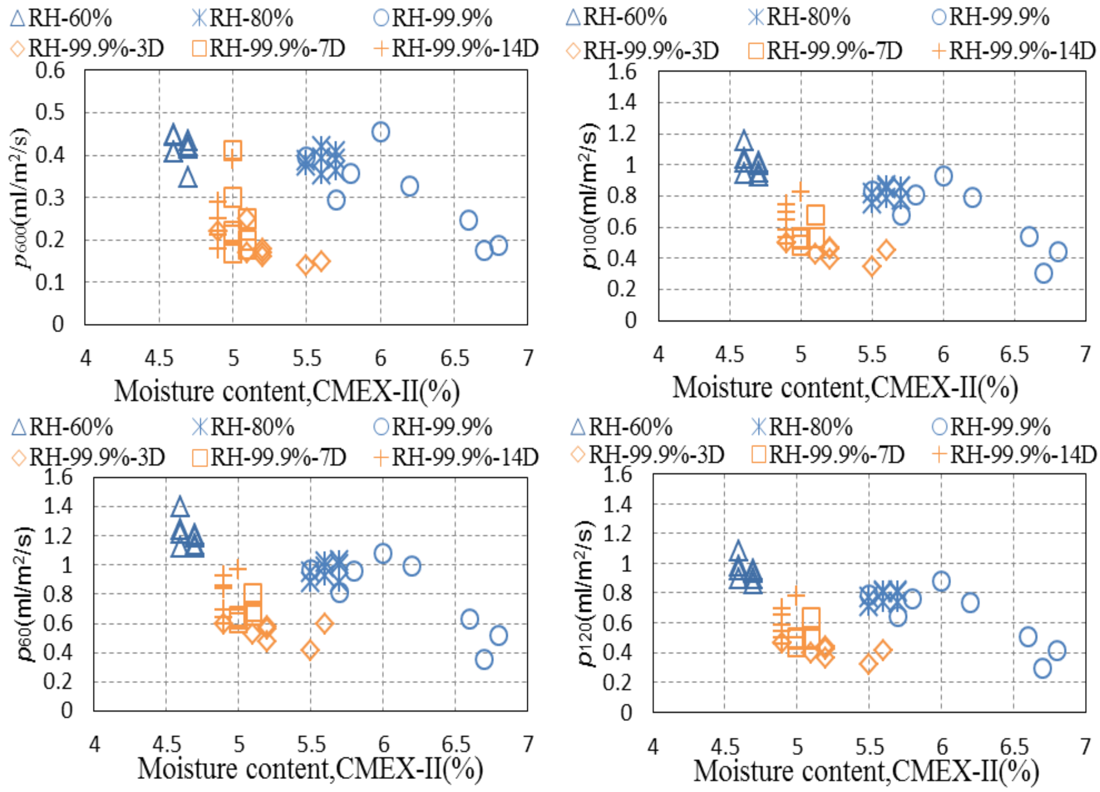

Fig.5.28 (a) SWAT absorption values (W/C=50%, 1 day in formwork)

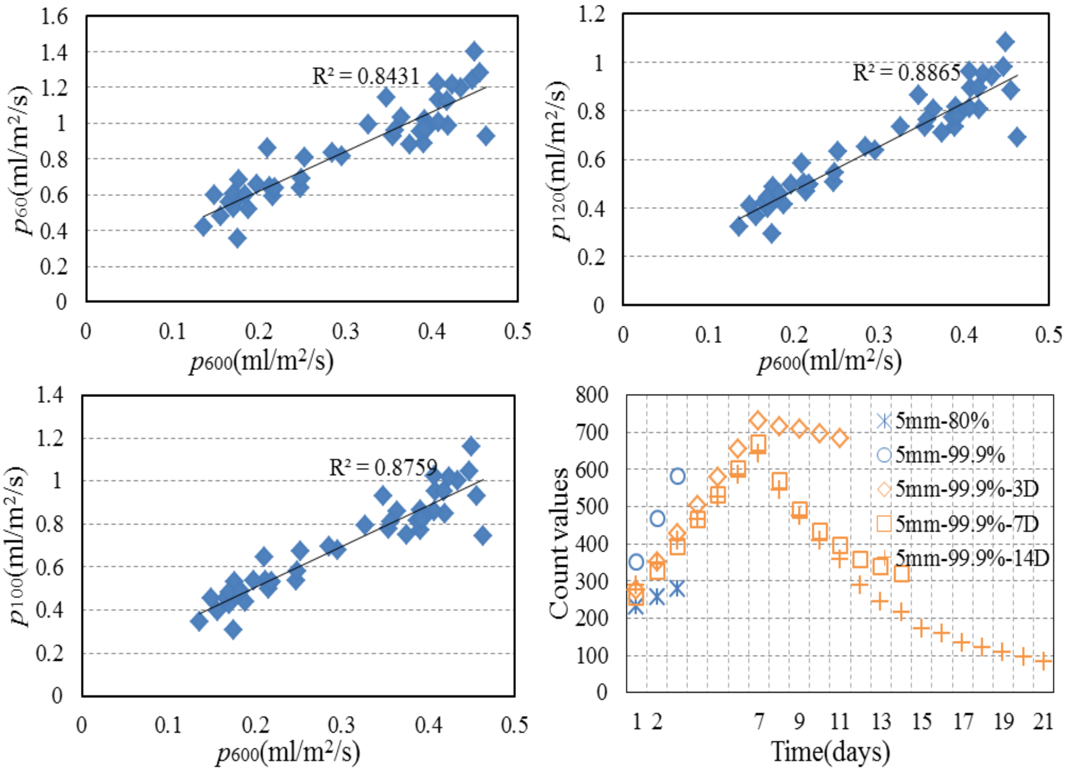

Fig.5.28 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600}, and Count values

(W/C=50%, 1 day in formwork)

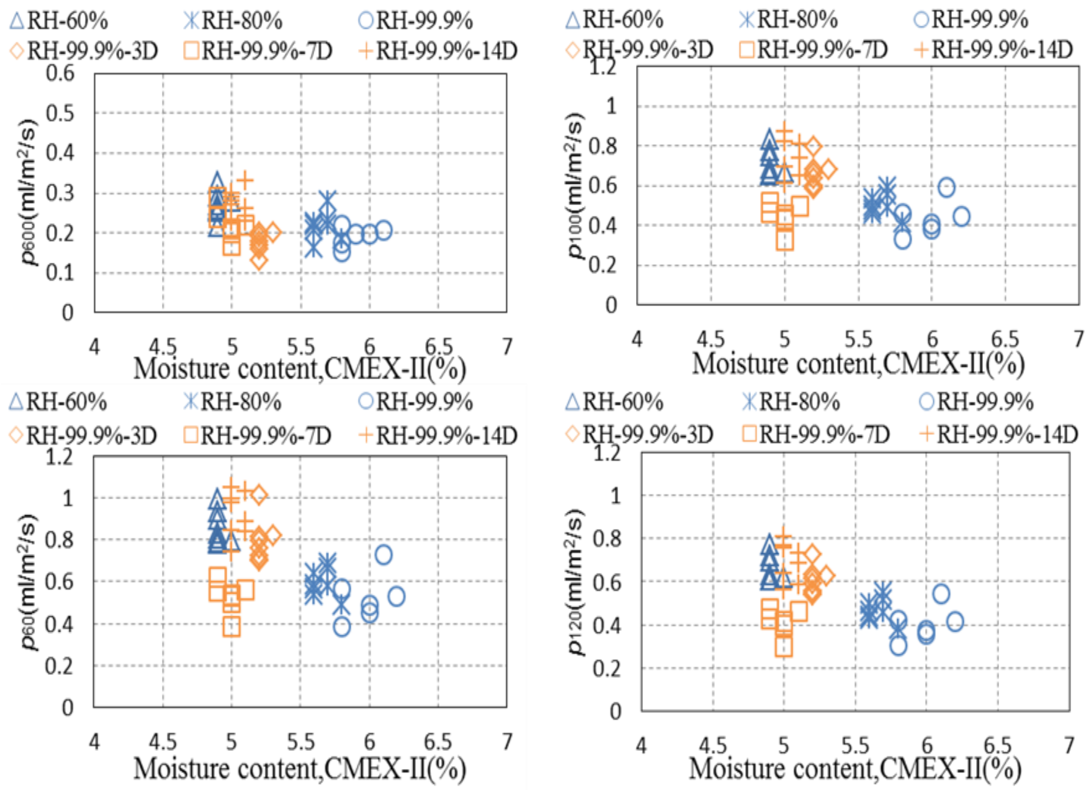

Fig.5.29 (a) SWAT absorption values (W/C=50%, 7 days in formwork)

