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MOISTURE BEHAVIOR IN GRANULAR BASE LAYER OF ASPHALT PAVEMENT

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A Thesis Submitted in Partial Fulfillment of the Requirements
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Thesis Title	MOISTURE BEHAVIOR IN GRANULAR BASE LAYER OF ASPHALT PAVEMENT
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เรนัลโด : พฤติกรรมของความชื้นในชั้นพื้นทางหินคลุกของผิวทางแอสฟัลต์. (MOISTURE BEHAVIOR IN GRANULAR BASE LAYER OF ASPHALT PAVEMENT) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร.บุญชัย แสงเพชรงาม, 69 หน้า.

ข้อมูลจากการศึกษาด้านวิศวกรรมงานทางทั้งในประเทศและต่างประเทศพบว่าความชื้น (ในรูปของฝน การระบายน้ำ และความชื้นในวัสดุงานทาง) เป็นปัจจัยหนึ่งที่เป็นสาเหตุหลักของความเสียหายแก่โครงสร้างชั้นทาง โดยเฉพาะอย่างยิ่งโครงสร้างชั้นพื้นทาง (Base Layer) ดังนั้นการตรวจวัดและบันทึกข้อมูลความชื้นในโครงสร้างชั้นทางจึงมีความสำคัญในการออกแบบโครงสร้างชั้นทาง เพื่อป้องกันความเสียหายที่จะเกิดแก่โครงสร้างชั้นทางในอนาคต ซึ่งปัจจุบันประเทศไทยยังไม่มีการตรวจวัดความชื้นในสนามและการจัดเก็บข้อมูลความชื้นที่มีสมบูรณ์เพียงพอต่อการนำไปใช้งาน นอกจากนั้นแล้วยังไม่ทราบถึงลักษณะของความชื้นที่เปลี่ยนแปลงไปตามช่วงเวลาเช่นกัน งานวิจัยนี้จึงศึกษาลักษณะการเปลี่ยนแปลงความความชื้นในชั้นพื้นทางในแต่ละช่วงเวลา โดยติดตั้งอุปกรณ์ตรวจวัดค่าความชื้น (Thetaprobe) ในชั้นพื้นทางที่ก่อสร้างด้วยหินคลุกแบบไม่เชื่อมแน่น ซึ่งเป็นรูปแบบที่พบได้มากที่สุดของถนนในประเทศไทย และบันทึกค่าความชื้นทุก 15 นาทีในแต่ละช่วงเวลาตลอดทั้งวัน ด้วยอุปกรณ์บันทึกค่า (Data Logger) ผลการศึกษาพบว่าความชื้นภายในชั้นพื้นทางมีการเปลี่ยนแปลงอย่างเป็นระบบในลักษณะของกราฟซายน์ (Sinusoidal) ซึ่งยืนยันลักษณะการเปลี่ยนแปลงได้จากข้อมูลที่บันทึกได้จากอุปกรณ์ชุดเดียวกันที่ติดตั้งที่ถนนสายทางอื่นอีก 2 สายทาง ที่มีลักษณะโครงสร้างชั้นทางเช่นเดียวกับตำแหน่งแรกที่บันทึกข้อมูล ซึ่งมีลักษณะการเปลี่ยนแปลงของความชื้นในลักษณะกราฟซายน์เช่นกัน จากการวิเคราะห์ข้อมูลพบว่าค่าเฉลี่ยของคาบการเปลี่ยนแปลง (Period) คือ 1290 นาที (21 ชั่วโมง) แอมพลิจูด (Amplitude) ของความชื้นที่เปลี่ยนแปลงไปไม่คงที่ในแต่ละรอบของการเปลี่ยนแปลง โดยมีค่าอยู่ในช่วง 0. 1 – 0.3% ซึ่งลักษณะของการเปลี่ยนแปลงที่เป็นระบบนี้มีประโยชน์ในการประมาณเวลาสำหรับการตรวจวัดและบันทึกข้อมูลในสนาม โดยสามารถตรวจวัดปริมาณความชื้นในชั้นพื้นทางซึ่งจะได้ค่าในช่วงที่เป็นค่าเฉลี่ยของวันได้ใน 2 ช่วงเวลา นอกจากนั้นยังตรวจพบว่าการแตกร้าวของผิวทางยังส่งผลต่อพฤติกรรมการเปลี่ยนแปลงของความชื้นในชั้นพื้นทาง ซึ่งค่าความชื้นที่ตรวจวัดได้จะเปลี่ยนแปลงเพิ่มและลดลงด้วยแอมพลิจูดที่สูงมากและรวดเร็ว อย่างไรก็ตามอุณหภูมิอาจจะส่งผลต่อการตรวจวัดค่าของ Thetaprobe แต่จากการทดสอบและงานศึกษาในต่างประเทศพบว่าอุณหภูมิไม่มีนัยสำคัญต่อการเปลี่ยนแปลงของค่าที่ตรวจวัดได้จาก Thetaprobe แต่อย่างใด

ภาควิชา วิศวกรรมโยธา ลายมือชื่อนิสิต ....

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก ....

ปีการศึกษา 2556

5570530621 : MAJOR CIVIL ENGINEERING
KEYWORDS: UNBOUND BASE LAYER / MOISTURE MEASUREMENT / MOISTURE SENSOR / THETAPROBE / ASPHALT PAVEMENT

REYNALDO: MOISTURE BEHAVIOR IN GRANULAR BASE LAYER OF ASPHALT PAVEMENT. ADVISOR: ASST. PROF. BOONCHAI SANGPETNGAM, Ph.D., 69 pp.

Moisture is one of the influential factors of an asphalt pavement structural condition generally, and base layer specifically. Having that said, having an adequate record of moisture condition data may prevent unwanted damage in the future. At the moment, in Thailand a proper field moisture measurement and time-series data are still unknown. Therefore, in this study moisture sensor (Thetaprobe) is installed in an unbound base layer of road section to monitor the moisture fluctuation all day for a long period. It was found that fluctuation of volumetric moisture content inside base layer apparently follows a systematic pattern that is similar to sinusoidal pattern. The pattern was confirmed by additional observations on two other sites with the same asphalt pavement structure. Fitting results shows the average period of the fluctuation is 1290 minutes (21 hour), and amplitude of the moisture reading is not consistent, which implies different fluctuation every day. The systematic pattern helps simplify time of field measurement to obtain average volumetric moisture content of the day into two times. Deep cracking effect was found on the moisture behavior to be related to leap of change and faster draining process. Temperature was suspected to have effect on Thetaprobe reading, but later considered to be negligible.

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Field of Study: Civil Engineering
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Student's Signature ....
Advisor's Signature ....

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1
Introduction

1.1 Background

Performance of a pavement structure is divided into its strength and service life. There are numerous factors influencing the quality and performance of a pavement structure. According to AASHTO 1993, these are among factors that critically affect pavement performance: design, material, traffic, construction quality, and an environmental factor, such as moisture and temperature conditions. Poor design and material will produce inadequate pavement strength to the traffic, and thus narrow the service life. Moreover, the service life also relies immensely on the environmental factor that is linked to climate, such as moisture and temperature. The unpredicted weather condition is a difficult yet a critical factor that has to be anticipated to preserve pavement strength.

Moisture condition of pavement layers has significant influence on structural strength generally, and on modulus of the unbound materials specifically. The latter is related to the bonding of aggregates inside base layer that creates the layer strength itself. Variation in the amount of moisture inside the unbound base layer can sensitively cause structural deformation and mechanistic performance of flexible pavement. Current guides and various studies have suggested that roughness, rutting, and cracking are among several damages that might appear due to moisture problem. At a certain level of moisture content, the reduction of structure strength could eventually reduce pavement service life. This is a condition we want the least to happen.

In general, water movement inside a pavement structure has two components, lateral movement and vertical movement. A. Dawson (2006) elaborates these components in his study about water movement in road structure. Vertical movement may consist of surface infiltration, infiltration caused by layer permeability, or even water suction due to difference of potential. Lateral movement mainly comprises of runoff, drainage related, and also can be water suction as well. Either way, the water movement remains unexpected, and thus leaves us with the changing value of the moisture condition.

Considering the risk it may bring, and the need of preventing early damage, it is highly necessary to have adequate information about the moisture condition of the base layer over time. Meanwhile, due to the complexity of water condition under the surface, appropriate measurement to help gaining the important information should be a critical tool. The need to conduct effective measurement is considered highly relevant.

Moisture measurement method can be classified as two methods comprise of direct and indirect measurement. Direct measurement is a field sample lab-analysis consisting of sample collection from field and oven-drying at laboratory. Indirect measurement does not require a sample for measurement, but instead measurement at the field. The indirect method measures other parameters to predict the real value of moisture instead of measuring the moisture itself directly.

1.2 Problem Statement

There are many alternatives, in terms of measurement method, to obtain moisture measurement data. However, a comfortable and reliable method should be preferable.

Some examples of moisture measurement methods that are popularly used until now are gravimetric analysis, dielectric method (moisture sensor), ground penetrating radar, and nuclear gauge. For many years, direct measurement or gravimetric method has considered strictly as reference value due to its inefficiency of time for moisture monitoring. It takes much more time and efforts for sampling and lab analysis compared to indirect methods. Moreover, it is impossible to do sampling repeatedly at the same point since it is a destructive method.

Having mentioned this fact, indirect measurement methods have been extremely developing to help moisture measurement does better, at least compared to direct measurement. As for example, the soil moisture sensor, nuclear density gauge, ground penetrating radar, etc. These types of indirect measurements are initially developed in a sense of soil type of ground, and mainly in agricultural discipline. However, the technology itself has been developing and used as measurement tools for other ground material.

The main goal of this research is to conduct a long term monitoring of moisture condition inside the base layer. While paying attention to this goal, author reviewed several methods available in the market based on flexibility of usage, long term suitability, and measurement result. Nuclear Gauge, Ground Penetrating Radar, and Moisture Sensor are the methods in the list. While nuclear gauge and GPR are incompatible for automatic long term data logging, moisture sensor is highly capable of doing so. Moreover, moisture sensor is the most flexible among listed methods in the sense that it can be used comfortably and put anywhere we would like to. Therefore, in this study to resolve the problem of moisture measurement, author choose moisture sensor, as will be explained later on Chapter 3, as measurement tool for data collection.

1.3 Research Objectives

- Implementing electrical-based moisture sensor for a long term moisture monitoring
- To present some moisture measurement data of field pavement to gain knowledge about real field moisture condition and behavior.
- To give recommendation related to moisture measurement procedure for specific method (moisture sensor)

1.4 Research Scope

- This study is focused on a typical flexible pavement with unbound material as base layer
- The measurement will be focusing on base layer
- Moisture sensor will be used as instrumentation to monitor moisture changes inside base material for long period of time
- Analysis excludes seasonal variation such as rainfall occurrence

1.5 Framework

1. Introduction

This part of the report will explain comprehensively about the overview of the research. Research background, problem statement, objectives and scopes are to be presented in this part.

2. Literature Review

This part of the report is divided as two parts, theoretical background review and past studies review. Theoretical background comprises of explanations and expositions related to methods of measurement that are being used for similar studies. Whereas, past studies review give the information of related studies in the past that may help this research by providing additional thoughts.

3. Methodology

In this chapter, author explains about the plan of research, process of data collection, and other details related to phases of doing the research.

4. Data Presentation, Analysis, and Discussion

This chapter presents data collection result during the time of research. Corresponding data analysis and discussion is presented as well as the primary findings of the study.

5. Conclusion

This chapter summarizes the research findings and answers for based on the research objectives.

Chapter 2
Literature Review

2.1 Introduction

Moisture content measurement of ground layers has been typically relying on gravimetric sampling, which is because that is the most fundamental one. However, as time-consuming matter and massive destruction caused takes more concern, several methods have been developed in the process. Resistivity blocks, nuclear-based methods, tensiometric, dielectric methods and neutron probes are some among numbers of other developing/developed methods. These methods are developed in a less time-consuming process, some can be operated automatically, some are portable or un-destructive and other particular advantages compared to basic oven-sampling method.

This part will expose several methods used in road maintenance nowadays, comprised of theory and application. Related studies to this research are going to be presented in this chapter as well, specifically at the last section.

2.2 Gravimetric Analysis

2.2.1 Theory and Calculation

Gravimetric is the most fundamental and basic moisture content measurement of all. This kind of measurement is a lab-scale activity, which uses samples obtained from the field. The need of having samples for the lab test causes this method as an utter destructive method of moisture measurement. It is not merely a problem in the case of soil investigation. However, when it comes to moisture content monitoring of road structures, destructive activities is a massive problem.

Moisture content can be expressed in two ways, volumetric and gravimetric. Volumetric moisture content is simply the ratio of water volume to the dry volume of a given solid mass sample (volume of the solid dry and pore). Gravimetric moisture content is expressed as the ratio of water mass to the dry mass of a given solid mass sample.

The representative formulas are given below.

Volumetric moisture content: $\theta = V_w / (V_s + V_p)$

Gravimetric moisture content: $u = m_w / m_s$

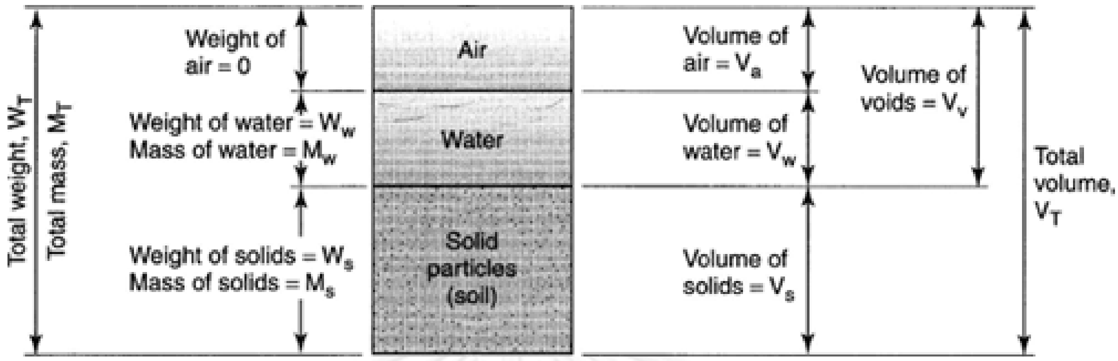


Figure 2. 1 Schematic of Solid Material Structure (Braja M. Das)

A sample taken is comprised of three main components: air, water, and solid particles (might be soil particle, gravel, etc.) as shown by the picture above. By removing the water through heating process, we may obtain the weight or volume of the rest components. This is the basic principle of oven-sampling method.

Since it includes digging activities and inevitably heating process, gravimetric methods is not highly preferable. It cannot help us get instantaneous results of the moisture content.

2.2.2 Procedure

This procedure below is presented based on AASHTO T265 – Laboratory Determination of Moisture Content of Soils.

1. Obtain sample from the field. In order to be a proper measurement, the sample must be an undisturbed sample.
2. Record the sample weight before oven drying
3. Dry the sample using oven specifically 110 ± 5°C overnight or 15-16 hours (drying to a constant weight)
4. Remove sample from oven and record sample weight
5. Calculate the percent moisture as follows:

$A = ((B - C)/C) \times 100$

A = Percent gravimetric moisture content

B = Weight of original sample

C = Weight of dry sample

2.3 Sand Cone Method

Sand cone method is a fundamental method to collect sample from an investigated ground. The steps can be explained as follow: digging a small hole in the ground, take a sample and retain the excavated sample in an airtight container. The standard procedure of conducting sand cone method is given in ASTM D1556-82 and AASHTO T191-82. The sample taken by sand cone method is considered to be an undisturbed sample. This is mandatory for laboratory proper laboratory analysis afterwards.

The sample taken through sand cone method is going to be analyzed gravimetrically in the lab. Engineer has been considering the result obtained from this analysis as the most reliable for years. However, the massive drawback of its destructive procedure is disturbing and thus reducing its popularity to be used.

2.4 Dielectric Method

Dielectric method estimates the moisture content based on dielectric constant (Ka_b) of the measured medium. Dielectric constant is a value that represents the velocity of an electromagnetic wave propagated through a medium (i.e. soil). In other words, dielectric constant represents the ability of a medium conducting electric force. The most fundamental basis of dielectric method is that water has significantly higher dielectric constant (Ka_w = 80) than other materials. The velocity of a wave going through a certain medium will be highly determined by the existence of water. Hence, it can help us estimate the moisture content.

There are many variations of dielectric measurement methods depending on the material type, sample geometry, and frequency range, of which three different types are going to be explained in the followings. Those are Time-Domain Reflectometry (TDR), Frequency Domain, and Amplitude Domain Reflectometry (ADR). Each type has significantly different working principle but as mentioned before, they estimate moisture content based on dielectric constant. Choosing one from the other is commonly based on the usage suitability.

The relationship between dielectric constant and volumetric water content has been developing for the last several decades. The most drawing attention is the works of Topp et al. (1980), as given below.

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\varepsilon_r - 5.5 \times 10^{-4}\varepsilon_r^2 + 4.3 \times 10^{6}\varepsilon_r^3 \quad \text{Eq. 2.1.}$$

This equation is compatible for various kinds of soil type. However, there are still doubts about its accuracy if used in specific soil type.

2.4.1 Time-Domain Reflectometry (TDR)

TDR is commonly used to detect discontinuity inside cables in electrical matters. An electronic wave is transmitted through the cable and a reflective wave will be sent back to its origin if a discontinuity found inside the cable. The location can be found by analyzing the information obtained, which is the velocity of the wave being reflected. The velocity depends on cable's dielectric constant. The output of TDR is time-based. Therefore, we can estimate where the discontinuity by comparing the velocity and the time needed by the wave.

By adapting the same principle we can do the same to detect moisture content inside a medium on a certain depth. But, instead of finding the location of discontinuity, we use TDR to find the dielectric constant, which is commonly unknown on a regular basis. As previously mentioned, the huge different of dielectric constant between water and other material inside a medium underground is the main key to measure such content.

A TDR probe is comprised of three main parts, an oscillatory reader (which is also the transmitter), coaxial cables and parallel rods, as can be seen on the picture below. The rod is the part that is going to be inserted into the medium. The coaxial cables are the connectors between transmitter (pulse generator) and the conducting rods. The transmitter and oscillatory reader is the main controller when doing the test. Details of the working process and usage of each part are going to be presented in the following paragraphs.

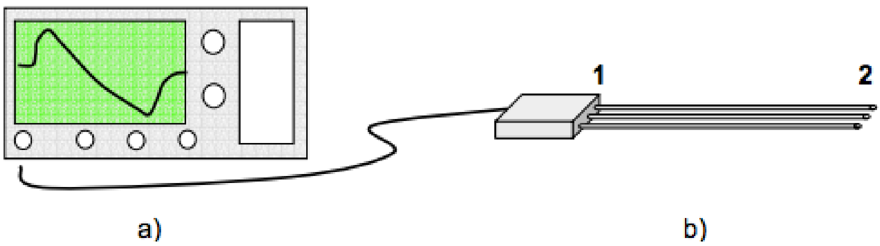


Figure 2. 2 (a) TDR Oscilator (b) TDR probe

The transmitter is where the measurement starts. A series of electrical pulse is to be timely propagated from this transmitter. As the pulse being transmitted, the oscillatory screen will record the change of the voltage over time through the cable and the rods. The transmitter commonly can be operated in high range of different frequencies. This is to minimize the dependency of soil/medium properties. The coaxial cable is simply conducting the wave to reach the rods.

The metal rods are the part that enables the wave to reach the medium. Once it is inserted into the measured medium, the travelling wave is now able to travel inside the medium also. Hence, we can practically measure the medium's dielectric constant near the rods. There are many configurations of TDR rods, produced by research to gain better dielectric constant representation of the measurement.

TDR operations

To help understanding the operations that happen behind the scene, picture below might be really helpful.

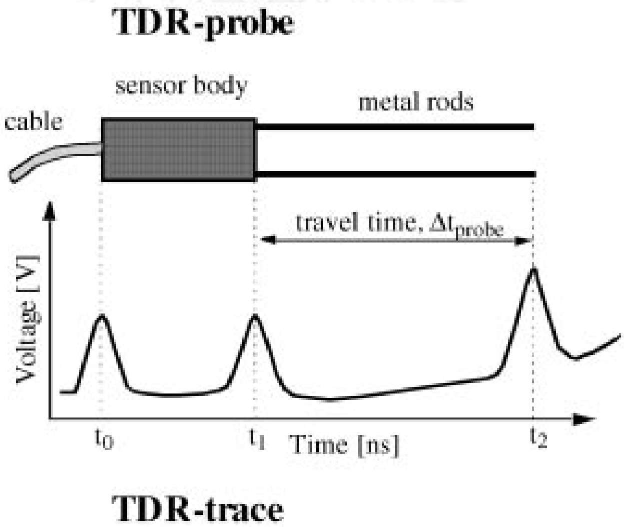


Figure 2.3 TDR Wave Result along the probe

A pulse generated by the transmitter and starts travelling through the coaxial cable. As the pulse travels, the oscillatory starts recording with time reference as x-axis and voltage as y-axis. As we can see in Figure 2.4, the travelling start point can be found on point A, representing the initial voltage. At locations where an impedance mismatch occurs, some of the energy from the step-pulse is reflected back to the source and can be viewed on an oscilloscope. As it travels through the coaxial cable, the voltage slightly changes until it reaches the first discontinuity, which is the transition from coaxial cable to metal rods. The voltage changes to point B. The curve drawn from point B to point C is the changing of the voltage when the pulse travelled along the metal rods. At point C, the second discontinuity is reached, which is the end of the metal rods. To be noted, the oscillatory picture that is recorded by the reader is basically the result of the reflected wave. When the wave travels, part of it is reflected back to the source and moreover by the time it reached the end of the metal rod, it is all being reflected back to the origin.

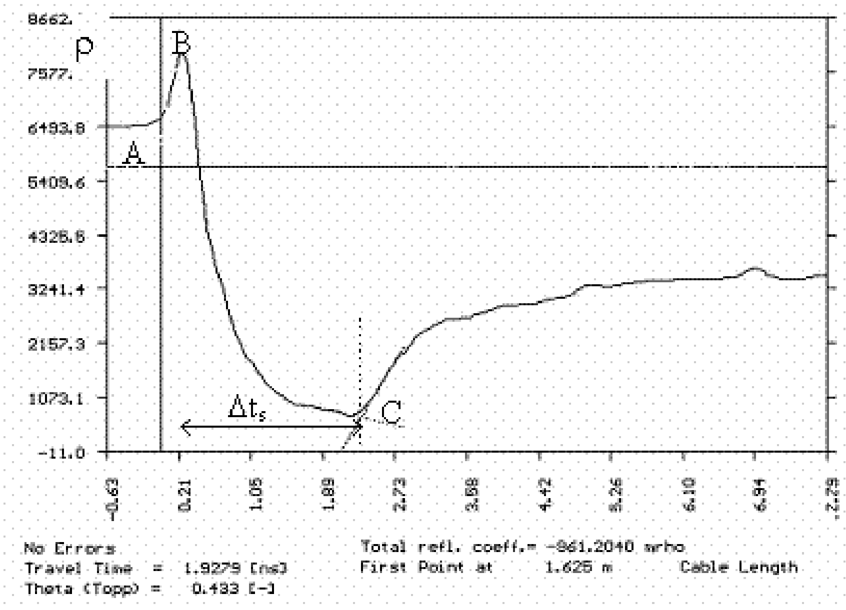


Figure 2.4 TDR Reading Result Example

<u>Analysis</u>

Lastly, the main point that is needed from the test is the dielectric constant of measured medium. The bulk dielectric constant of medium is calculated based on the time needed by electromagnetic pulse to travel through transmission line (TL), the metal rods, which are surrounded by the medium. The determining equation is provided as below:

$$K_{ab} = (c/v)^2 \qquad \text{Eq. 2.2.}$$

In this case, v is derived using travel time (t) and length (l). Therefore, we can rewrite the equation as below:

$$K_{ab} = ((c.t)/(2.L))^2 \qquad \text{Eq. 2.3.}$$

where :

c = velocity of electromagnetic waves in vacuum medium (3*108 m/s)

L = the length of transmission line embedded in the soil

t = travelling time through transmission line

Moisture content measured by TDR is the average value of the medium based on the length of transmission lines embedded. If the transmission lines are injected 20cm deep, the measurement will give the average moisture content of medium's part from surface to 20cm depth.

TDR method is relatively non-destructive, quick, inexpensive, and might suit for various kind of layer profile measurement, such as surface, base, sub base and subgrade. It is not complicated to use and quite portable to bring for in-situ measurement. For timely monitoring, it can be connected to automatic data logger and then the result may be easy to control by surveyor.

The drawback of this method is that it still needs certain calibration related to the type of the medium. It has to be calibrated for a specific soil type to make sure that the result is accurate.

2.4.2 Frequency-Domain: Capacitance and FDR

Frequency-Domain technique has a similar basic understanding in its relation of moisture content measurement. FDR also has the basis that apparent dielectric constant of a medium (e.g. soil) is empirically related to volumetric moisture content. However, the electrical principle and equipment used in FDR are completely different from TDR.

A set of electrodes connected to high frequency (≈150MHz) transistor oscillator if embedded into a media such as soil will form an ideal capacitor. A capacitor is a device used to store an electrical charge. Since our ground is technically a perfect conductor, the connection between oscillator, electrodes, and ground is simply an electrical circuit. Changes in the operating frequency of this circuit can represent the changes of soil moisture content. This is basic working principle of Frequency-Domain technique regarding volumetric moisture content measurement.

There are two kinds of sensors in FD-technique. In Capacitance sensors the dielectric permittivity of a medium is determined by measuring the charge time of a capacitor made with that medium. In FDR, the oscillator frequency is swept under control within a certain frequency range to find the resonant frequency (at which the amplitude is greatest), which is a measure of water content in the soil. The next picture is an example of Frequency Domain probes.

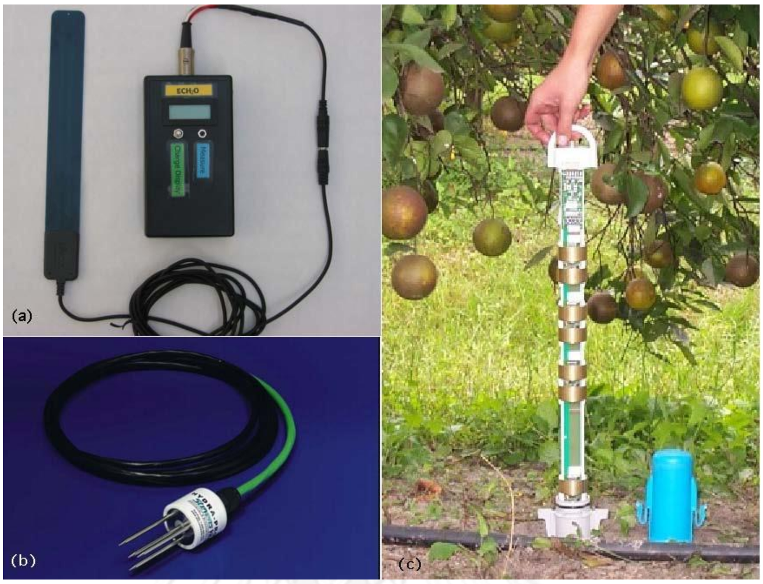


Figure 2.5 FDR and Capacitance (Muñoz-Carpena, 2004)

2.4.3 Amplitude-Domain Reflectometry (Impedance)

Electromagnetic wave that travels through two mediums with different impedance will produce reflection energy back to the source. Impedance is the effective resistance of an electrical circuit or component to alternating current. In ADR, when the wave travelling along the transmission line and reaches a section with different impedance, e.g. soil, it will reflect part of the wave back into the source. The reflected wave will interact with previously transmitted wave, thus produce a change of amplitude along the transmission line. The change of amplitude can be used to obtain the volumetric moisture content of the measured medium.

Almost similar like the pervious, ADR consists of an oscillator that generates sinusoidal electromagnetic wave, a coaxial transmission line that passes through the wave, and parallel metal rods as transmission line that will be embedded inside the measured medium. A schematic illustration can be seen below.

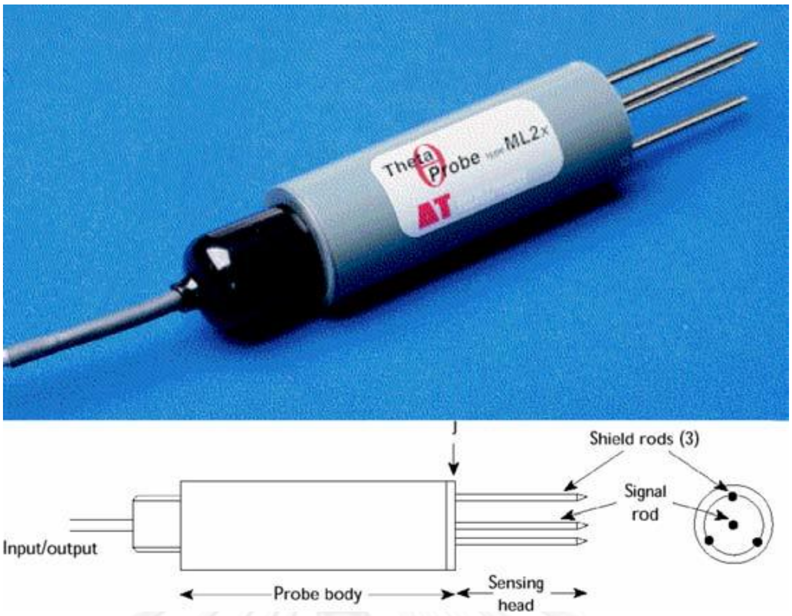


Figure 2.6 ML2x-Thetaprobe Moisture Sensor (Muñoz-Carpena, 2004)

Impedance has two components: electrical conductivity and dielectric constant. The electrical conductivity of the medium may contribute to the attenuation of the transmitted wave and, to some extent, its reflection. Therefore, in order to overcome the influence of electrical conductivity, suitable signal frequency must be used from the beginning of preparation.

ADR is extremely portable and easy to use for mobile measurement. However, ADR can only measure small volume of medium (around 0.27 $inch^3$).

2.5 Ground-Penetrating Radar

Ground Penetrating Radar (GPR) is an electromagnetic energy signal that penetrates through the subsurface. GPR systems consist of three main parts, which are the control unit, the antenna and the survey encoder.

The antenna has a transmitter and a receiver. When the signal returns to the antenna, travel time and amplitude will be reported on the screen. The antenna itself has different frequencies for different specific use. The radar pulse’s central frequency ranges from 10 MHz up to 2.5 GHz. High frequencies are used for shallow depth of observations whereas low frequencies are used for deep depth and large targets of observations.

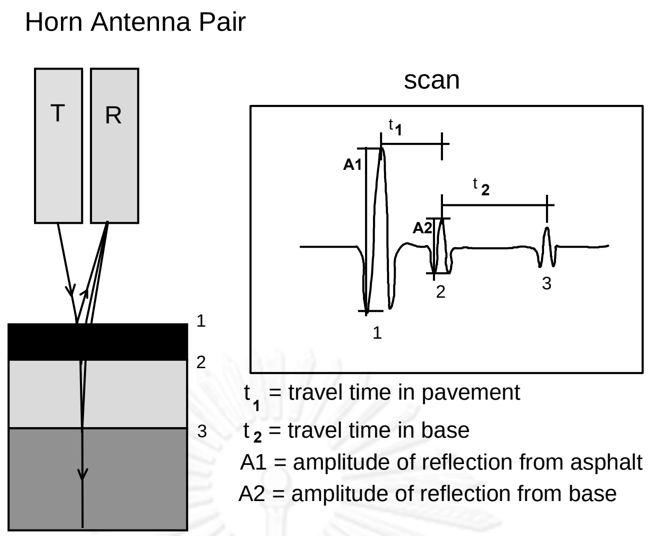


Figure 2.7 Basic Working Principle of GPR (Saarenketo, 2008)

The pulse is used to resolve the locations and dimensions of electrically distinctive layers and objects in materials. Pulse radar systems transmit short electromagnetic pulses into a medium and when the pulse reaches an electric interface in the medium, some of the energy will be reflected back while the rest will proceed forwards.

The basic steps in GPR-based moisture content estimation are commonly done by the single offset reflection as shown in previous picture. Signals propagated from the radar travels at different speed through different mediums. Fundamentally, propagation and reflection of the radar pulses is controlled by the electrical properties of the materials, which comprise of magnetic susceptibility, relative dielectric permittivity, and electrical conductivity. However, due to specific frequency usage some electrical properties become negligible, and in practice, the travel speed mainly depends on the dielectric constant of the medium. Radar can travel faster in a low dielectric than in a higher dielectric. As water has higher dielectric constant than others, the signal travels longer when water exists. Petrophysical relation between volumetric moisture content and dielectric constant is the background principal that makes the use of GPR versatile to moisture estimation. The dielectric constant can be estimated in the same way as TDR, which is using equation below:

$$K_{ab} = (c/v)^2 \qquad \text{Eq. 2.4}$$

In order to convert dielectric constant to volumetric moisture content, Topp’s equation is also used as previously mentioned in TDR-section.