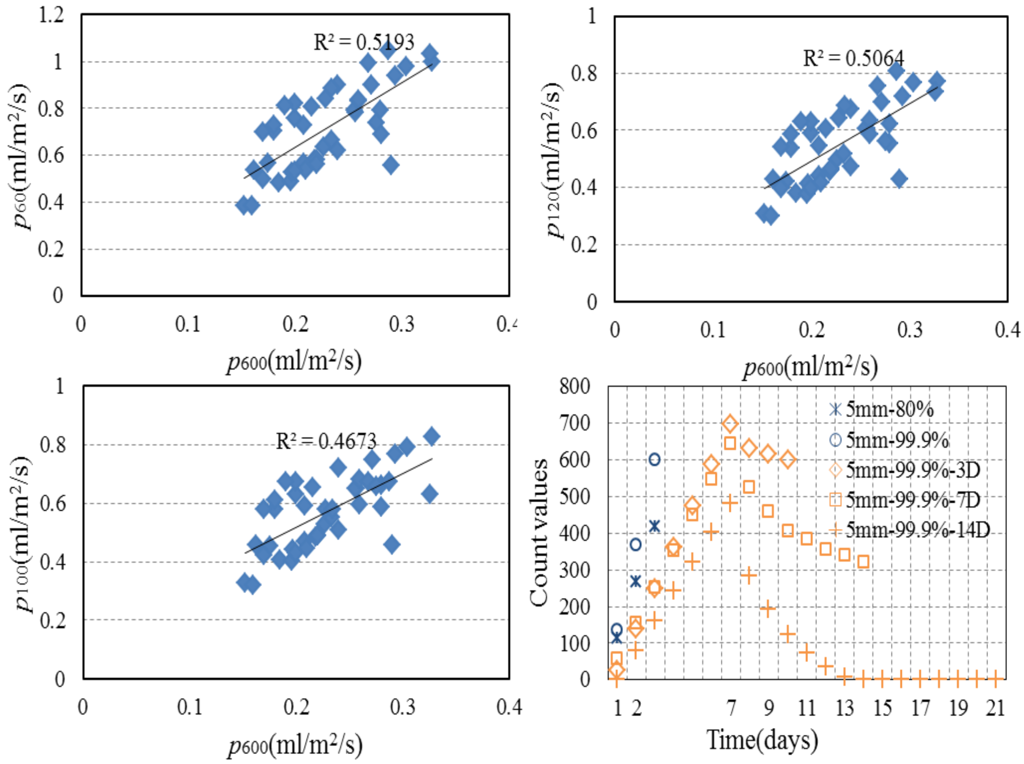

Fig.5.29 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600}, and Count values

(W/C=50%, 7 days in formwork)

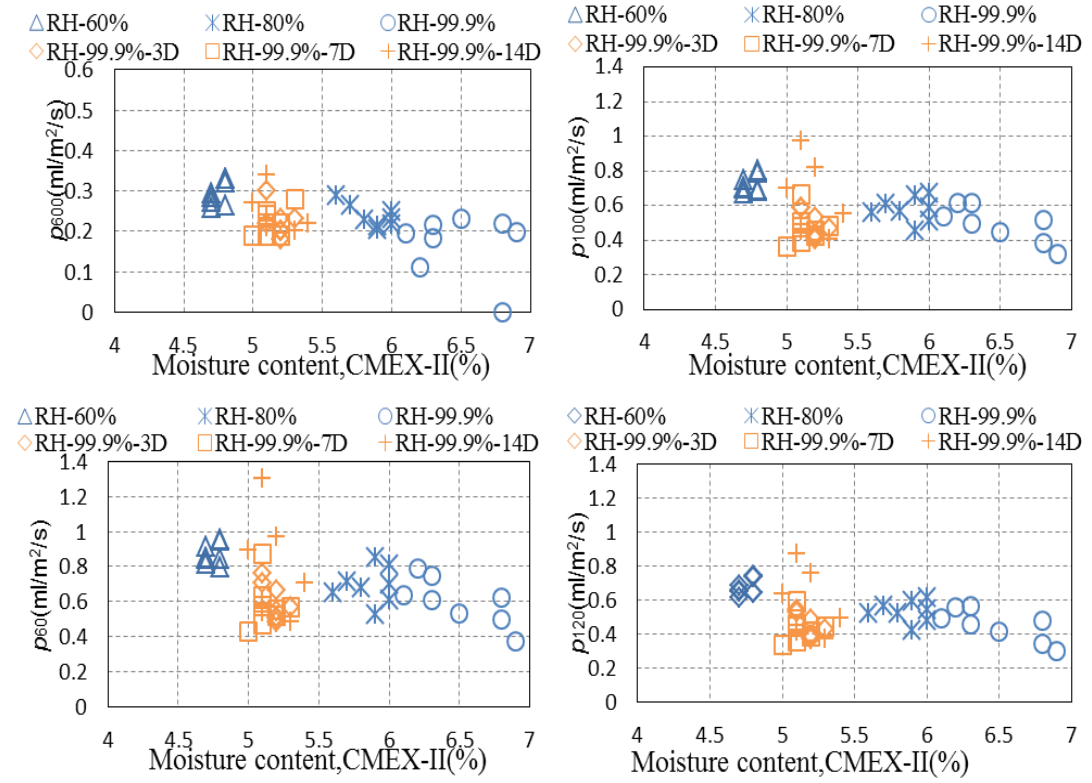

Fig.5.30 (a) Water absorption results and count values (W/C= 50 one day sealing and 6 day immersing in water)

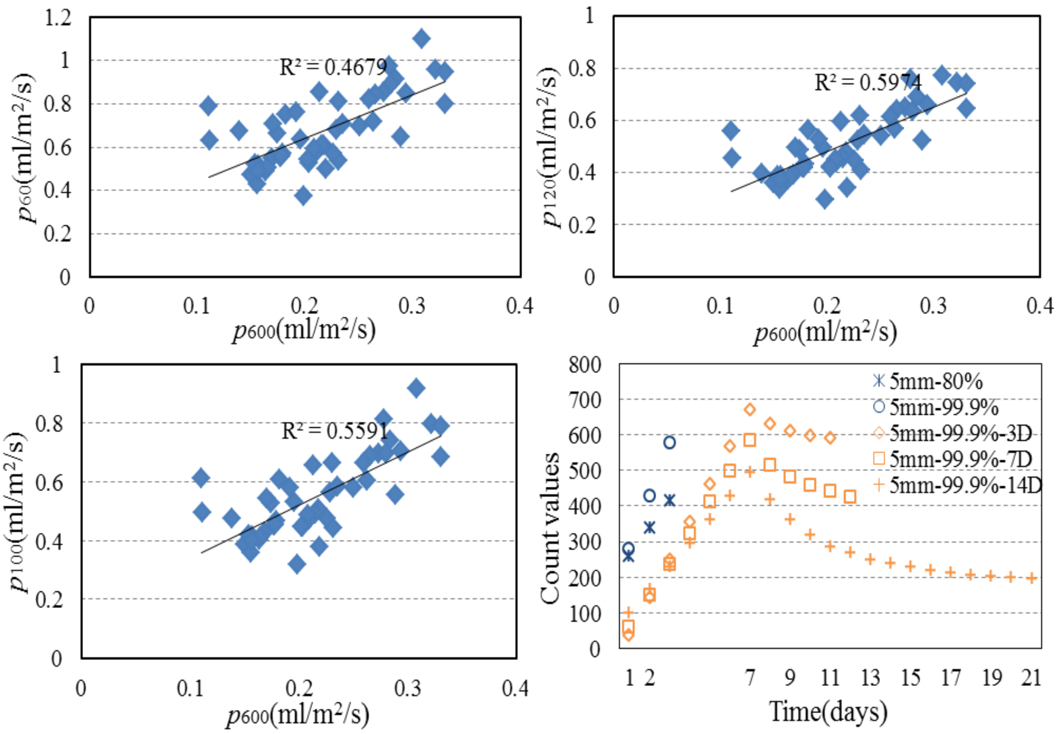

Fig.5.30 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600}, and Count values