One thing that we should remember is that GPR is an electromagnetic instrument, which means the use of cellphones or two-way radio may interfere the measurement. It may not cause any damage but it may create noise and interference, which will make the data more difficult to see and even to interpret.

2.6 Nuclear Density/Moisture Gauge

NDG is a radiation-based instrument. NDG works by releasing gamma radiation, 'fast' neutrons into the material. Moreover, gamma radiation is absorbed by three means, depending on the energy source: (a) photo electric effect (low gamma energy), (b) Compton Effect (medium gamma energy), and (c) ionpair production (high gamma energy).

When a high-energy neutron collides with a nucleus of another atom that is heavier than it, it will lose small amount of energy. However, when it collides with another atom that similar in mass with it, it may lose some amount of energy and be slowed down. Hydrogen, which forms water particle, has fairly same mass as the neutron released by the nuclear gauge. Therefore, principally the gamma radiation will be slowed down whenever there is an interaction with hydrogen atom, or water in other word.

NDG detectors will count the gamma rays that passed through the material. This counted number is the basis to estimate the moisture content. Basically, the more neutrons counted, the higher the moisture content of the material.

The gauge can generally determine the level of moisture under the gauge to a depth of 4-8 inches. The level of moisture controls this depth. The higher the moisture content becomes, the shallower the depth of measurement will be.

There are two different types of NDG process.

1. Direct transmissions, measures both gamma photons that are generated directly from the source and those that have been scattered back to source by Compton Effect.
2. Backscatter, are predicated on the use of the Compton Effect absorption principle of medium-energy gamma photons. It counts the gamma photons that bounce back to the source.

A definite relation exists between the number of gamma photons that are scattered back from a material and the density of the material. The number counted by the detector is inversely proportional to pavement density, and on the other hand directly proportional to moisture content.

A special case for backscatter method is that air gap between the radiation source and the material surrounding the source may cause problems in measurement. Therefore, it is necessary to keep as tiny as possible air gap when operating the gauge.

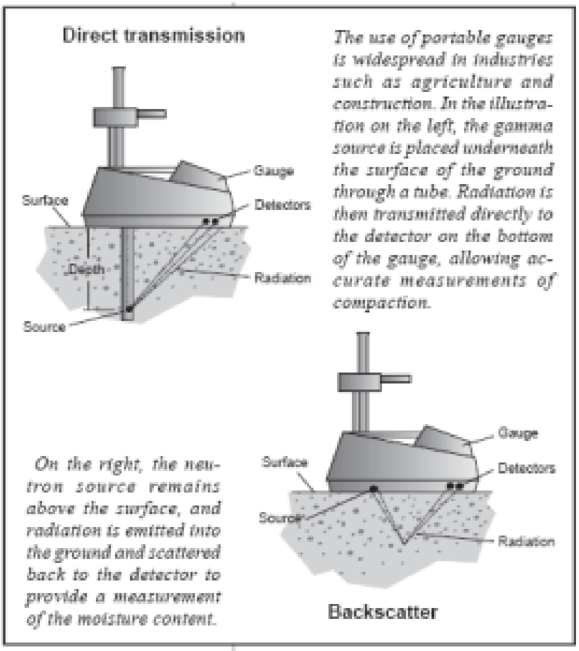


Figure 2.8 Two types of Nuclear Gauge Operation (Canadian Nuclear Safety Commission, 2007)

Therefore, the difference in the depth of material that influences each detector and mathematical modeling allow the gauge to determine the density of only the top, newly placed lift (Troxler, 2002).

The real time measurement capability and non-destructive characteristic are the big advantages that we can have using nuclear gauge. However, the drawback of this method is that it is highly related to chemical composition. A certain calibration relation has to be made with respect to soil types, or ground material in this matter. A standard guide of nuclear gauge calibration is provided in ASTM D7759 - 12a (Standard Guide for Nuclear Surface Moisture and Density Gauge Calibration). Another drawback is that despite its portability it is not an automatic instrument, which means the usage is limited to accessible locations for operator.

2.7 Related Studies

- *Measurement of Soil Water Content Using a Simplified Impedance Measuring Technique (Gaskin and Miller, 1995)*

Gaskin and Miller experimented on the application of simplified impedance technique to measure soil water content under field condition. This type of instrument was found reliable and suitable for determining changes in water content. Moreover, the low price and the easiness to install are additional advantages on this instrument. The major advantage compared to other techniques is that the ease with which its output can be continuously or periodically monitored and this would help capturing critical changes in water content in soil studies.

- *Field Devices For Monitoring Soil Water Content (Muñoz-Carpena, 2004)*

Muñoz-Carpena reviewed a number of monitoring devices that can be used in the field to measure soil moisture condition. Most are electrical-based tools including dielectric methods, which is the most popular that has been used in agriculture discipline. The like of Thetaprobe has some advantages, such as high accuracy, better resolution than TDR, flexibility in design, and connectable with conventional logger. However, some drawbacks are it needs to have as low as possible air gap to ensure contact between sensor and the soil, and sometimes is more sensitive to temperature than other instruments.

- *Field calibration of the theta probe for des moines lobe soils (Kaleita et.al, 2005)*

The purposes of this study were to calibrate Thetaprobe for soils of Central Iowa through field sampling, secondly to determine the number of samples needed for field calibration, and to study the effect of temperature on calibration. Calibration was conducted by comparing measurement reading in the field to gravimetric lab analysis result using field sampling. The major finding related to this study is that the inclusion of temperature into calibration equation does not necessarily improve the calibration. A recommendation in relation to field sampling for calibration is that the minimum number of samples needed is 20 samples.

- *Analysis of the influence of soil temperature and soil surface conditions on soil moisture estimation using the ThetaProbe (Dilawari, 2006)*

This objective of this master thesis was to learn Thetaprobe performance with regard to the change in surface condition and also temperature. The test setup was made in a laboratory, where sand sample was stored in a topless box container. The surface of the sand was design to be able to change over time through several types of artificial environmental changes. Temperature was also measured using thermal sensor embedded in the soil. Soil specific calibration equation was determined in multiple steps to see the improvement by including temperature effect. In conclusion, it was learned that temperature apparently does not improve the calibration equation significantly, or in other word it does not extreme effect on ThetaProbe reading.

- *Effect of soil texture on moisture measurement accuracy with Theta probe ML2 in Sistan region (Sarani and Afrasiab, 2012)*

Sarani and Afrasiab studied about the effect of different kinds of soil texture on moisture reading of ML2 Thetaprobe. There are four types of soil that was used in the study: clay, loam, sandy loam, and sand. The experiment was conducted in the lab by comparing the measurement value from Thetaprobe to gravimetric analysis result. The result shows that Thetaprobe has the highest precision and accuracy on sandy soil. The accuracy was found becomes lower as the amount of clay increased in the soil. Based on this study, soil texture is apparently has effect on moisture reading by Thetaprobe.

Chapter 3
Methodology

3.1 Introduction

The objective of this study is focusing on gathering information related to moisture measurement of flexible pavement in a real field condition. The behavior of its changing activity is primarily targeted, while the lesson from field moisture measurement would be the secondary finding extracted from this study. The latter would be very useful information for further study and implementation of similar instrumentation. Related to this objective, through this chapter author explains the data collection and series of corresponding activities.

This chapter will present data collection method (such as instrumentation, site selection, instrument installation, etc.), supporting procedures for analysis, and data analysis method.

3.2 Properties Measured

The main properties collected in this study are:

- Field pavement structure dimensions
- Base layer volumetric moisture content
- Time series of day
- Pavement temperature

The first three are the primary properties that were collected. The latter was collected to support analysis and finding for the conclusion.

3.3 Data Collection Method

In order to obtain the information pertaining to moisture changes over time inside the unbound base layer, we conducted a monitoring process on a typical flexible pavement section. Moisture monitoring was conducted inside Chulalongkorn University property in Saraburi province of Central Thailand region.

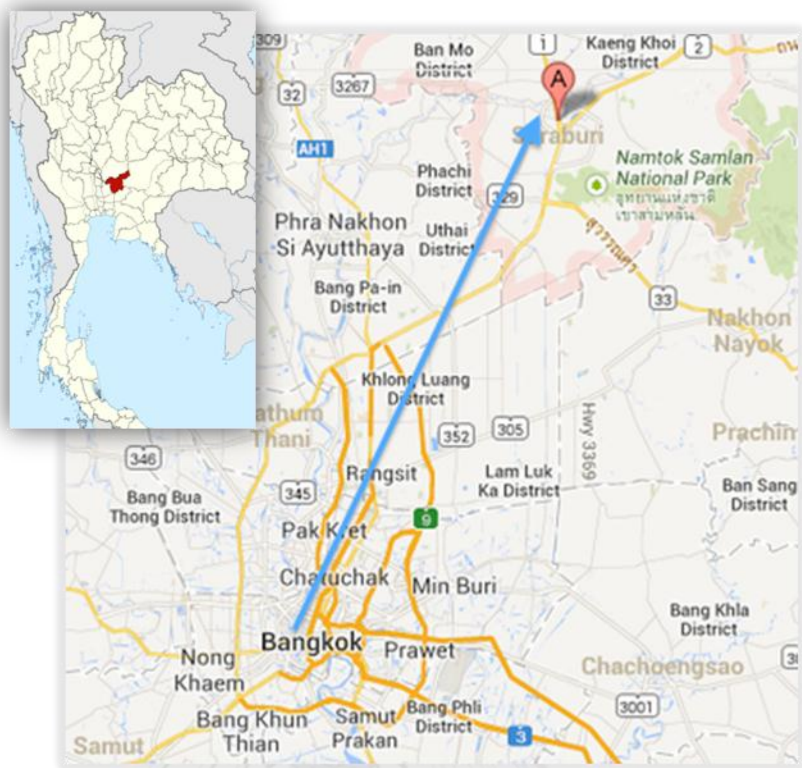


Figure 3. 1 Map of Site Location

Moisture sensor was installed in three different locations inside Chulalongkorn University (Saraburi) area. However due to limitation of the quantity of data logger, we were only able to install the sensor at one location at a time. Initially, there was only one moisture sensor in possession, but two other similar sensors were ordered later in the time of the study to support the data from the first sensor. On the other hand, there was only one GP1 data logger that can be used until late in the time of the study for both field monitoring and laboratory temperature verification.

Detail of three site locations can be seen in the following figures.

Site 1 and Site 3 are located in the same part of Chulalongkorn University area, which is in front of i-ENG Laboratory Building, and have a distance of 32.5 meters. The differences between site 1 and 3 are the elevation, surrounding area, and surface thickness. Site 3 has a 10-cm deep surface.

Figure 3.2 Location of Installation Site 3 to Installation Site 1

Site 2 is located approximately 880 meters from site 1 and 3, and has fairly different condition of surrounding area. The surface thickness is the same as the surface thickness of Site 1 (5cm).

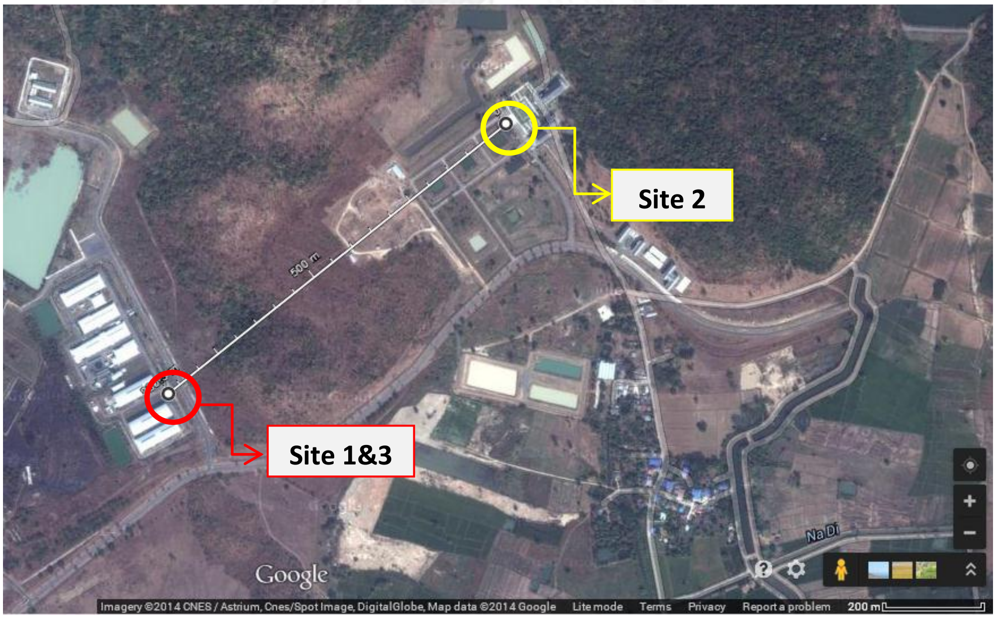


Figure 3.3 Map Location of Installation Site 1, 2 and 3 in Chulalongkorn University (Saraburi)

The following picture is landscape view of Site 1, on which the yellow box shows the shelter where GP1 logger was kept. This kind of method of keeping the logger was used both in Site 1 and Site 2. Since there is no shelter nearby the installation point, in Site 3 we used a safe box to keep the logger away from animals, and also weather issues..

Figure 3.4 Site Location 1: In front of i-ENG Laboratory Building

The following figure is a sketch of cross section of Site 1 installation. The scale of this Image does not represent the real scale. Site 1 has a canal located around 6 meters from the road shoulder. Some vegetation were also existed near the canal. The road section has 8cm of surface thickness.

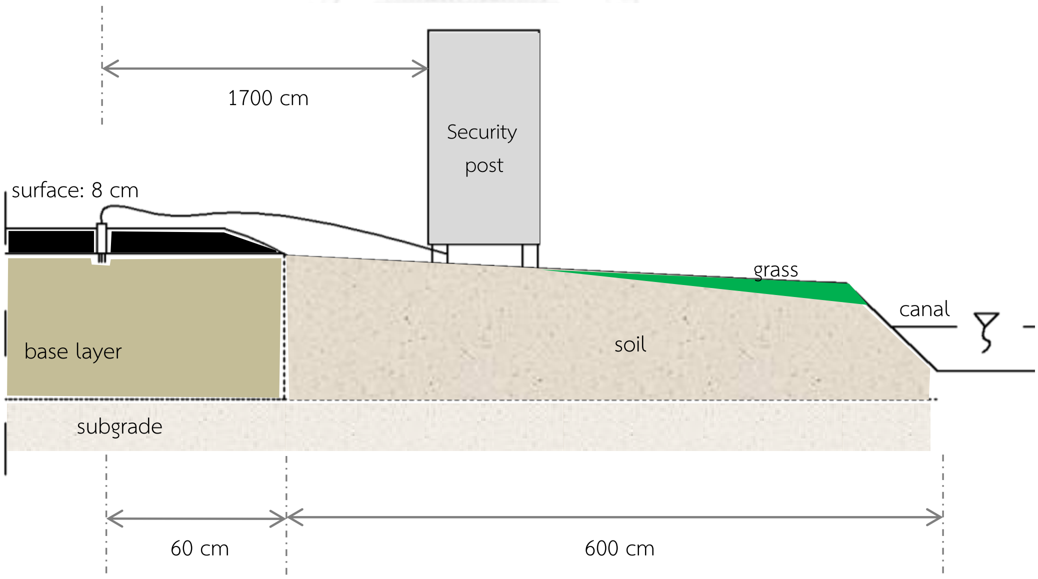


Figure 3. 5 Cross Section of Site 1

The following figure is a sketch of cross section of Site 2 installation. Image dimension does not represent real dimension. Site has a small canal located around 2 meters from the road shoulder. Since the surrounding area was office and administrative building, the canal was a lot smaller than the one at Site 1.

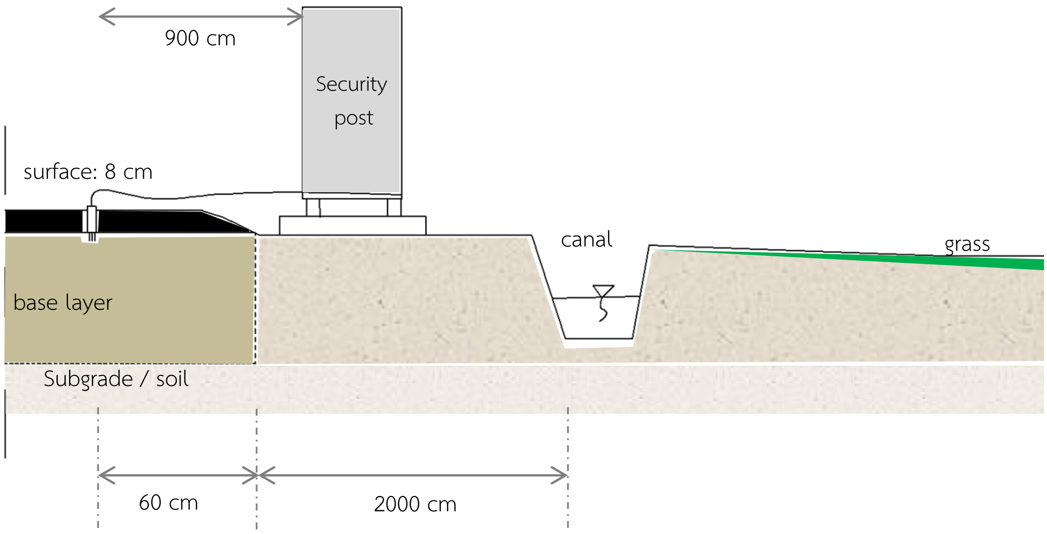


Figure 3. 6 Cross Section of Site 2

Figure 3.7 Site Location 2: In front of Saraburi 1 and Saraburi 2 Building

The following figure is a sketch of cross section of Site 1 installation. Image dimension does not represent real dimension.

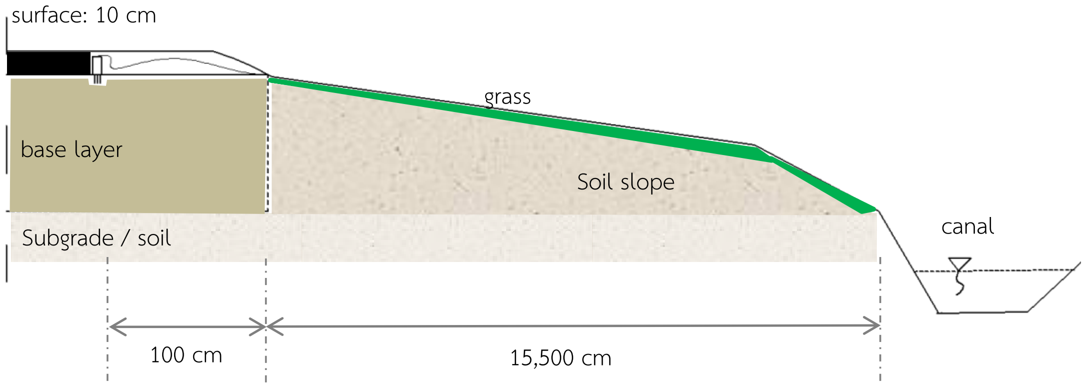


Figure 3. 8 Cross Section of Site 3

Figure 3.9 Site Location 3: On the Main Road Parallel to Site 1 Road Section

Summary of the site location, sensors used, and date of measurement is presented in the following table.

Table 3.1 Summary of Site Information

Site Location	Moisture Sensor	Date of installation	Period of Recorded Data
Site 1: In front of i-ENG3 Building	ML2x-Thetaprobe	November 29, 2013	November 29, 2013 – May 5, 2014 & May 12 – May 28, 2014(thermal sensor added)
Site 2: In front of Saraburi2 Building	SM150	May 5, 2014	May 5 – May 12, 2014
Site 3: In front of i-ENG3building (Parallel to Site 1)	SM300	June 10, 2014	June 10 – June 25, 2014

From this summary, it is noticeable that we needed to move the logger from site 1 to Site 2 in order to record the measurement from Site 2, and removed back to continue data logging of Site 1 after May 12, 2014. There is no recording between May 28 and June 10 because we found some cracking damage in Site 1, and decided to move the sensor and logger to another location (Site 3).

The base moisture monitoring is an automatic process conducted with a set of instrumentation, comprises of a moisture sensor and an automatic data logger.

3.3.1 Measuring Instruments

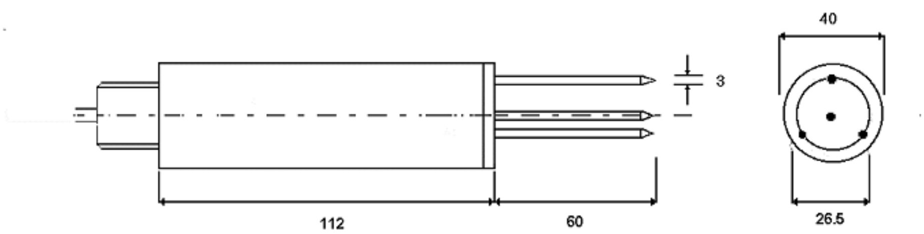
The instrument used for data collection in the field is moisture sensor, which is an electrical-based tool to measure moisture value of a medium. As already being mentioned in chapter 1, moisture sensor is the most suitable measuring tools for the study because it supports long-term monitoring data collection. In addition, it gives a quick result and has flexibility to be used in any medium for a long period.

a. ML2x Thetaprobe (Moisture Sensor)

One of the most popular and widely used moisture sensors is ML2x Thetaprobe by the Delta-T United Kingdom. It has been used to help various kind of ground moisture problem, especially problems that are related to irrigation.

Figure 3.10 ML2x-Thetaprobe in the Field
source: hydropedologie.agrobiologie.cz

ML2x-Thetaprobe is an electrical-related moisture sensor. Based on the working principle, it can be specifically categorized as Amplitude Domain Reflectometry. ADR works by analyzing the change of amplitude to obtain the volumetric moisture content of the measured medium. ML2x-Thetaprobe is inserted into the pavement layer to measure the moisture content of a certain depth of the ground. As previously explained on chapter 2, the measurement area is relatively small, taking shape of a cylinder (about 1.2-inch), but has fair amount accuracy.



(dimensions in mm)

Figure 3.11 ML2x Thetaprobe Dimensions
source: Thetaprobe user manual

b. SM150&SM300

SM150 and SM300 has the same dimension, but different in accuracy. SM300 has higher accuracy (±2.5% over 0 to 50% volume) than SM150 (±3.0%), which is almost similar to ML2x Thetaprobe.

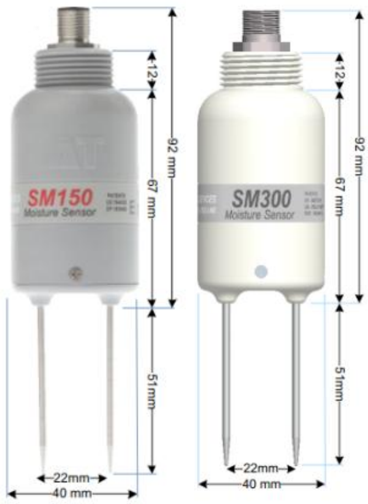


Figure 3.12 SM150 and SM300

Detail technical specification of each moisture sensor can be found in the appendix part of this report.

c. ML2x-Thetaprobe Calibration

Information in this section is taken directly from ML2x-Thetaprobe User Manual file, though it is also applicable to the same type of moisture sensor (SM150 and SM300). These two curves are generalized examples for mineral and organic soils. The calibration curve for any specific soil would be slightly different from either of these because the *ThetaProbe* is actually sensing the dielectric constant, (**ε**) of the soil, and the relationship between the measured dielectric constant of a soil and its water content (θ) depends on the particular composition of the soil. If using a generalized calibration, typical errors of ±0.05 m3.m-3 should be expected.

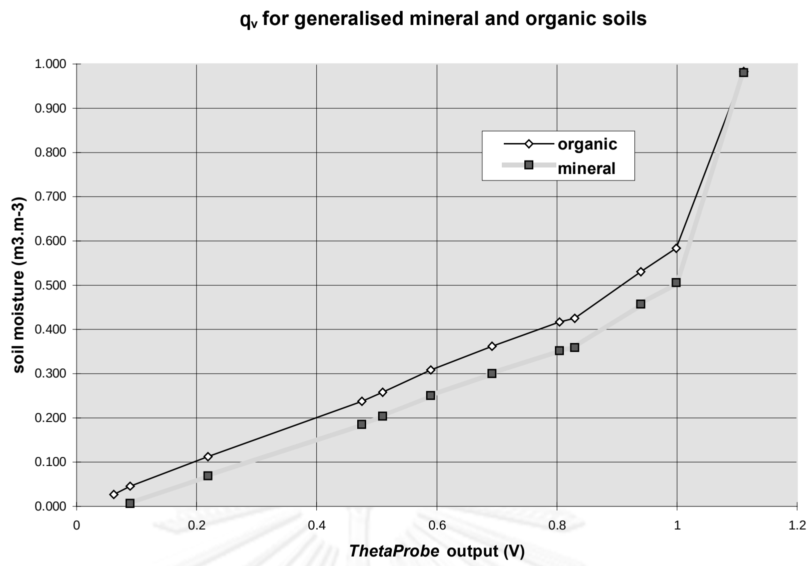


Figure 3.13 Relationship between *ThetaProbe*output and soil moisture content
source: Thetaprobe user manual

In order to minimize the errors in converting *ThetaProbe* output (V) to soil water content, we need to calibrate the sensor for specific soil.

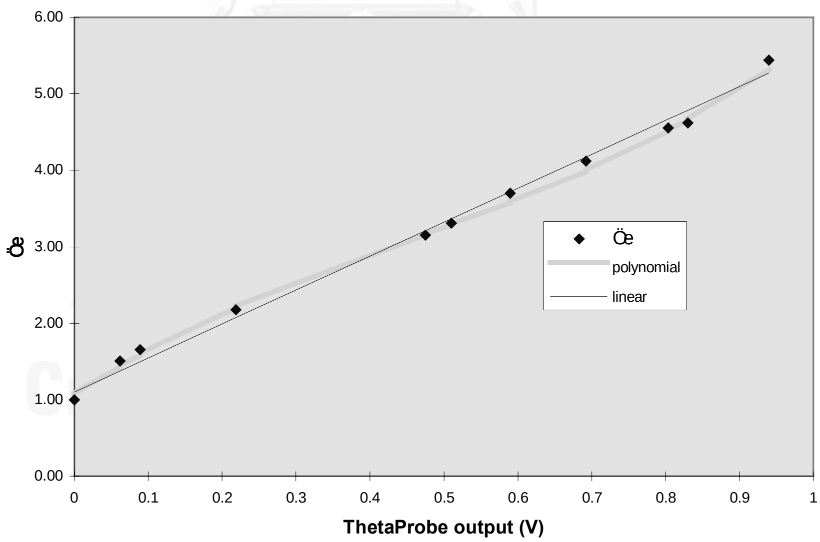


Figure 3.14 Relationship between Thetaprobe output and √**ε**
source: Thetaprobe user manual

Response to dielectric constant

Performing a soil-specific calibration is relatively straightforward, because all ML2x *ThetaProbes* respond to dielectric constant in the same stable, uniform way, so it is only necessary to do this once for one probe.

The relationship between *ThetaProbe*output, (V), and square root of dieletric constant, ($\sqrt{\varepsilon}$), is presented in Figure 3.13

In the range 0 to 1 Volt (corresponding to a soil moisture range 0 to ~ 0.55 by volume), this relationship can be fitted very precisely by a 3rd order polynomial:

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \qquad R^2 = 0.998 \qquad (1)$$

,or by the linear relationship:

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \qquad R^2 = 0.99 \qquad (2)$$

Soil-specific Calibration

Whalley, and White, Knight, Zeggelin and Topp have shown that there is a simple linear relationship between the complex refractive index (which is equivalent to$\sqrt{\varepsilon}$and volumetric water content, θ of the form:

$$\sqrt{\varepsilon} = a_0 + a_1.\theta$$

Since the relationship between ThetaProbe output and $\sqrt{\varepsilon}$ is already known, it is only necessary to determine the two coefficients, a_0 and a_1. Calibration manual suggests to use the following protocol:

Step 1

Collect a sample of damp soil, disturbing it as little as possible so that it is at the same density as in situ. Insert the *ThetaProbe*into the sample and measure the probe output, V_w. Use equation (1) or (2) to calculate $\sqrt{\varepsilon_w}$. Weigh the damp sample, (W_w), and measure its volume (L).

Step 2

Oven-dry the sample, insert the *ThetaProbe* into the dry soil ($\theta \approx 0$), and measure the probe output, V_0. Weigh the dry sample (W_0). Use equation (1) or (2) to calculate $\sqrt{\varepsilon_0}$. This equals a_0. It will usually have a value between 1.0 and 2.0.

Step 3

Calculate the volumetric water content $\sqrt{\varepsilon_w}$ of the original sample:

$$\theta = \frac{W_w - W_0}{L}$$

Step 4

Then, $a_1 = \frac{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_0}}{\theta_w}$

It will usually have a value between 7.6 and 8.6.

Step 5

By inverting equation [3], and substituting from equation [2], the water content determined from a calibrated *ThetaProbe* will then be:

$$\theta = \frac{[1.1 + 4.44V] - a_0}{a_1}$$

The corresponding equation using the polynomial relationship is:

$$\theta = \frac{[1.07 + 6.4V - 6.4V^2 + 4.7V^3] - a_0}{a_1}$$

Using this relationship (rather than the linear form) will enable the *ThetaProbe* to achieve full accuracy over the full-specified range, particularly for wetter soils with $0.5 < \theta < 0.6$.

3.3.2 Sensor Installation and Setup

The following exposition will explain installation steps and activities on Site 1, which is quite identical with Site 1 and Site 2.

We chose a feasible road section that has typical structure to avoid specific measurement bias. The feasibility criteria consists of various matter such as availability to be placed in a long time period, disturbance effect to traffic, safety from unexpected external interference (i.e. animals). Moreover, in order to keep the logger safe from unexpected weather factor, or might as well theft, we planned to set up the logger on a nearby shelter adjacent to the road shoulder. We positioned the point of instrument installation at the edge of the pavement. Top view of field setup plan is presented in Figure 3.14.

The selected road section has 8-meter total lane width, two directions, and asphalt concrete surface layer. The road section can be considered as newly constructed structure as it was just finished constructed several years ago. Since it is a newly constructed structure, the condition of the pavement structure is still in a good condition. In other words, we could expect no crack influence to the moisture condition.

The effect of crack to the moisture condition, as well as the measurement, is not included as part of analysis for this study, but to be explained later in chapter-4 as complementary information.