(W/C=50%, one day sealing and 6 day immersing in water)

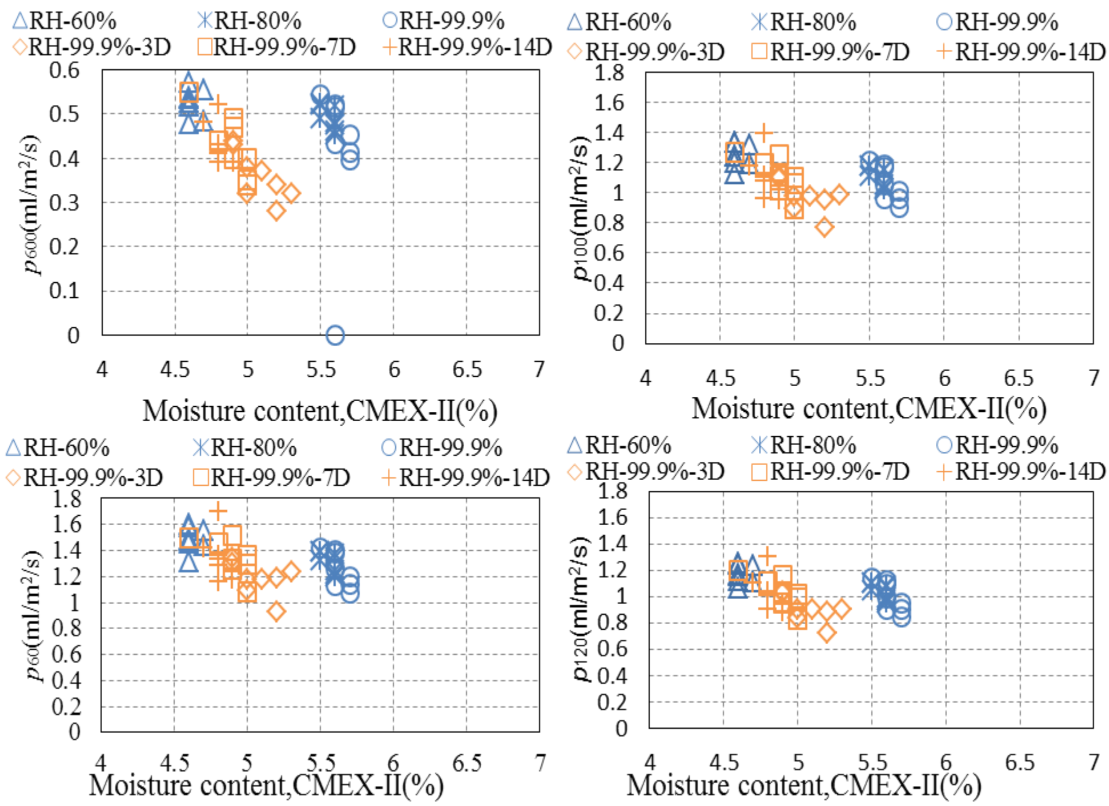

Fig.5.31 (a) SWAT absorption values (W/C=60%, 1 day in formwork)

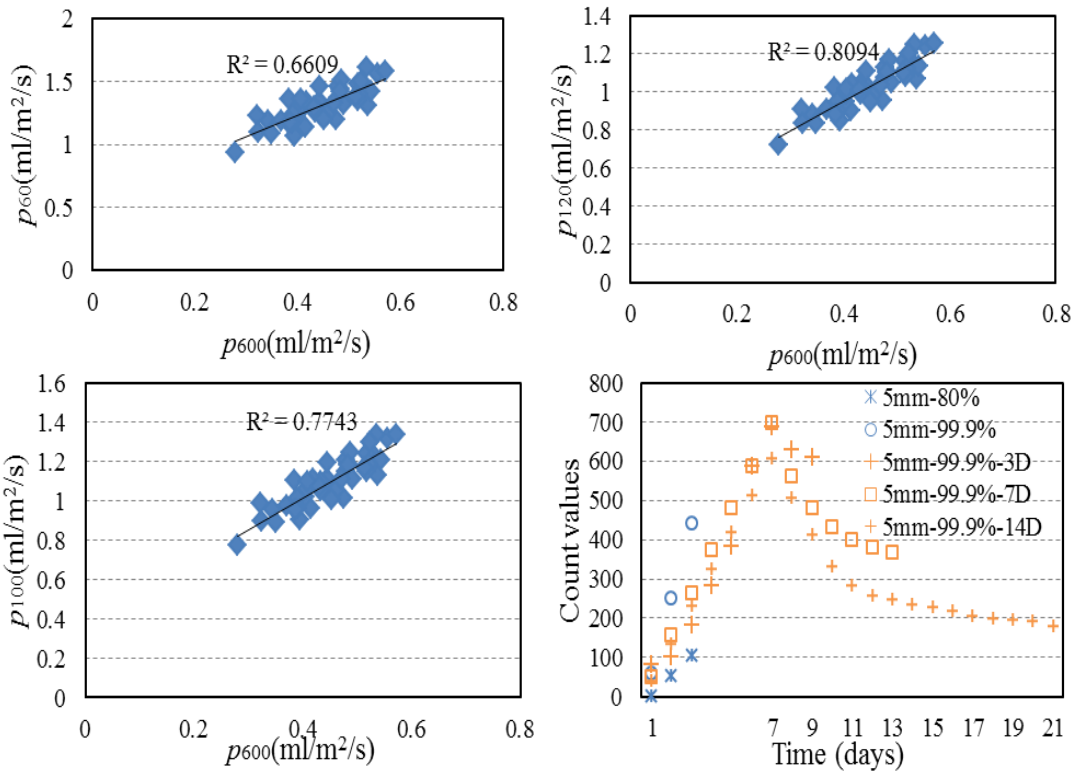

Fig.5.31 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600}, and Count values

(W/C=60%, 1 day in formwork)

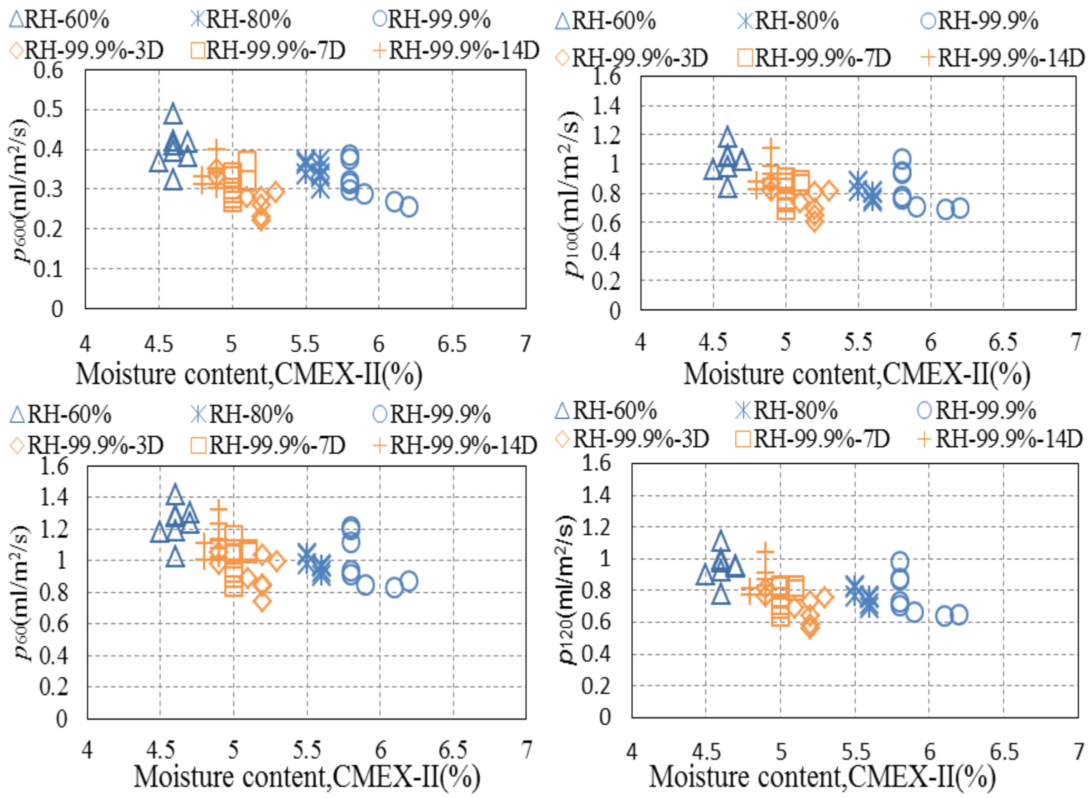

Fig.5.32 (a) SWAT absorption values (W/C=60%, 7 days in formwork)