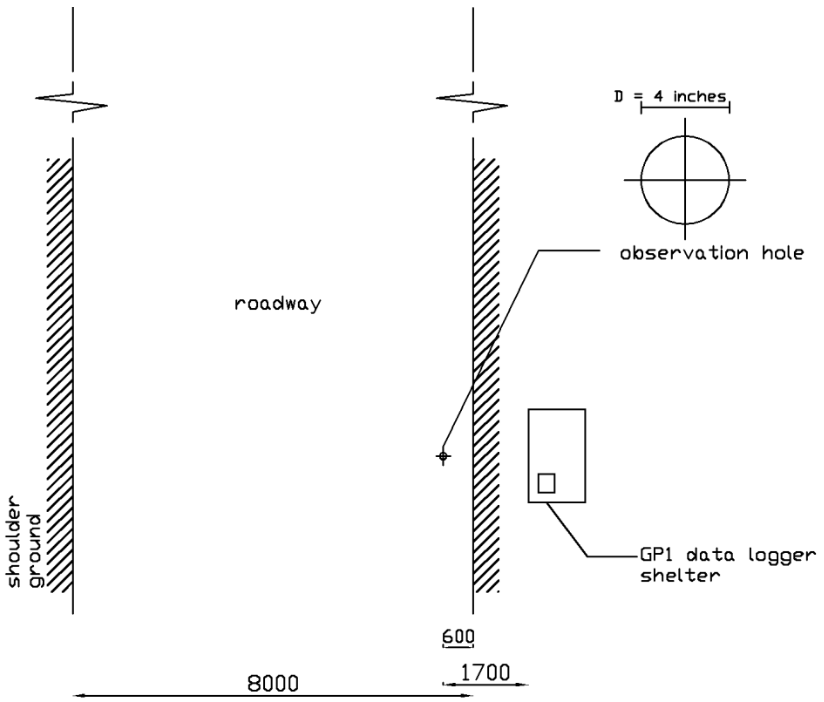


Figure 3.15 Top View of Site Plan (dimension in mm)

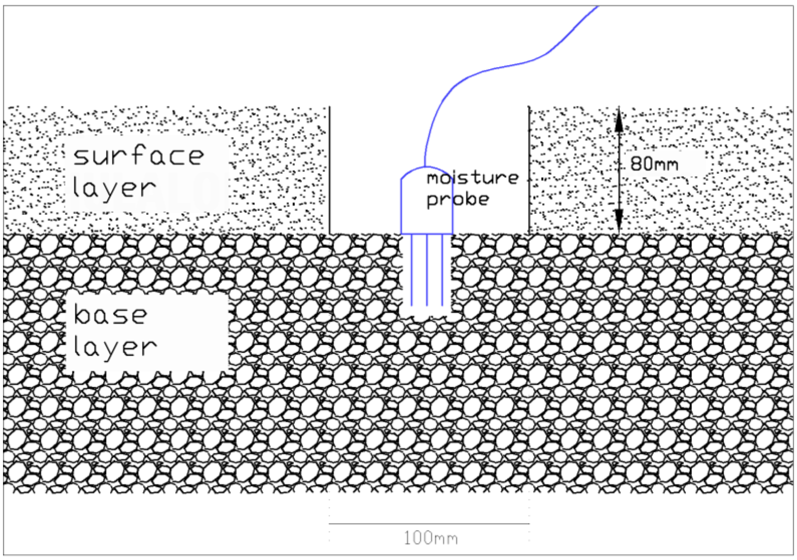


Figure 3.16 Cross section view of sensor installation plan

a. Installation

In order to reach the base layer to insert the moisture sensor, the asphalt surface had to be removed temporarily. A diesel core drilling machine with 4-inch diameter head was used to remove the surface layer. Both wet and dry coring can be performed using this core drilling machine. For the purpose of this study we chose to follow dry coring procedure. This was intended to keep the moisture condition of the base layer undisturbed by water during wet coring procedure.

Figure 3.17 Measuring and Core-Drilling Activity

The depth of drilled hole is 8 cm, or as deep as surface layer thickness. The distance between center-point of the hole to the edge of pavement is 60 cm. Surface core was then removed from the ground. Figure 3.17 shows the condition after the dry core drilling procedure.

Figure 3.18 Core-Drilling Result and Spot Removal

ML2x Thetaprobe has four rod on its head as sensors. Inserting the four rod by forcing it to the hard and dense base layer would damage the sensor. To prevent damage, before insertion we prepared 4 small holes using nails to give the rods space. By doing this, the moisture sensor can be inserted without risking the rods being damaged while penetrating the base layer.

Figure 3.19 Hole and Sensor Preparation

The sensor was covered with layers of plastic and plaster to protect it from water, and asphalt during reparation after the installation. The cover was not covering the rods since it would affect the measurement and give invalid result.

GP1 data-logger was connected to the sensor to record the measurement at a determined frequency. This data logger is supplied with 9-volt battery power. The frequency of measurement was set as one measurement every 15 minutes all day every day. Recorded data was stored in GP1 data-logger memory, and can be collected each time of site visit without stopping the logging process. To set the automatic data collecting of GP1, a computer and Delta-T software is needed.

Figure 3.20 Sensor Installation and Setting

b. Reparation

Repairing the drilled hole is important not only to keep the moisture condition of the base layer from direct water pouring, but also to preserve the pavement structure as a whole. The surface was partially damaged at that moment, and needed to be repaired to prevent future structural damage.

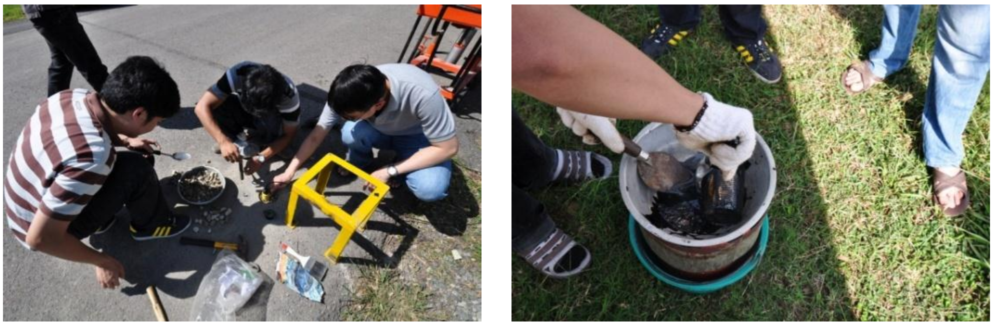


Figure 3.21 Preparations for Surface Restoration

Hot in place mixing procedure was conducted to repair the removed surface spot of the road. Similar crushed stone aggregate was placed on top of the sensor before lastly topped with hot asphalt mixed with fine-graded aggregates. The asphalt mixing was done using a portable gas stove and laboratory mixing bowl.

Figure 3.22 On-Site Asphalt Concrete Mixing

As we can see in the following picture below, the ML2x Thetaprobe sensor was partially embedded in the road. At this condition, the sensor had a high risk of getting disturbed by passing vehicles, or even animal. Related to this matter, we set up a surrounding simple frame to protect the sensor on the surface, and also to give warning for passing vehicles. The yellow frame was positioned stuck on the road surface, and topped with heavy stones to keep it steady.

Figure 3.23 Finishing the Installation and Restoration

In the pictures below, we can see the finished sensor installation for long term monitoring. This condition will be maintained until the end of the period of this study.

Figure 3.24 After Installation

3.3.3 Control and Maintenance

The moisture measurement is set to operate continually for a long period of time. Since the GP1 logger is supplied with 9-volt battery power, the performance of measurement would be affected by battery power at some level of remaining voltage. The user manual explained that ML2x Thetaprobe needs at least 5.0V battery power to produce good measurement. The distortion of data logging caused by power supply problem will be presented in the chapter 4. To keep the sensor performance in good level, the sensor needed to be checked frequently. Therefore, in this period of data collection, we did several site-visiting trips.

Figure 3.25 Equipment Control and Maintenance

The surface condition is another concern for controlling this long term period of monitoring. We did visual check on the surface and the surrounding area to make sure that the surface was not affected by crack or other damage. Since the damage would possibly affect the moisture condition of base layer, this kind of checking needed to be done in every site visit.

Chapter 4
Data Presentation, Analysis, and Discussion

4.1 Introduction

The objective of this study is to investigate the characteristic of moisture measurement on the base layer of a road section, specifically granular unbound base layer. The result of this study is specific for measurement using moisture sensor technology, and mainly focusing on the behavior of moisture changes in a specific period of time. Analysis was made based on collected data from 23 weeks of data-logging in the field.

Chang (2008) did a similar study to predict moisture migration inside flexible pavement. The study was conducted on test pads of flexible pavement that were constructed specifically to monitor the moisture migration. Most of the parameter that can be found in the field were controlled and monitored. The instrument used in this study to monitor moisture content is Time Domain Reflectometer. In the study, it was found that moisture inside deeper base layer (more than 2 inches) changed more significantly. Corresponding to this thesis study, we only inserted the moisture sensors on the upper part of the base layer (approximately 2 inches). Chang also stated that moisture apparently migrates much faster in the horizontal direction than in the vertical direction. Learning from this, we could consider that it might be the cause of the increasing speed of draining process after crack occurred since crack actually opened more space for water to migrate laterally.

Gupta et.al (2008) conducted a similar study in a real flexible pavement in the field in relation to study the cause of longitudinal cracking. The study shows analogous result of moisture fluctuation due to rainfall. The study utilized moisture probe as a moisture measuring instrument and recorded moisture profile for approximately one year. The moisture profile and level were similar to what we found in this study. Moreover, the advantage of the study was it uses a lot more moisture measurement tools, which can be installed in various points of the flexible pavement. Therefore, it can capture moisture behavior inside base layer more comprehensively.

Result and findings in this study are considered preliminary and need further more comprehensive method to obtain more detailed behavior and explanations. Analysis of the characteristic of measurement is focused on no-rainfall field condition on a flexible road structure. Moreover, detailed assumptions and findings related to the objectives are presented in the following sections.

4.2 Effect of Temperature to Moisture Sensor Measurement Result

According to past studies, one of the factors influencing moisture sensor performance is the change in temperature. Gaskin and Miller (1996) did an evaluation over similar type of moisture sensor, and concluded that the sensor performance was apparently less sensitive to temperature. Kaleita et.al (2005) suspected slight effect of temperature in Thetaprobe performance in the field. However, the effect of temperature was regarded as less significant than other factors in the field. Nemali et.al (2006) operated Thetaprobe in many level of soil temperature ranged from 10 to 40 degrees of Celsius, and found out that the temperature has little or no effect on Thetaprobe performance. Lastly, Gilawari (2006) echoes the findings of other studies. Gilawari conducted several steps of calibration that included temperature, and concluded that temperature effect on Thetaprobe performance is not significant.

In order to verify this information, temperature sensor was installed near the Thetaprobe. During 8 days of data logging, we was able to collect 576 measurements data for both temperature and volumetric moisture content. Using this data, correlation test was conducted using SPSS statistical software in order to find the correlation significance between both parameters. Test result shows no correlation between temperature and base layer volumetric moisture content in the field. The following is the test result from SPSS.

Table 4.1 Correlation Test between Volumetric Moisture Content and Temperature in the Field

Correlations

		moist_field	temp_field
moist_field	Pearson Correlation	1	.057
	Sig. (2-tailed)		.170
	N	576	576
temp_field	Pearson Correlation	.057	1
	Sig. (2-tailed)	.170	
	N	576	576

A corresponding lab test was also conducted to ensure the effect of temperature is not negligible. Granular base aggregate of known parameters was prepared to use as laboratory sample. The amount of water was designed similar to the field and slightly below optimum water content of the aggregate (4.5%).

Figure 4.1 Aggregate and Water Weight Measurement

Built on experience, aggregates that has been mixed with water needs to be stored for a day in a container in order to make the water distributed evenly all over the aggregate. The aggregate was kept in a plastic bag immediately after mixing in the bowl. This is to keep the moisture stayed the same as the designed value.

Figure 4.2 Mixing Aggregate with Water and Storing in Plastic Bag

The aim of the test was to keep the moisture constant and see the measurement result of Thetaprobe when the temperature is changed. In order to keep the moisture constant inside the granular layer, both top and bottom side of the granular layer was sealed with hot mix asphalt mixed with dense aggregate. According to Thetaprobe manual, the effective measurement area of the sensor is 4-

cm diameter and 6-cm height. In this test, we used CBR mold that has 6-inch diameter and 7-inch height, which is big enough to secure the effective measurement area. The detailed of layering is available on figure below.

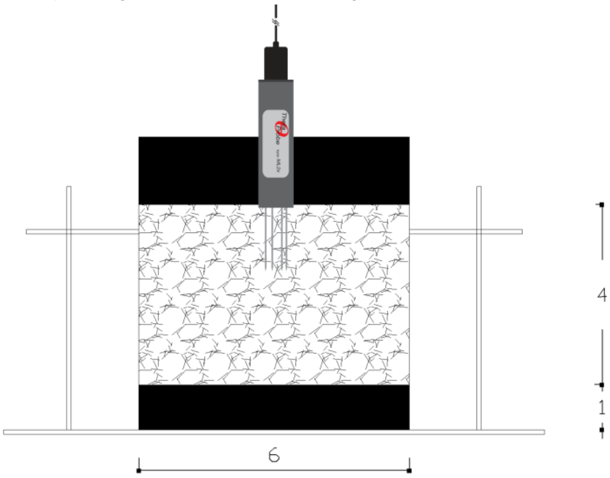


Figure 4.3 Layers Detail on CBR Mold (dimension in inches)

Asphalt layer on the bottom was lightly compacted before the granular layer was placed. The granular layer was then compacted as well according to sample design before penetrated with Thetaprobe. The moisture sensor was placed and inserted in the center to avoid disturbance from the metal wall of the mold.

Figure 4.4 Compaction of Laboratory Sample for Temperature Verification

Figure 4.5 Insertion of Thetaprobe into Compacted Laboratory Sample

Figure 4.6 Sealing Top Side of Laboratory Sample

Figure 4.7Oven Setup for Controlling Laboratory Sample Temperature

Sample was kept inside an oven to make the temperature conditioning possible. Temperature was set similar to the field condition, with a range of 15 degree Celsius. Based on field experience, the minimum temperature was 40 degree Celsius, and maximum temperature was 55 degree Celsius. Initial temperature was set at the minimum, and was increased after moisture reading looks stable in the PC monitor. Temperature of the oven was increased up to the maximum designed temperature, so that the temperature inside the granular layer would gradually increase. By doing this, we were aiming to see the effect of temperature on Thetaprobe performance.

The result of the reading is presented in Figure 4.8. Correlation test was also conducted to the recorded data. Table 4.2 displays the result of the correlation test using SPSS statistical software. The value of Pearson correlation coefficient was found to be high and, the value was also significant towards the presented data. It was apparently found that temperature has an effect on Thetaprobe's reading. However, the amount of changes in moisture reading was considered insignificant compared to the amount of changes in field moisture reading under the same temperature incremental condition. The reading was changing by a maximum value of 0.3% when the temperature was raised, whereas in the field moisture reading, the moisture changes by more than 0.3% on average. Thetaprobe manual provides information that inside 40-70 degree Celsius of operating temperature, the reading has an accuracy of 2%.

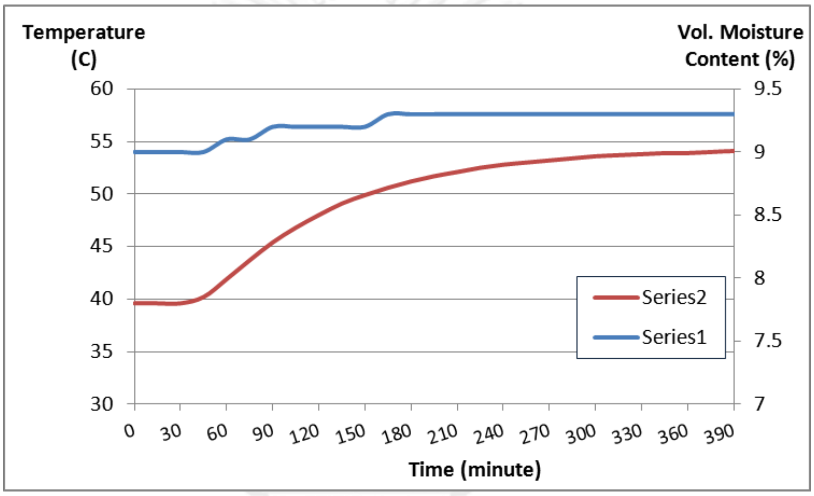


Figure 4.8 Laboratory Result for Temperature Effect on Thetaprobe Reading

Changes in moisture reading in the conducted lab test were most likely not related to sensor error (by temperature direct effect), but more likely related to the movement of water inside the sealed environment itself. It is possible that the water was evaporating when we increased the temperature, and thus trapped on the minor layer of plastic below the asphalt surface. After opening up the sample set, we found that the plastic layer was dampened on the bottom side. Therefore, we consider that temperature does not affect the sensor, but more probably does affect the movement of water inside observed medium instead.

This finding actually echoes previous studies discussed at the beginning of this section. The effect of temperature is considered fairly existed on Thetaprobe. However, it is unlikely to become an immense influential factor, compared to other factors in the field.

Table 4.2 Correlation Test Result between Volumetric Moisture Content and Temperature in the Laboratory

Correlations

		moist_lab	temp_lab
moist_lab	Pearson Correlation	1	.972**
	Sig. (2-tailed)		.000
	N	40	40
temp_lab	Pearson Correlation	.972**	1
	Sig. (2-tailed)	.000	
	N	40	40

**. Correlation is significant at the 0.01 level (2-tailed).

4.3 Moisture Fluctuation over Long Term Data Logging

Collected data from GP1 logger was started on November 29, 2013 in the late afternoon, and ended on June 23, 2014 in the afternoon. However, in the analysis we only included data from a full day recording, and stable reading several hours after the installation or raining. Therefore, in the following data presentation the date will start on December 1, 2013.

4.3.1 Site 1: Ml2x Thetaprobe Moisture Sensor

Over 23-week of nonstop recording, any moisture changes activity can be viewed by plotting the values stored in GP1 data logger. The overall finding of our long term data logging is presented in Figure 4.9. Looking at Figure 4.9, visually we may find the result approves the underlying argument of this study by showing that moisture definitely fluctuates over the weeks of measurement. Each x-axis major gridline of the graph represents 1 week, of which starts at 00:00 time of day. Between November 29, 2013 and March 14, 2014 is the period of time where rainfall did not occur, while the ensuing weeks are the period of time where rainfall did occur.

In the enlarged view, we can see that the fluctuations activity appeared to follow a pattern, which is an approachable one. The blue-colored border graph in Figure 4.9 shows us the enlarged view of several days inside the overall data. It was taken from two weeks recorded data, in which each x-axis major gridline represents one day. By considering this detailed view, we can see that two extreme moisture values are consistently found in each day. The fluctuation is more systematic. Therefore, based on this early finding, we approach the fluctuation pattern with the most plausible one, which is sinusoidal pattern.

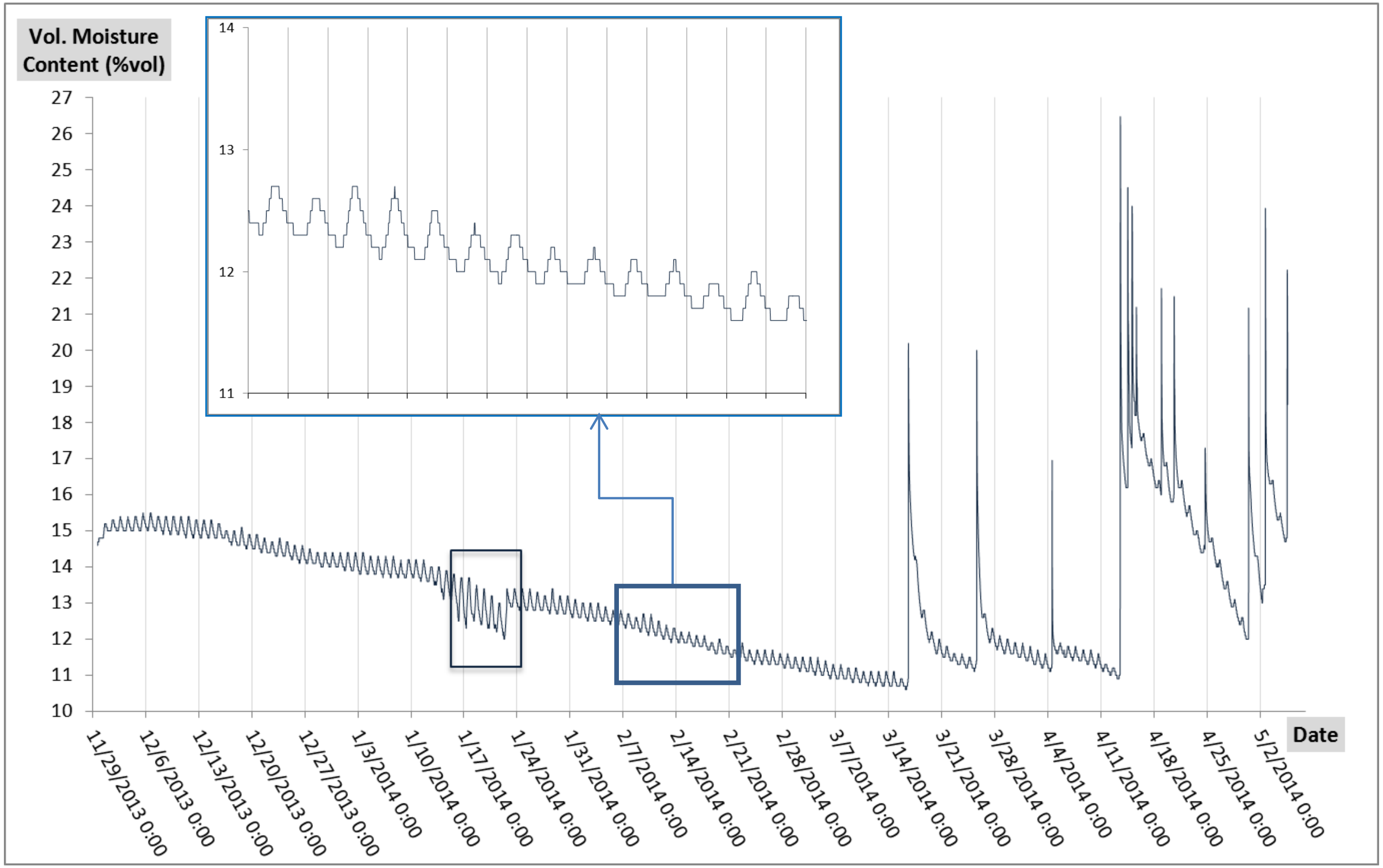


Figure 4.9 Moisture FluctuationData from Site 1

During the long term monitoring, a major technical problem was occurred that caused distortion in GP1 logging process. In Figure 4.9, the distortion can be seen inside the small black box, between January 10 and January 22. Fluctuation shown by the recorded data was found to be peculiar. The cause was further found as a power supply failure. Thetaprobe moisture sensor manual states that the recommended battery level was 5V. During the period of distortion, apparently the battery level was depleting under that level. Battery replacement was subsequently conducted immediately. On account of this matter, the recorded data between 10-January and 22-January is not included in further analysis.

4.3.2 Site 2: SM150 Moisture Sensor

The following figure is the result of SM150 moisture reading in the period of time between May 7, 2014 and May 13, 2014. On this site, a thermal sensor was also installed along with the moisture sensor at the same depth to capture temperature change. Temperature is represented by the red line in the following graph.

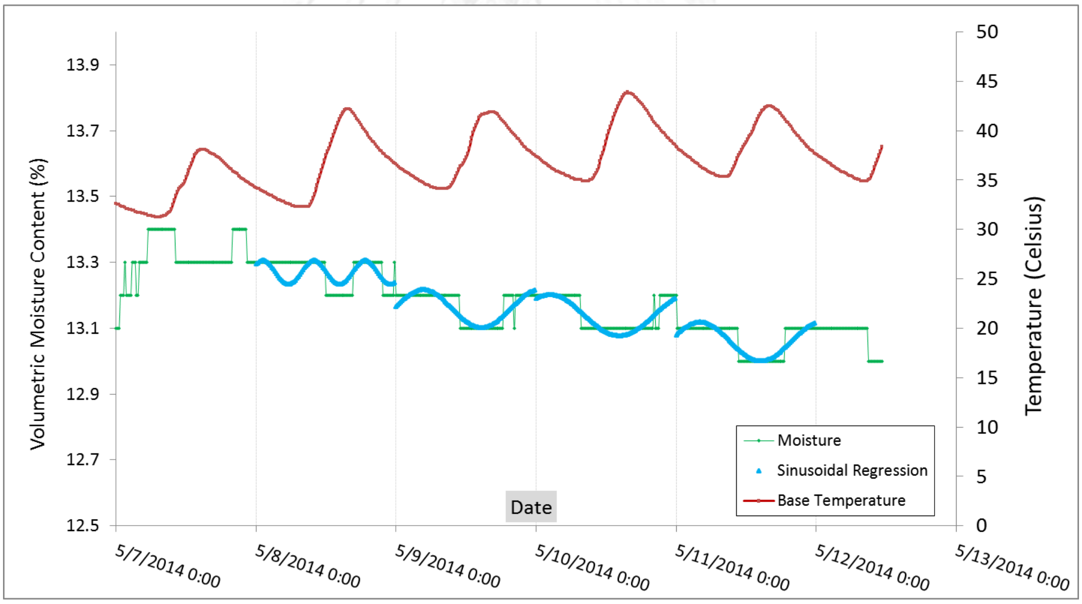


Figure 4.10 Moisture Fluctuation Data from Site 2

Data recording for this site was started on May 5, 2014 in the late afternoon (5pm). However, due to rainfall on May 6 we only use the recorded data starting from May 7.

4.3.3 Site 3: SM300 Moisture Sensor

The following figure is the outcome of SM300 moisture reading in the period of time between June 11, 2014 and June 23, 2014. On this site, thermal sensor was also installed at the same depth as the moisture sensor to capture temperature changes. Based on the graph and information obtained, rain occurred on June 14 and June 16, and hence we excluded data from these days.

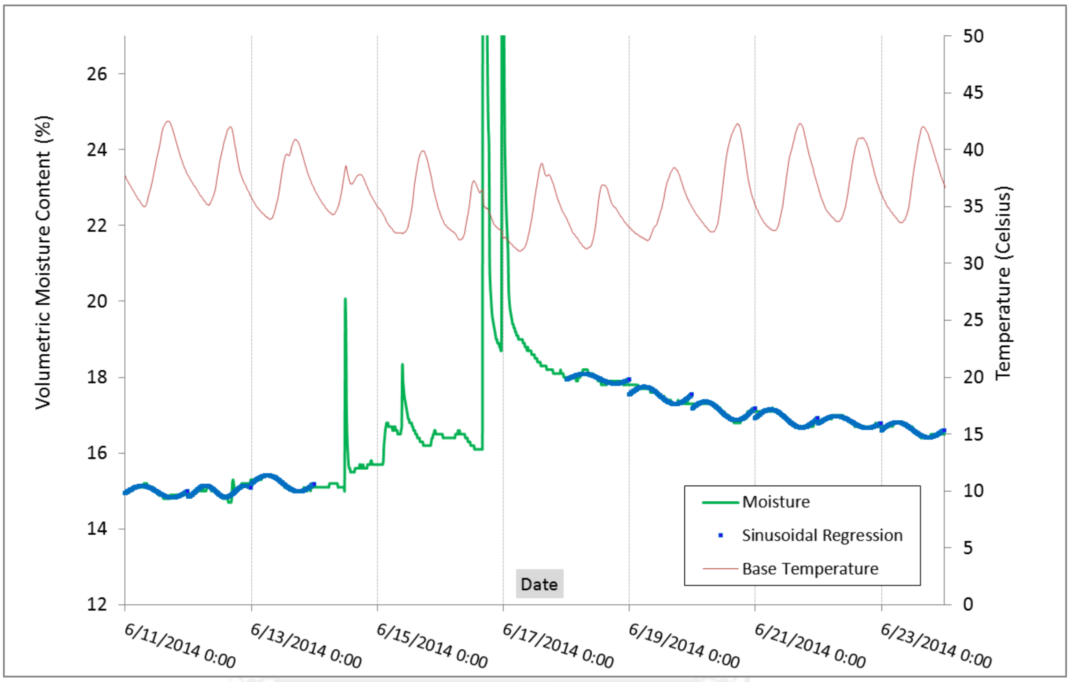


Figure 4.11 Moisture Fluctuation Data from Site 3

A very unusual leap of moisture change between June 16 and June 17 reached a peak of 40% volumetric moisture content is even more than the sudden leap due to rainfall in the data from Site 1. The actual cause of this dramatic change is unknown, but since there was no crack found around the hole (Figure 4.12), it was most likely caused by sudden surface runoff on the sensor.

As we know, the location of Site 3 observation point is near to the edge of the road shoulder, and some vegetation also exists in the soil beside the road. It is possible that when rain occurred, big amount of surface runoff got drained to the shoulder and passed by the sensor. Based on recorded data, the duration of that leap was around one hour and thirty minutes. Therefore, this data fact may clearly explain the sudden rise of SM300 reading.

Figure 4.12 Observation Point of Site 3

4.3.4 Comparison of Sinusoidal Regression of Recorded Moisture Value between 3 Sites

Recorded data of moisture fluctuation from Site 1 shows a very definite shape to sinusoidal graph. This was later upheld by the result of the other sites (Site 2 and 3). Depending upon this finding, we are sure that the corresponding shape is not caused by equipment malfunction, or other external issues. However, we can spot a difference between data findings from all sites, which lie in the phase shift of the sinusoidal shape.

Figure 4.13 shows a comparison of volumetric moisture content measurement from a selected day of each site. It is noticeable that Site 2 and Site 3 has quite similar phase shift, which visually can be observed in the graph as both of those maximum moisture peak happened early in the morning whereas the minimum peak happened in the late afternoon. Data from Site 1 shows the opposite as the maximum moisture peak was recorded in the late afternoon, and the minimum moisture peak was in the early morning. The genuine cause of this dissimilarity is not yet clear, but the fact that it happens to both sensors in Site 2 and 3 should confirm that it was not an equipment malfunction.

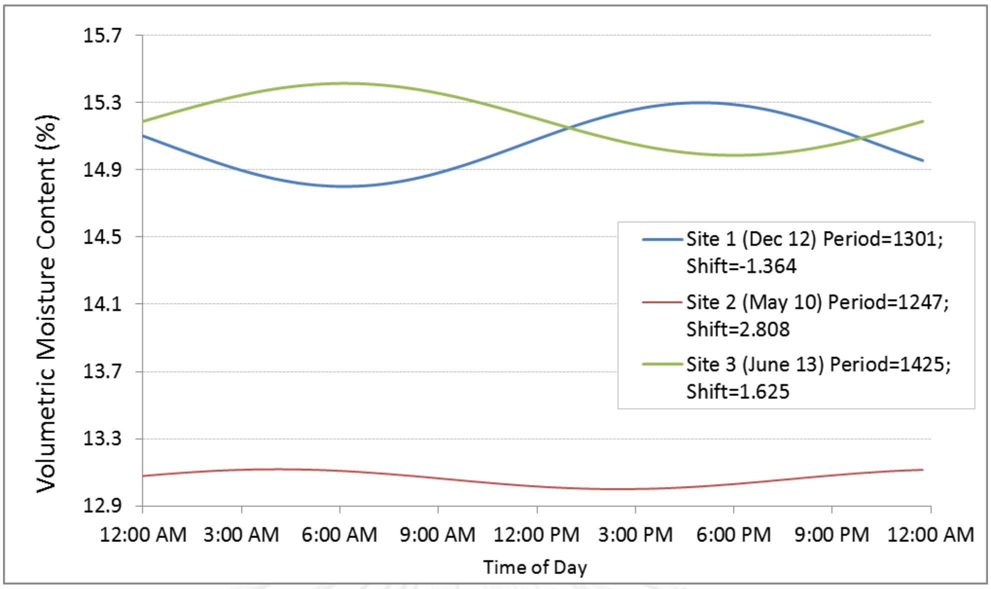


Figure 4.13 Comparison of Sinusoidal Regression of Recorded Moisture Value between 3 Sites

It was discussed earlier in section 4.2 that we have the notion that water is moving upward (evaporating) when temperature increases, which causes more water surrounding the sensor rod. And it would be drained away from the rod downwardly (or laterally) due to decreasing temperature, and layer's permeability. However, the same argument cannot be applicable to what have been found in Site 2 and 3. Nevertheless, the behavior of sinusoidal fluctuation pattern remains conclusive. Moreover, by looking at the previous graph we can also see the accuracy difference between these three sensors by looking at the amplitude of the sinusoidal graph. SM300 and ML2x Thetprobe do have comparable accuracy and measurement range, whereas SM150 has lower accuracy than the other two according to the technical specification.

4.4 Sinusoidal Pattern of Daily Volumetric Moisture Content

As previously stated, the analysis in this study will be focused on the period of time where rainfall did not occur. Due to this matter and data omitting, further approach using sinusoidal function only uses the data from 14-week effective measurement, specifically on the following time period: November 29, 2013 – January 9, 2014, and February 1, 2014 – March 14, 2014.