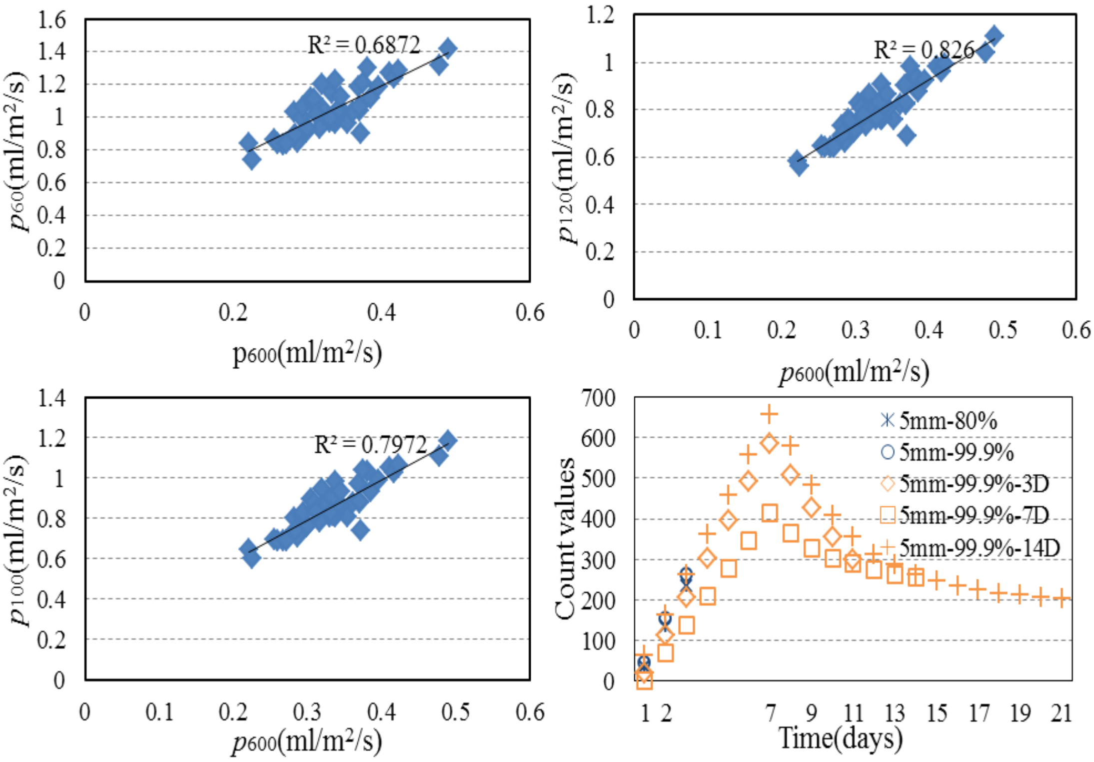

Fig.5.32 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600}, and Count values

(W/C=60%, 7 days in formwork)

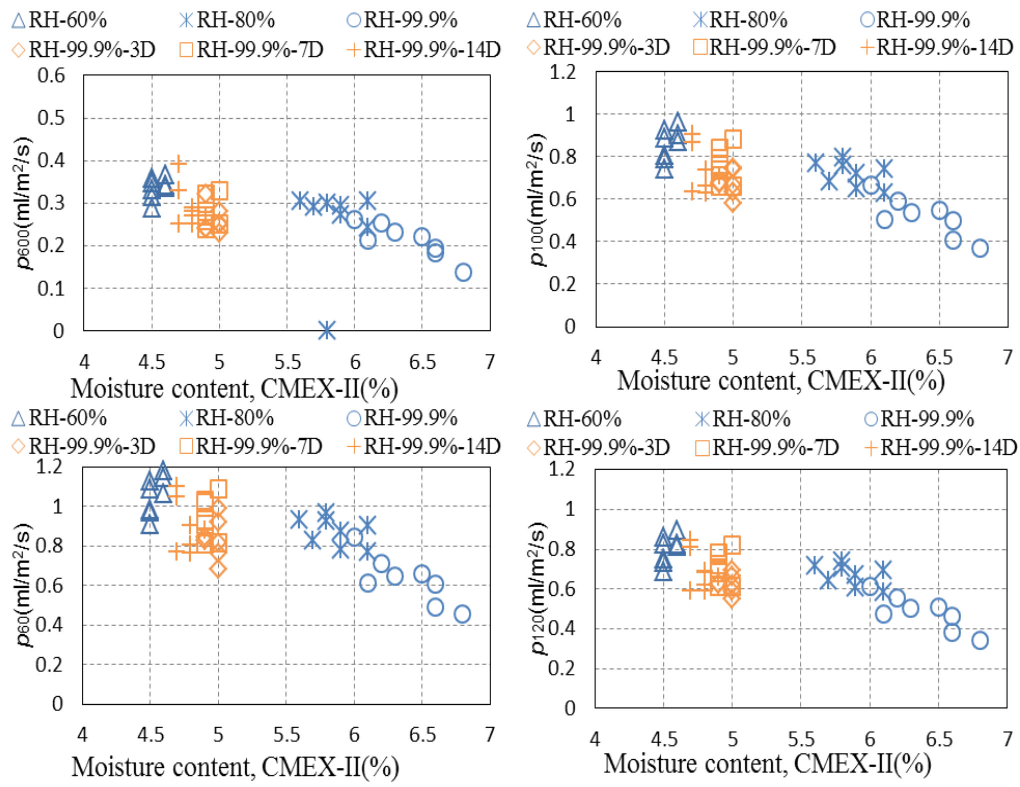

Fig.5.33 (a) SWAT absorption values (W/C=60%, 1 day sealing and 6 days in water)