Sinusoidal regression was conducted to validate the relevancy of sinusoidal approach to our existing data. Since the fluctuation pattern is daily systematic, we applied the regression for each day data. Supposing that the mean of moisture values is linear in one day, we fitted sinusoidal equation to moisture data on each day, and collect the R-square for each day. In this study, regression is conducted using PAST 3.01 statistical software. The sinusoidal generalized formula as the result of the regression is given as following:

$$y = A.\cos(Bx - C) + D \qquad \text{Eq. 4.1}$$

Where:

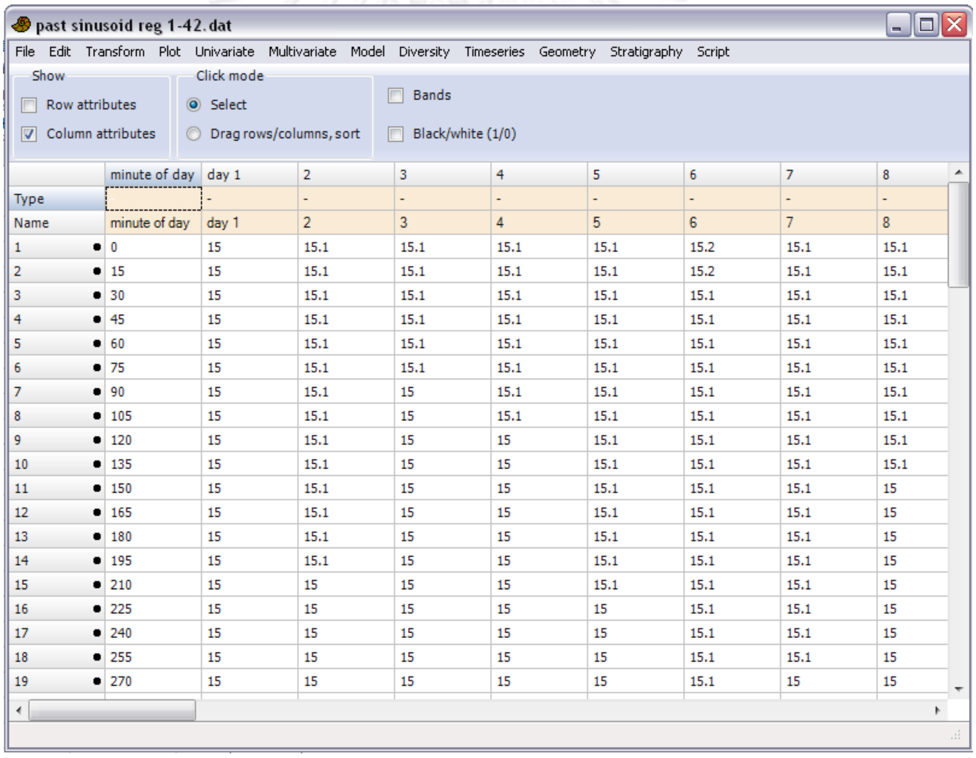
A = amplitude

B = 2π/T

C = phase shift

D = mean offset

T = period (minute)



	minute of day	day 1	2	3	4	5	6	7	8
Type		-	-	-	-	-	-	-	-
Name	minute of day	day 1	2	3	4	5	6	7	8
1	0	15	15.1	15.1	15.1	15.1	15.2	15.1	15.1
2	15	15	15.1	15.1	15.1	15.1	15.2	15.1	15.1
3	30	15	15.1	15.1	15.1	15.1	15.1	15.1	15.1
4	45	15	15.1	15.1	15.1	15.1	15.1	15.1	15.1
5	60	15	15.1	15.1	15.1	15.1	15.1	15.1	15.1
6	75	15	15.1	15.1	15.1	15.1	15.1	15.1	15.1
7	90	15	15.1	15	15.1	15.1	15.1	15.1	15.1
8	105	15	15.1	15	15.1	15.1	15.1	15.1	15.1
9	120	15	15.1	15	15	15.1	15.1	15.1	15.1
10	135	15	15.1	15	15	15.1	15.1	15.1	15.1
11	150	15	15.1	15	15	15.1	15.1	15.1	15
12	165	15	15.1	15	15	15.1	15.1	15.1	15
13	180	15	15.1	15	15	15.1	15.1	15.1	15
14	195	15	15.1	15	15	15.1	15.1	15.1	15
15	210	15	15	15	15	15.1	15.1	15.1	15
16	225	15	15	15	15	15	15.1	15.1	15
17	240	15	15	15	15	15	15.1	15.1	15
18	255	15	15	15	15	15	15.1	15.1	15
19	270	15	15	15	15	15	15.1	15	15

Figure 4.14 Example of Past 3.01 User Interface

The first column in Figure 4.14 is the minute of the day, of which '0' means the first measurement of the day. Since the recording frequency was set to be 15-minute, the next measurements of the day are going to be multiples of 15. Based on equation (1), the unknown variables to be found are: A, B, C and D. Instead of being set as fixed, period is set to be fitted as well to see the difference of moisture fluctuation period for each day. Since the logging interval is every 15 minutes, period value is in minute unit. Inside the data of each day, time of zero minute is equivalent to 00:00 hour (midnight).

4.4.1 Sinusoidal Model Fitting

Past 3.01 algorithm is based on a least-squares criterion and singular value decomposition. The “Fit periods” option will sequentially optimize the period of each sinusoid (over the full meaningful range from one period to the Nyquist frequency), after subtracting all previously fitted sinusoids. This is a simple example of the “matching pursuit” algorithm. The algorithm is slow but robust and will fairly reliably find the global optimum. The results of all R-square values after regression using included data are above 0.850 with an average R-square value 0.900. This value indicates a very good fitting.

Considering these results, we may conclude that sinusoidal approach is suitable to use as reference for daily moisture measurement under the condition stated in the first section of this chapter. Figure 4.15 illustrates a fitting example from one day of the recorded data.

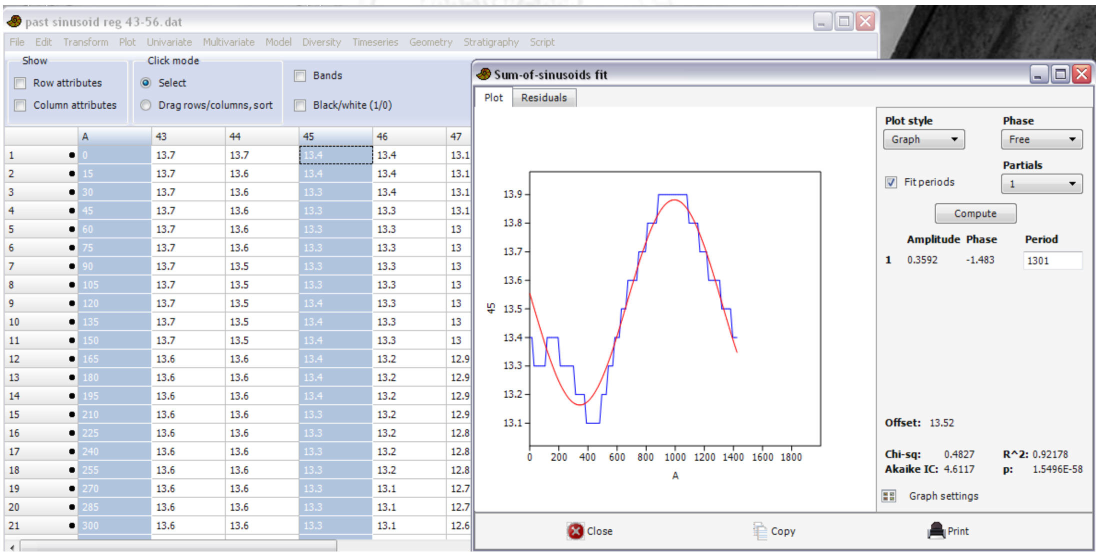


Figure 4.15 Example of Past 3.01 Sinusoidal Regression

After fitting the data into sinusoidal equation, we found that the equations for each day are not the same. This is caused by the variation of amplitude of measurement on each day. Amplitude size represents the range of fluctuation value on each day, which means the larger the amplitude, the bigger the moisture fluctuation range. In other words, the fluctuation range of moisture value is apparently different every day. This is expected to be happened since each and every day both external and internal conditions of the road are not the same as well. Figure 4.16 shows us the variation of amplitude based on the 14-week recorded data. Therefore, due to the daily inconsistency and unexpected changes of moisture value, it is considered unreasonable to set the number of days for one sinusoidal equation.

The result of sinusoidal fitting on 92 days recorded data is presented in the following table. The omitted data due to power supply deficiency was started on January 10, as being shown by the red line after the 40th data.

Table 4.3 Detailed Result of 92-day Sinusoidal Fitting from Site 1

Day	T	A	B	C	D	R-square	Date
1	1425	0.1668	0.004409	-1.712	15.12	0.897	1-Dec
2	1301	0.1760	0.00483	-1.374	15.15	0.907	2-Dec
3	1360	0.1712	0.00462	-1.561	15.13	0.919	3-Dec
4	1360	0.2147	0.00462	-1.575	15.17	0.950	4-Dec
5	1360	0.2182	0.00462	-1.562	15.20	0.935	5-Dec
6	1301	0.2196	0.00483	-1.429	15.22	0.907	6-Dec
7	1301	0.2053	0.00483	-1.419	15.19	0.921	7-Dec
8	1301	0.2238	0.00483	-1.354	15.15	0.928	8-Dec
9	1301	0.2599	0.00483	-1.356	15.14	0.949	9-Dec
10	1301	0.2327	0.00483	-1.384	15.11	0.925	10-Dec
11	1301	0.2649	0.00483	-1.368	15.09	0.922	11-Dec
12	1301	0.2491	0.00483	-1.364	15.05	0.950	12-Dec
13	1360	0.2407	0.00462	-1.507	15.03	0.945	13-Dec
14	1247	0.2424	0.005039	-1.240	15.02	0.928	14-Dec
15	1301	0.2190	0.00483	-1.464	14.98	0.938	15-Dec
16	1152	0.1137	0.005454	-1.066	14.88	0.886	16-Dec
17	1247	0.1704	0.005039	-1.289	14.79	0.847	17-Dec
18	1301	0.2373	0.00483	-1.497	14.77	0.916	18-Dec
19	1301	0.1899	0.00483	-1.401	14.69	0.899	19-Dec
20	1301	0.2067	0.00483	-1.473	14.66	0.923	20-Dec
21	1247	0.1898	0.005039	-1.320	14.58	0.909	21-Dec
22	1360	0.1544	0.00462	-1.643	14.50	0.864	22-Dec
23	1360	0.2321	0.00462	-1.596	14.50	0.936	23-Dec
24	1301	0.2091	0.00483	-1.486	14.47	0.933	24-Dec
25	1197	0.1836	0.005249	-1.065	14.38	0.890	25-Dec
26	1301	0.2007	0.00483	-1.437	14.32	0.909	26-Dec
27	1247	0.1788	0.005039	-1.324	14.26	0.884	27-Dec
28	1301	0.1638	0.00483	-1.479	14.21	0.886	28-Dec

29	1301	0.2002	0.00483	-1.373	14.17	0.915	29-Dec
30	1247	0.1820	0.005039	-1.257	14.16	0.888	30-Dec
31	1301	0.1807	0.00483	-1.449	14.14	0.917	31-Dec
32	1301	0.2417	0.00483	-1.430	14.13	0.926	1-Jan
33	1301	0.2499	0.00483	-1.422	14.09	0.931	2-Jan
34	1301	0.2870	0.00483	-1.384	14.07	0.935	3-Jan
35	1301	0.2395	0.00483	-1.366	14.01	0.929	4-Jan
36	1301	0.2335	0.00483	-1.425	13.99	0.927	5-Jan
37	1301	0.2326	0.00483	-1.378	13.98	0.928	6-Jan
38	1301	0.2533	0.00483	-1.386	13.96	0.914	7-Jan
39	1197	0.1852	0.005249	-1.235	13.89	0.880	8-Jan
40	1425	0.2580	0.004409	-1.688	13.92	0.953	9-Jan
41	1301	0.2399	0.00483	-1.437	13.09	0.919	23-Jan
42	1301	0.2595	0.00483	-1.370	13.06	0.911	24-Jan
43	1301	0.2754	0.00483	-1.370	13.02	0.928	25-Jan
44	1301	0.2490	0.00483	-1.391	12.99	0.914	26-Jan
45	1301	0.2100	0.00483	-1.478	12.96	0.927	27-Jan
46	1301	0.3023	0.00483	-1.511	12.98	0.883	28-Jan
47	1301	0.2365	0.00483	-1.408	12.91	0.920	29-Jan
48	1301	0.2396	0.00483	-1.434	12.88	0.925	30-Jan
49	1247	0.2327	0.005039	-1.258	12.82	0.925	31-Jan
50	1301	0.2154	0.00483	-1.433	12.76	0.932	1-Feb
51	1301	0.2211	0.00483	-1.386	12.72	0.891	2-Feb
52	1360	0.2343	0.00462	-1.540	12.70	0.914	3-Feb
53	1247	0.1852	0.005039	-1.246	12.65	0.893	4-Feb
54	1247	0.1608	0.005039	-1.258	12.57	0.865	5-Feb
55	1301	0.1760	0.00483	-1.435	12.54	0.923	6-Feb
56	1301	0.1818	0.00483	-1.434	12.50	0.891	7-Feb
57	1301	0.1558	0.00483	-1.191	12.42	0.891	8-Feb
58	1301	0.2406	0.00483	-1.433	12.41	0.912	9-Feb
59	1301	0.2278	0.00483	-1.375	12.35	0.903	10-Feb
60	1247	0.1941	0.005039	-1.230	12.26	0.884	11-Feb
61	1247	0.1556	0.005039	-1.029	12.15	0.886	12-Feb
62	1301	0.1826	0.00483	-1.306	12.11	0.910	13-Feb
63	1152	0.1221	0.005454	-0.927	12.02	0.798	14-Feb
64	1360	0.1277	0.00462	-1.749	11.99	0.865	15-Feb
65	1247	0.1425	0.005039	-1.135	11.92	0.854	16-Feb
66	1301	0.1288	0.00483	-1.440	11.88	0.828	17-Feb
67	1197	0.1104	0.005249	-1.145	11.79	0.891	18-Feb
68	1360	0.1999	0.00462	-1.552	11.76	0.935	19-Feb

69	1197	0.1171	0.005249	-0.975	11.68	0.847	20-Feb
70	1197	0.1068	0.005249	-0.975	11.60	0.853	21-Feb
71	1301	0.2191	0.00483	-1.374	11.58	0.901	22-Feb
72	1247	0.1396	0.005039	-1.271	11.52	0.856	23-Feb
73	1360	0.1632	0.00462	-1.522	11.49	0.866	24-Feb
74	1301	0.1731	0.00483	-1.373	11.47	0.872	25-Feb
75	1247	0.1788	0.005039	-1.227	11.44	0.892	26-Feb
76	1360	0.1394	0.00462	-1.453	11.40	0.864	27-Feb
77	1301	0.1652	0.00483	-1.307	11.36	0.906	28-Feb
78	1301	0.1544	0.00483	-1.331	11.31	0.883	1-Mar
79	1247	0.1834	0.005039	-1.207	11.28	0.887	2-Mar
80	1247	0.1831	0.005039	-1.168	11.24	0.858	3-Mar
81	1301	0.1872	0.00483	-1.400	11.20	0.855	4-Mar
82	1301	0.1819	0.00483	-1.382	11.15	0.894	5-Mar
83	1247	0.1725	0.005039	-1.148	11.08	0.895	6-Mar
84	1301	0.1787	0.00483	-1.334	11.04	0.917	7-Mar
85	1301	0.1595	0.00483	-1.359	11.01	0.885	8-Mar
86	1301	0.1902	0.00483	-1.343	10.97	0.892	9-Mar
87	1247	0.1405	0.005039	-1.215	10.92	0.877	10-Mar
88	1360	0.1583	0.00462	-1.563	10.90	0.834	11-Mar
89	1301	0.1702	0.00483	-1.363	10.87	0.856	12-Mar
90	1360	0.1940	0.00462	-1.488	10.86	0.913	13-Mar
91	1247	0.1895	0.005039	-1.188	10.84	0.859	14-Mar
92	1247	0.1112	0.005039	-1.243	10.77	0.838	15-Mar

Moreover, Figure 4.16 also shows us that during the period between December 2013 and March 2014, the moisture value deviates 0.1% up to 0.3% from its average moisture value. This value is still inside the accuracy range of ML2x Thetaprobe, which means the variation was not caused by equipment bias.

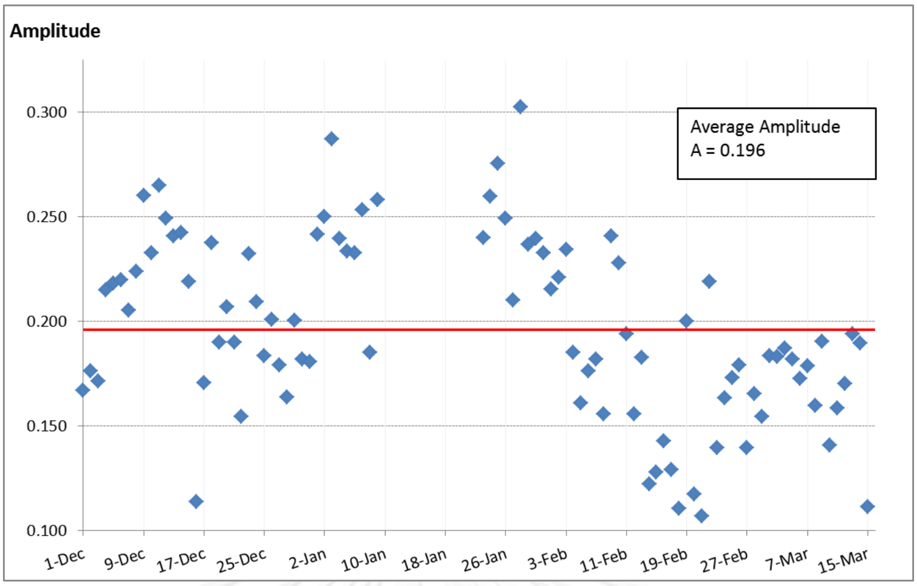


Figure 4.16 Variation of Sinusoidal Equation Amplitude

On the other hand, the period (T) value shows fairly similar value on each day fitting. We may regard this finding as reference to determine our measurement timing for daily measurement. This passable consistent value gives us more confidence to conclude that daily moisture fluctuation time is similar one day to another, and only distinguished by the amplitude.