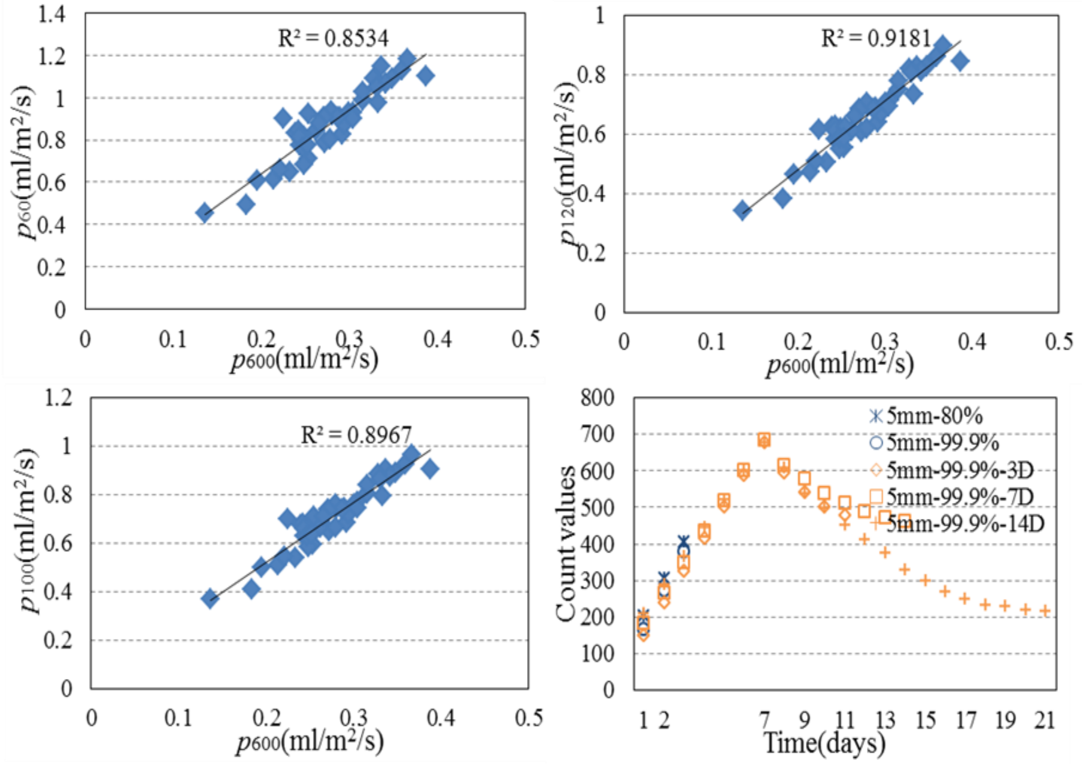

Fig.5.33 (b) Relationships between p_{60}, p_{100}, p_{120} and p_{600}, and Count values (W/C=60%, 1 day sealing and 6 days in water)

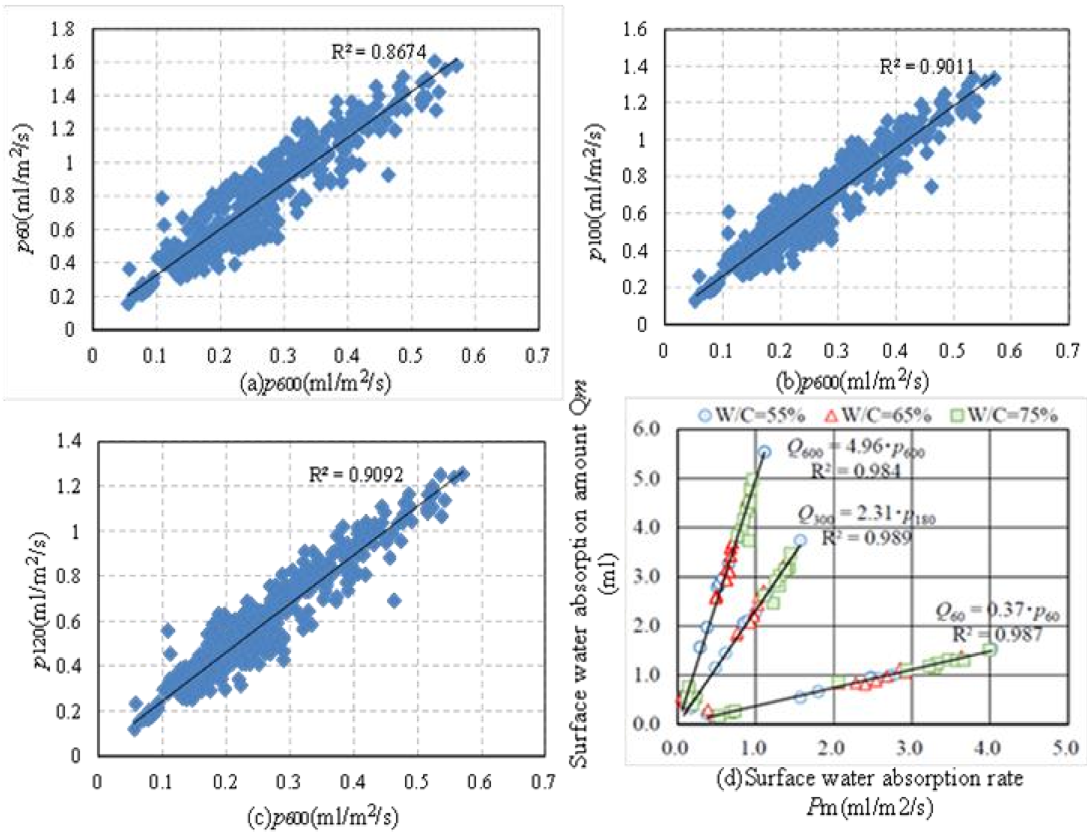

Fig.5.34 Relationships between p_{600} and p_{60}, p_{100}, p_{120} and between Qm and Pm

5.8 Summary and Conclusions

Moisture meters, CMEX-II, and HI-520-2 are used to determine the moisture content in covercrete before conducting SWAT and double chamber air permeability Test. HI-800 is utilized to detect the movement of water into concrete through the count values of sensors. DUCOM and COM3D software are applied to simulate the rehydration of concrete stored in high R.H condition for long term. From the above explanations, conclusions have been driven as follows:

1) It has been revealed that CMEX-II and HI-520-2 devices are unable to detect the moisture content at 5mm depth in case of concrete in wet condition for a long time. Therefore, it is not sufficient to use CMEX-II and HI-520-2 to detect moisture content for conducting SWAT in case concrete kept for a long time in a wet condition. It is also advised that CMEX-II is designed to measure moisture in new concrete floor slabs which are drying from construction moisture. It was not designed to measure moisture content with accuracy in concrete which is rewetted.
2) It has been found that after long term storing in wet condition, good curing concretes exhibited almost no rehydration, while poor curing concretes exhibit rehydration. However rehydration is inconsiderable, so it can be ignored.
3) It has been observed that there exists no good relationship between water absorption results at 600 seconds and those at 60, 100 and 120 seconds. It indicates that water absorption behavior of specimen at one to two minutes is different compared to that at 10 minutes measured by SWAT (p_{600}) affected by moisture contents of inner concrete where CMEX-II and HI-520-2 devices cannot detect moisture content.
4) It has been observed that relationship between *Q*m and *P*m in SWAT results obtained in the research conducted by Ikawa,in 2018 [5.2] had higher R2 or higher coefficient of determination than that in current investigation. This is because of the fact that Ikawa's specimens [5.2] were in dry condition, while specimens in the present investigations were measured when the surface of concrete was not completely dry.
5) Count values related to electric resistance of concrete at 5mm depth might be useful to evaluate whether covercrete is sufficiently dry or not for application of SWAT and double chamber air permeability measurements. This is appropriate for laboratory research, but it is not suitable for real structures.

References

[5.1] Maekawa, K., Ishida, T.,Kishi, T., “Multi-Scale Modeling of Structural Concrete”, Taylor and Francis Group, London and Newyork, 2009.

[5.2] Ikawa, M., Tamaoka, Y. and Hosoda, A., “Fundamental Study on Evaluation Criteria of Surface Quality of Concrete Structure by Surface Water Absorption Test”, Concrete Engineering paper, Vol. 29, pp.101-109, 2018. (In Japanese)

Chapter 6

PROPOSAL OF THRESHOLD VALUE OF MOISTURE CONTENT BY AN APPROPRIATE MOISTURE METER AND A NEW INDEX TO EVALUATE WATER ABSORPTION RESISTANCE

6.1 Introduction

A new method for evaluating the quality of top surface of RC slabs was investigated with a surface water absorption test (SWAT) developed by Komatsu et al. in 2018 [6.1]. In this investigation, moisture meter HI-100 was used to measure threshold values of moisture content of RC slabs. However, the mechanism of evaporation of coverctere of slabs and walls are different. Therefore, the proposal of threshold value of moisture content measured by HI-100 for concrete walls is investigated in this part of research which will contribute to evaluate the drying condition of wall covercrete before conducting SWAT.

When concrete structures are dried after a long term wet condition, surface of concrete is dried at up to shallow depth while inside of concrete is still wet. In such case, SWAT results in ten minutes (p_{600}) may not be reliable to evaluate water absorption resistance of covercrete due to the effect of high moisture content inside the concrete. In this context, an initiative has been taken to propose a new SWAT index called water absorption coefficient to evaluate water absorption resistance instead of p_{600}.

6.2 Objectives

The aim of this chapter is to propose the threshold value of moisture content measured by HI-100 for applying SWAT measurement. A new index called water absorption coefficient with appropriate measurement time for SWAT is proposed to evaluate water absorption resistance of covercrete.

6.3. Experimental Procedures

48 specimens of 300x300x150mm were provided with three kinds of W/C such as 40%, 50%, and 60%. Five electric resistance sensors were located at 5mm, 10mm,

20mm, 30mm and 50mm from the surface of those specimens to detect moisture content of inner concrete. Specimens were cured in three different patterns. After the age of 60 days from casting day, these specimens were stored in three relative humidity conditions such as 60% (curing room), 80% and 99.9% at temperature at 20^{o}C. After 3 to 5 days SWAT and double chamber air permeability tests were conducted. The location of sensors and the shape of specimens are shown in Fig.6.1.

The moisture content in concrete was measured through the change in electric resistance (count value) between embedded electrode steel bars (sensors). Moisture meter HI-800 was used to measure count values of electric resistance.

Fig.6.1 Picture of specimen

1) Materials and mix proportion: Materials and concrete mix proportion of specimens are shown in Table 6.1 and 6.2 respectively.

Table 6.1 Material information

Material	Type	Density(g/cm^3)
Water	Tap water	1.00
Cement	Ordinary Portland Cement (OPC)	3.16
	Blast furnace cement type B (BBC)	3.04
Aggregate	Fine	2.58
	Coarse	2.62
Admixture	AE	1.02
	AE water reducer	1.01

2) Curing conditions: 48 specimens were cast in the curing room. There were three kinds of W/C ratios, 40%, 50% and 60% with OPC concrete. There were 12 specimens for each kind of W/C ratio. Blast furnace cement type B (BBC) was used for more 12 specimens of W/C=50%. 12 specimens were removed from formwork after one day of casting, other 12 specimens were removed from formwork after 10

days casting, and the remaining 12 specimens were removed from formwork after one day and immersed in water for nine days before all of them were exposed in curing room at temperature of 20^{0}C, and R.H.60% . The curing process was shown in Fig.6.2.

Table 6.2 Mix proportion of concrete specimens

Type	W/C(%)	s/a(%)	Unit amount(kg/m^3)					
			W	C	S	G	Ad	AE
OPC	40	45	160	400	776	687	1	0.0025
	50	47	160	320	841	688	1	0.0025
	60	48.5	160	267	890	684	1	0.0025
BB	50	47	160	320	831	688	1	0.025

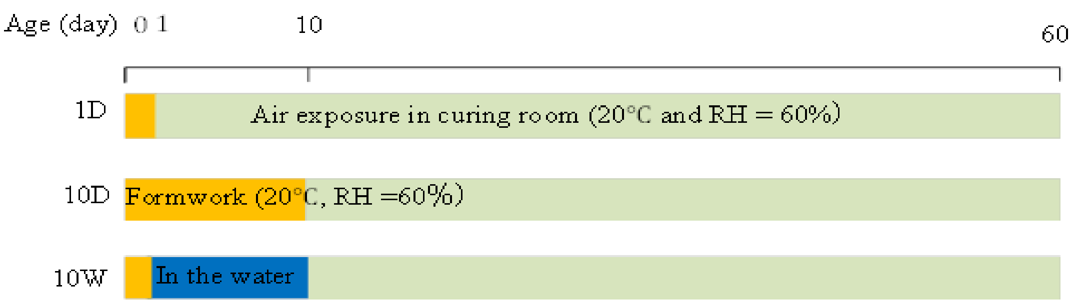

Fig.6.2 Curing conditions

Table 6.3 Commercial devices (moisture meters) used to detect moisture content

Name of moisture meters	HI-100	CMEX-II	HI-800
Measuring method	Electric resistance	Electrostatic capacity	Electric resistance
Measured objects	Concrete slab	Concrete	Concrete, mortar
Measuring range	0−6 (%), 40−990 (count)	Concrete 0-6.9 (%)	Concrete 0−10(%), Mortar 0−15(%)
Appearance			

At the age of over 90 days, all specimens were conducted SWAT in curing room. After that, four specimens with the same W/C ratio and curing condition were stored in two different R.H. conditions (80% ±2%) and 99% for 5 days before returning to curing room. SWAT and double chamber air permeability test were conducted after two to five days in curing room. The moisture contents of specimens were measured by three moisture meters such as CMEX-II, HI-800 and HI-100. Electric resistance values of sensors were measured by HI-800. Moisture meter devices were shown as Table 6.3.

3) Measurement principle of moisture meter HI-100: HI-100 is an electrical resistance moisture meter. The moisture content is determined from the amount of ions in ionized with water. The result is displaced in count value or moisture content. Count value detected by HI-100 is different with count values measured by HI-800.

6.4 Results and Discussion

Figures 6.3-6.5 present the relationship between p_{600} and moisture content measured by HI-100. In all cases it was seen that when moisture content values measured by HI-100 were higher than 190, p_{600} values were apparently small. It is shown in Fig.6.6 (a) that p_{600} of specimens in Series-2 (blue color) were lower than that in Series-1 (red color) although moisture content measured by CMEX-II were the same in two processes. On the other hand, count values related to moisture content of Series-2 measured by HI-100 and HI-800 were higher than that of Series-1 as can be seen in Fig.6.6(c) and (d) (count values of HI-800 are taken from measured points in circle). Furthermore, there is a good relationship between count values measured by HI-100 and count values measured by HI-800 as shown in Fig.6.6 (b). HI-100 can measure moisture content at 5mm depth of concrete. CMEX-II cannot detect moisture content in this case. Therefore, HI-100 can be utilized to determine the threshold values of moisture content of concrete before conducting SWAT.

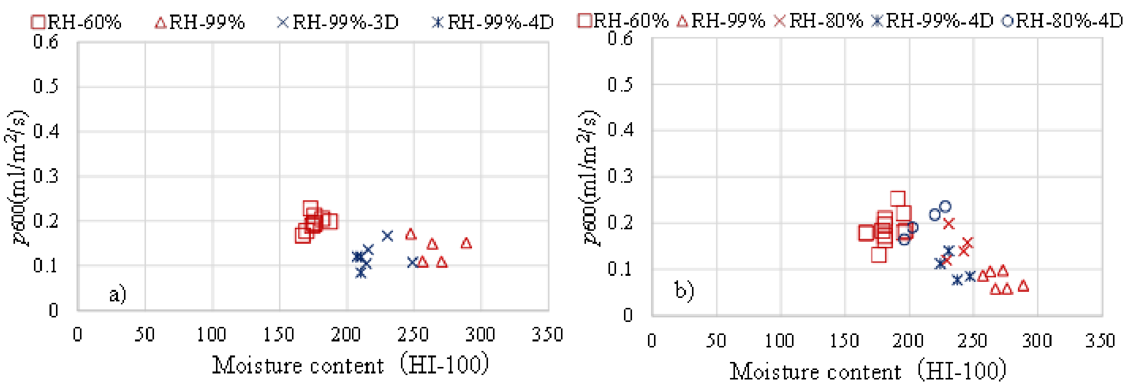

Fig.6.3 Relationship between p_{600} and moisture content measured by HI-100

(W/C=40%, a) sealed one day and b) sealed 10 days)

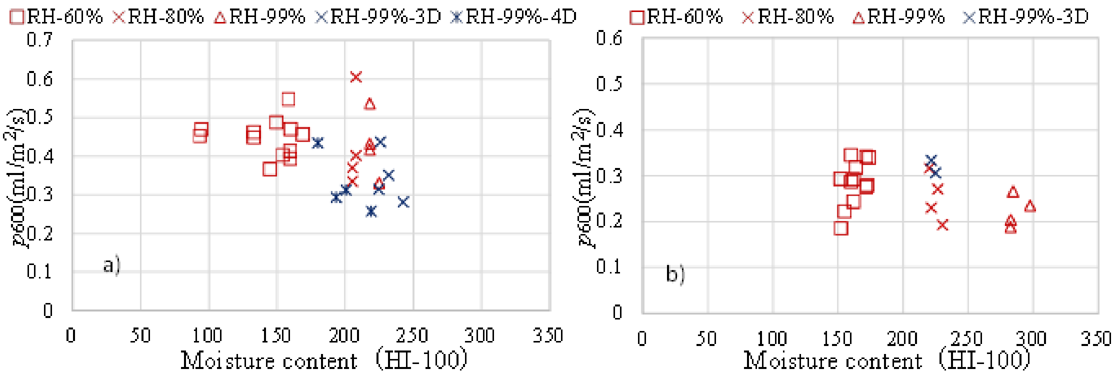

Fig.6.4 Relationship between p_{600} and moisture content measured by HI-100 (W/C=60%, a) sealed one day and b) sealed 10 days)

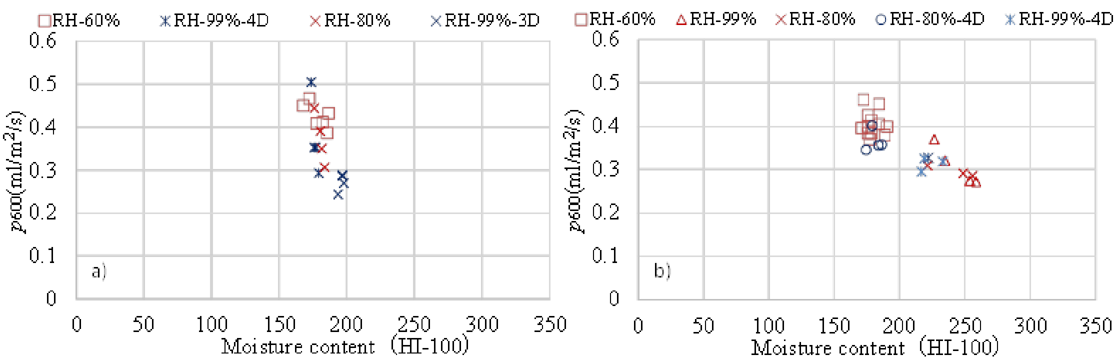

Fig.6.5 Relationship between p_{600} and moisture content measured by HI-100 (W/C=50%, a) sealed one day of OPC, and b) sealed 10 days of BBC)

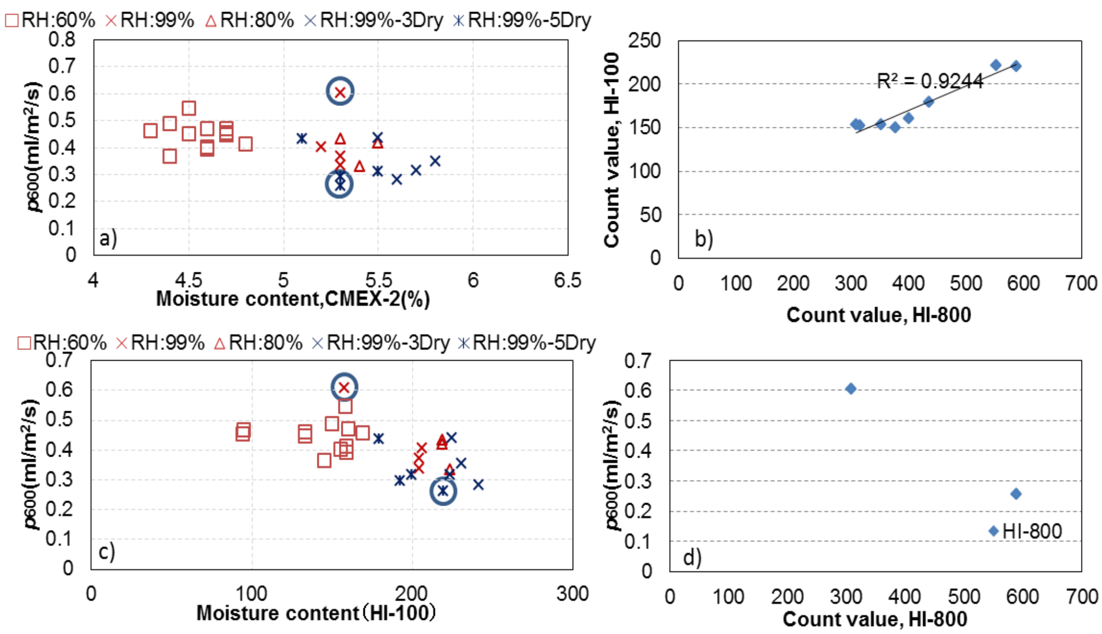

Fig.6.6 Relationship between p_{600} and moisture content measured by HI-100, by CMEX-II and count values measured by HI-800, and relationship between count values measured by HI-100 and HI-800 (W/C=60%, sealed one day)

6.5 Proposal of a new index to evaluate the quality of covercrete by Surface Water Absorption Test

It is observed that when moisture content inside the concrete is high at shallow depth, p_{600} results to evaluate the quality of concrete is not reliable since moisture content will affect water absorption in 10-minute measurement exhibiting nonlinear characteristic. A new index called water absorption coefficient is proposed which may reduce the measurement time for SWAT and can evaluate quality of covercrete reliably. It is considered as slope of cumulative water absorption with respect to time square root exhibiting linear behavior. Unit of water absorption coefficient is ($ml/m^2/s^{1/2}$).

It is observed in Fig.6.7 that there is a good relationship between water absorption coefficient and water absorption rate. Fig.6.7 (a) and (c) show the relationship between p_{600} and water absorption coefficient and cumulative water absorption with time square root of specimen for W/C 60%, one day sealed condition. Fig.6.7 (b) and (d) show the relationship between $p600$ and water absorption coefficient and cumulative water absorption with root square time of specimen for W/C 40%, 10 days sealed condition. In figures, RH-60%, RH-99% and RH-99%-Dry are the curing conditions of specimens at 60%, 80% and 99% humidity respectively. Afterward, the specimens were exposed in curing room. It is also observed from Fig.6.7 (c) and (d) that there is a linear relationship between cumulative water absorption and time square root. This helps to calculate the slope of cumulative water absorption and measurement time square root termed as water absorption coefficient.

The reason why water absorption coefficient is used to evaluate the water absorption resistance is because the relationship between cumulative water absorption and time square root is linear.

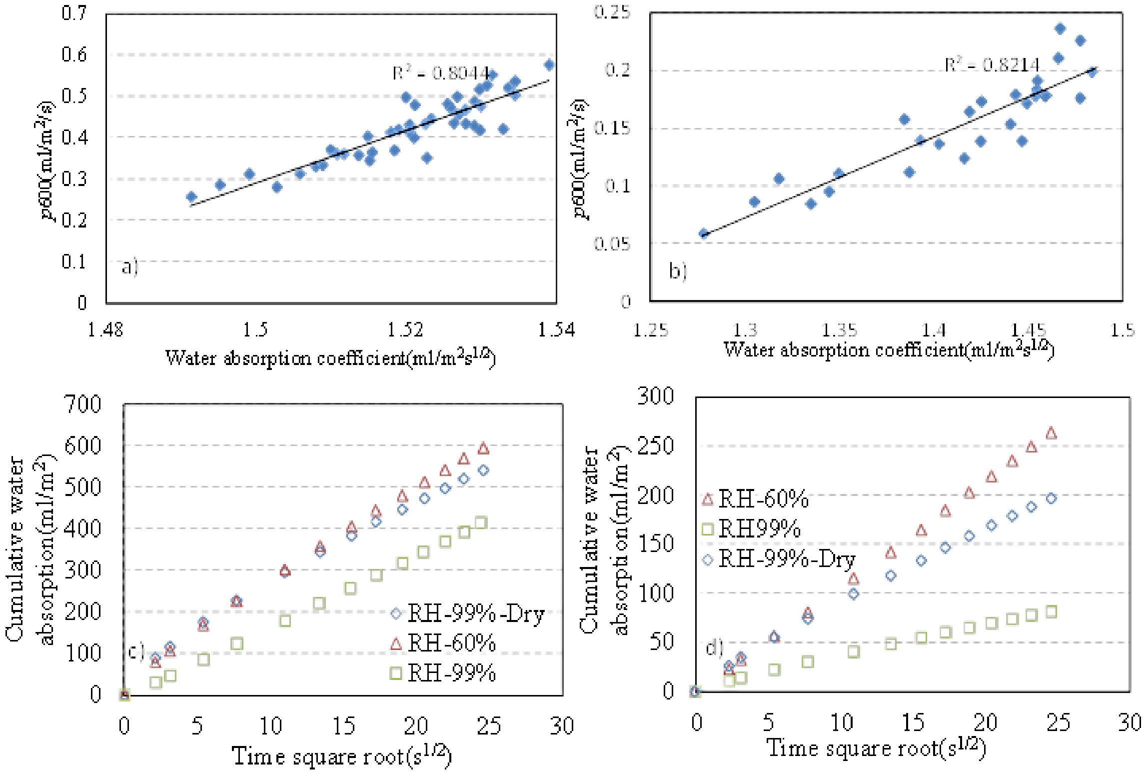

Fig.6.7 (a) and (b) relationship between *p600* and water absorption coefficient, (c) and (d) relationship between cumulative water absorption and time square root

The cumulative water absorption amount using SWAT is shown in Fig.6.8 (in the specimen with W/C = 40%). Measurement was conducted when the count value of the moisture meter (HI-100) was below 190. The measurement results of cumulative water absorption in the same specimen with different moisture contents are also shown in the same figure, i.e. the result when the concrete was sufficiently dried (before wetting). Comparing these results, the cumulative amount of water absorption when the concrete is sufficiently dried (before wetting) and when the count value is below 190 are nearly equal until the duration of 100 seconds from the start of the measurement. However, after 100 seconds, the water absorption rate decreased in the specimen with a count value below 190. It might be due to the fact that the moisture content of the concrete in the region deeper than 5mm from the surface was higher than that of the concrete before wetting. This is similar to the relationship between cumulative water absorption and time square root.

Based on the results, the new index for evaluating the water absorption resistance is proposed in duration of 100 seconds after the start of SWAT measurement. The measured value represents the quality of concrete up to 5 mm from the surface of concrete.

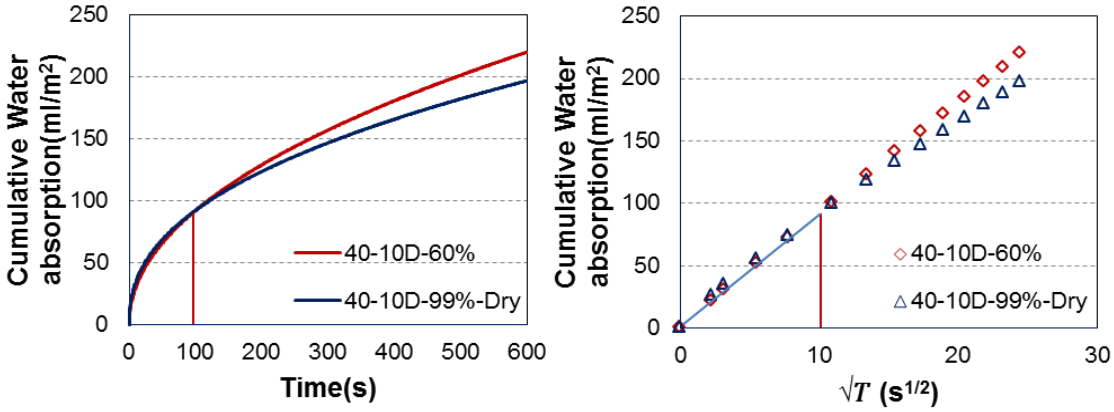

Fig.6.8 Cumulative water absorption amount follow the time and time square root (W/C=40%, sealed ten days)

6.6 Summary and Conclusions

Moisture meters, CMEX-II, and HI-100 are used to determine the moisture content in covercrete before conducting SWAT. Conclusions have been driven as follows:

1) It has been determined that HI-100 can be used to detect moisture content inside concrete before conducting SWAT. In order to evaluate water absorption resistance of covercrete accurately, SWAT should be conducted when count value of moisture meter HI-100 is lower than 190 which is the threshold value of moisture content.
2) A new index entitled water absorption coefficient can be proposed to evaluate water absorption resistance of cover concrete. It can determine water absorption resistance of concrete until measurement duration of 100 seconds.

References

[6.1] Komatsu, S.,Tajima,T., and Hosoda, A.,"Proposal of Quality Evaluation Method for Upper Surface of Concrete Slab with Surface Water Absorption Test," Concrete Research and Technology, Vol.29, pp.33-40, 2018.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 General

Necessary results about applying an appropriate moisture meters to detect moisture contents in covercrete before conducting SWAT and double chamber air permeabilitytest for evaluating the quality of covercrete are abstracted in this chapter. Furthermore, recommendations for further study to find out deeply about the effect of moisture content on SWAT and double chamber air permeability results as well as relationship between moisture content in covercrete measured by moisture meters are proposed.

7.2 Conclusions of the Study

1) A new version of SWAT device was investigated which had more many advantages than old device and the results obtaining from new one were more accurate due to its efficient design.
2) In original device, surface water absorption test is conducted in 10 minutes. Following this measurement period, SWAT can evaluate the quality of covercrete in terms of short and long term absorptions. Recent investigations [7.1], in 2018, have shown that there was a good relationship between SWAT results in one minute with that in ten minutes. It indicates that SWAT conducting time can be shortened from ten minutes to one minute.
3) It has been revealed that water absorption resistance at ten minutes (p_{600}) is influenced by moisture content in concrete. P_{600} values obtained by conducting SWAT are apparently small when moisture contents measured by CMEX-II, and HI-520-2 were higher than around 6.0% and 5.0% respectively. It indicates that when moisture contents measured by CMEX-II and HI-520-2 were lower than 6.0% and 5.0% respectively the results obtained from SWAT are accurate.
4) It has been observed that moisture content in concrete influenced the air permeability of coefficient (*kT*). If moisture content measured by CMEX-II is more than 6.0%, *kT* showed smaller values. In case of HI-520-2, the threshold value of moisture content was around 5.0-5.5%. Therefore, *kT* is reliable when

moisture contents in concrete measured by CMEX-II and HI-520-2 are lower than 6.0% and 5.0%-5.5%, respectively.

5) When HI-100 is used to determine the moisture content in concrete before conducting SWAT, its count value must be lower than 190. The count value 190 ensures that concrete is sufficiently dry up to the depth of 5mm from the concrete surface.
6) When concrete is kept in wet condition for a long duration, CMEX-II and HI-520-2 is not reliable to detect moisture content before conducting SWAT.
7) When conducting SWAT for concrete kept in long term wetting, concrete surface should be left some days for drying before measuring SWAT. The measurement time should be between one to two minutes.
8) It has been revealed that count values related to electric resistance of concrete at 5mm depth may be helpful to evaluate whether covercrete is sufficiently dry or not for SWAT and double chamber air permeability permeability measurements.
9) It has also been found that after seven days of storing in wet condition, good curing concretes were nearly not rehydrated, while poor curing concretes exhibited rehydration. However, such rehydration is inconsiderable, so it can be ignored.
10) A new index of SWAT result "Water absorption coefficient" was proposed to evaluate water absorption resistance of covercrete. Measurement duration for SWAT can be 100 seconds.

7.3 Recommendations for Future Research

SWAT is an efficient device to evaluate the water absorption resistance of covercrete. In order to fully understand the physical meaning and applications of SWAT indices, extensive investigations are required as discussed below.

1) Relationship among SWAT, sorptivity and water penetration rate has not been considered in this research. Future researches could be conducted to relate different indices with SWAT.
2) SWAT and all available test methods are dependent on the moisture content of covercrete. There are some moisture meters to detect the moisture content in concrete. Investigating and applying moisture meters to detect moisture content for conducting SWAT is necessary. Furthermore, future research could be focused

to analyze the correlation between the moisture condition of concrete and that of the SWAT indices.

3) Aggregate types may be one of the factors affecting SWAT indices of concrete. Investigating the water absorption resistance of concrete using recycled aggregate and normal aggregate by conducting SWAT and other test methods are recommended.
4) Water absorption coefficient can have many more advantages than p_{600}, it should be investigated extensively in terms of the effects of changing moisture conditions.

References

[7.1] Ikawa, M., Tamaoka, Y. and Hosoda, A., "Fundamental Study on Evaluation Criteria of Surface Quality of Concrete Structure by Surface Water Absorption Test", Concrete Engineering paper, Vol. 29, pp.101-109, 2018. (In Japanese)