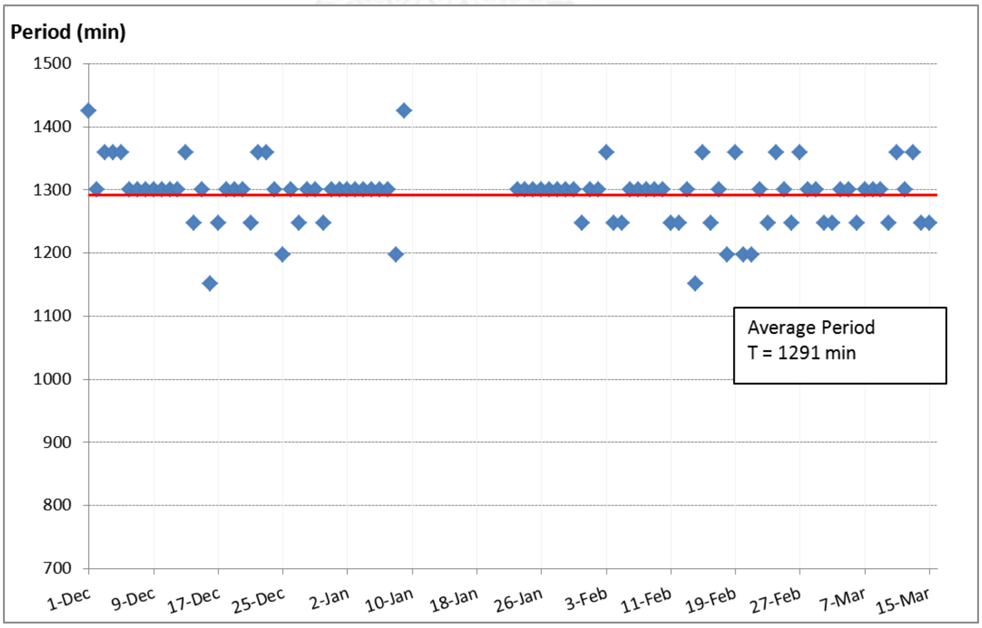


Figure 4.17 Variation of Period Based on Sinusoidal Fitting

4.4.2 Moisture Measurement Timing and Average Moisture Content

As previously mentioned, the representing value of volumetric moisture content is considered best taken from average value for each day. In relation to this matter, it is beneficial to use the sinusoidal approach. The sinusoidal generalized formula as presented before shows D as an offset value, which is in fact the mid-value of the sinusoidal graph. Based on trigonometric theory, the offset value can be determined by averaging two values separated by half-a-period time span.

In Figure 4.17, we can see the variation of the period on each day from included data of 15-week logging. While the red line is the average value of the period, the distribution of each day period is fairly consistent and not immensely scattered. The average value of the period (T) based on data analysis using 92-day of measurement was 1,300 minutes. This value can be considered as reference to conduct measurement in the field by using moisture sensor based equipment. While the period is the distance between the same extreme values, our time span between measurements should be half-of the period value. In conclusion, the time difference between the first and second measurement should be 650 minutes (approximately 10 hours).

By utilizing this finding, we can plan two measurements on the schedule with a time span of approximately 10 hours between each measurement. Instead of randomly taking numerous of measurements of the day, this method should be more time-saving, and provide more precise result in obtaining the average moisture content.

4.5 Daily Averaged Moisture Trend in Unbound Base Layer

Since D coefficient of each sinusoidal equation fitted is actually the average volumetric moisture content of each day, we can simply see the trend of the volumetric moisture content inside the base layer during our long-term data logging time period. As we can see in figure 4.19, the volumetric moisture content has been showing a decreasing trend since December 1, 2013. The trend was extremely consistent and linear. This is normal knowing that Thailand is entering summer season during the logging activity at that time period, in which a lot of evaporation is normally expected to be happened.

Time-series information of moisture content presented in the previous graph can be helpful to predict the modulus strength of the base layer. Based on Ekblad (2008 & 2011) and Phommavone (2013) studies, a change in moisture content of granular material is going to make changes to strength of the modulus. As the moisture content of granular material decreasing, the modulus is reduced by some level. Moreover, the amount of change in the resilient modulus caused by moisture depends also on the gradation.

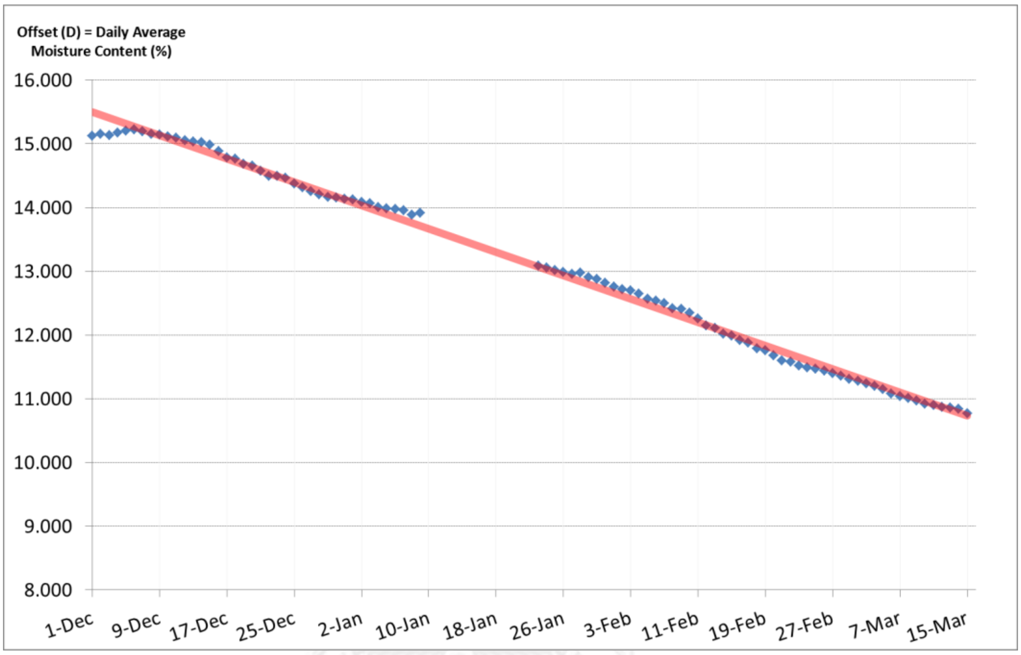


Figure 4.18 Base Layer Daily Average Moisture Trend based on 92-day Recorded Data

By having this kind of real time information, we can predict the condition of the base layer over time, and prevent certain structural damage in the future. In this case, the trend presented in the graph gives us a general illustration of how fast and much the moisture of the base layer in flexible pavement decreasing on summer season in the Central Region of Thailand. In four months of the summer season and completely without rainfall, the moisture decreases by approximately 4.5% by volume, or around 1.93% by weight (assuming dry density of granular material = 2.33gr/cm3). See section 2.2 to understand how to convert volumetric water content by gravimetric water content.

4.6 Moisture Reading due to Cracking and Rainfall

In section 3.3, it was mentioned that cracking line was found on the vicinity surface of Site 1 observing point. Despite the unknown exact date of crack occurrence, it can be assumed that it was happened weeks before May 1, 2014. The following image was taken on May 1, which is the first time we knew crack had occurred on the surface.

Figure 4.19 Occurrence of Cracking in Site 1 & Reparation Using Asphalt Binder

Assuming that the crack only occurred on the surface, we repaired the crack using asphalt binder. However, the crack actually did occur deeper than the surface as we can see in Figure 4.21. Due to this crack problem, the recording in this site was considered inappropriate to give the expected measurement that was needed, and Ml2x Thetaprobe was then removed from the observation point.

Figure 4.20 Cracking on Observation Point of Site 1

In relation to this matter, Site 2 has no crack problem at that time, but both have recorded moisture profile on rainy days. The comparable graphs of each Site during rainfall are shown in the following figures.

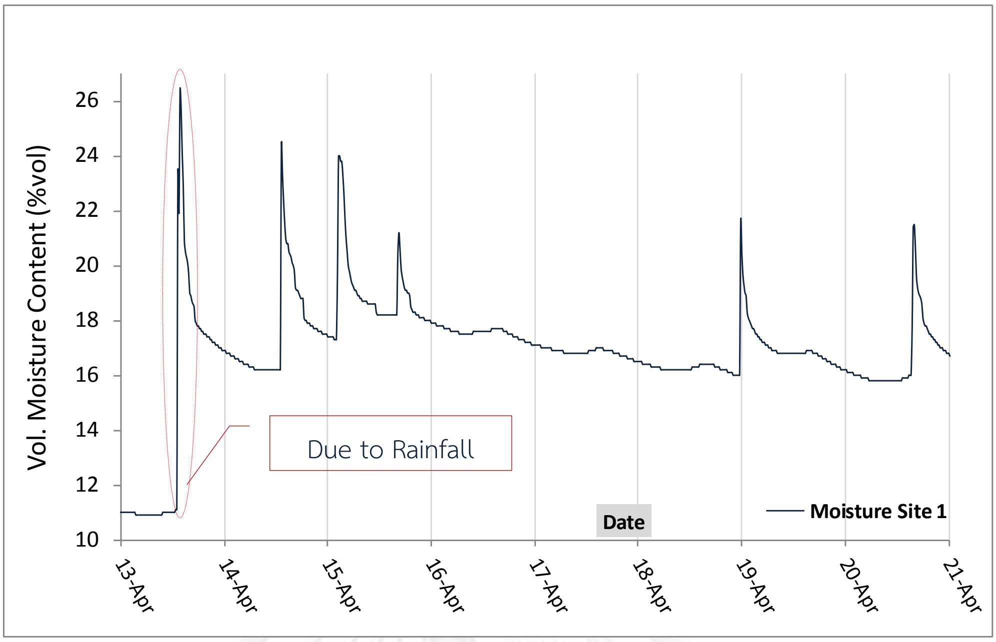


Figure 4.21 Moisture Profile during Rainfall (Crack Occurred) in Site 1

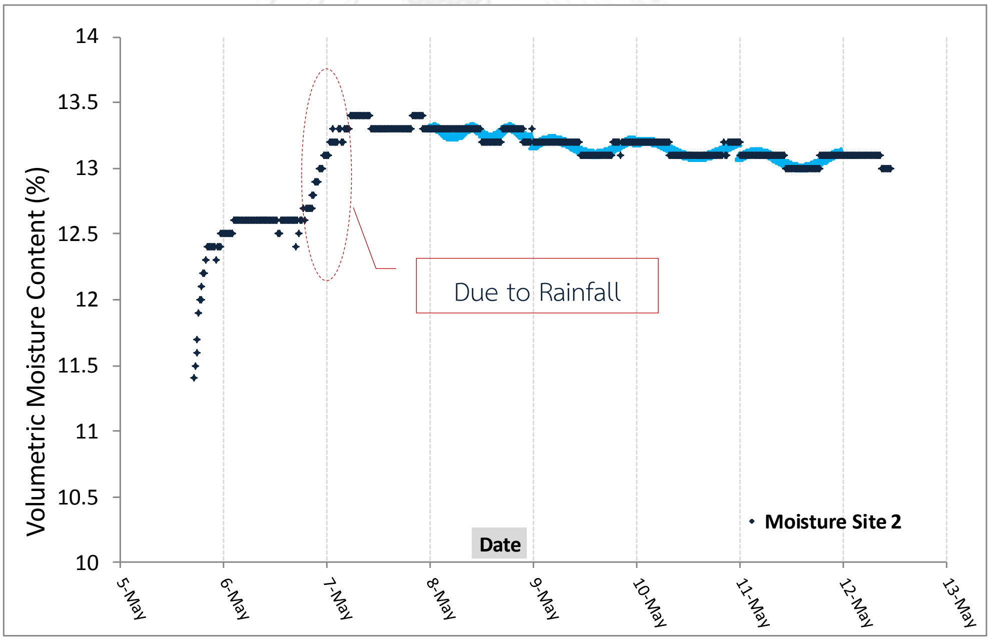


Figure 4. 22 Moisture Profile during Rainfall (No Crack) in Site 2

Figures 4.21 and Figure 4.22 shows us moisture profile of two different sites with the occurrence of rain, but different surface condition. Figure 4.21 represents the moisture profile in Site 1 where crack had occurred on the surface and reached the base layer as well whereas Figure 4.22 represents the moisture profile in Site 2, where no crack had occurred. We can notice that due to the rainfall in Site 1 the volumetric moisture content leaped from 11% to approximately 26% whereas in Site 2 the occurrence of rainfall only changed the volumetric moisture content less than 1%. Based on this data, we can conclude that on rainy day the existence of crack on the surface increased the volumetric moisture content inside the base layer dramatically. Moreover, the level of increase might relate highly on the amount of rainfall on that day.

Not only there is a leap of changes in moisture value, but also we can see that the draining processes inside the base layer after rainfall on both sites are different. In Figure 4.21, the volumetric moisture content of Site 1 was drastically decreasing after rainfall in several hours. If we compare this graph to what we can see in Figure 4.22, in Site 2 the draining process took much longer time. The descending trend of the moisture value in Site 2 was slower than what we found in Site 1.

Based on this finding, crack damage on the pavement surface will influence the moisture value inside base layer. This is most likely caused by the increasing possibility of water infiltrating into the pavement surface during rainfall. In relation to pavement structural performance, the sudden changes caused by water on a damaged surface would change the pavement strength and increase the possibility of other further permanent damages.

Chapter 5
Conclusion

5.1 Summary of Findings

Moisture is among the key factors affecting modulus and strength of unbound materials in flexible pavement structure. In this study, moisture condition in the unbound base layer is the primary focus, particularly its alteration. The volumetric moisture content of unbound base layer was monitored for a long period of time on a flexible pavement section representing a typical thin surfaced structure. Thermal sensor was later integrated with the monitoring system to capture temperature changes on the layer. The observation site consisted of three different places inside Chulalongkorn University (Saraburi) with the same typical structure of pavement. By setting up the long term monitoring system, the aim was to learn the real time behavior of moisture content inside the base layer, specifically without the effect of seasonal variation such as rainfall.

The result of moisture measurement in the period of time between November 2013 and June 2014 from three different sites showed that moisture inside base layer fluctuates daily in a systematic pattern similar to a sinusoidal shape. The sinusoidal shape was found initially in Site 1 recorded data, and later was upheld by the result of the other two sites data. The sinusoidal shape happens daily, and was repeating with variation in amplitude (A), phase shifting (C), and offset (D) value. Slight variation was found on the amplitude value that represents the diurnal fluctuation range. A range of approximately 0.4-0.5% (between maximum and minimum) was calculated from the moisture reading after sinusoidal regression. Moreover, based on the regression analysis using Past3.01 statistical software, the average sinusoidal period is 21.67 hours.

Temperature was initially regarded as an influential factor on the sensor reading, but later was turned down in consideration of our laboratory test result and field finding. Laboratory test was carried out in order to see the effect of temperature change on the reading. Supported by field findings, it was found that the temperature does not directly affect the sensor performance, but rather the water movement inside the layer. The change in temperature found in lab test was small and most likely caused by the upward movement of water (evaporating) due to increase of temperature.

Research finding suggests that moisture measurement using this type of moisture sensor for determining the mean value of moisture content to represent the condition for each day can be done in a more simplified way. Instead of randomly measuring moisture in a day for several times, it is advisable to conduct only two measurements in a day. Based on the analysis in this study, the time span between these two measurements should take approximately 10 hours. Since the shape of daily fluctuation was sinusoidal, the average of two half-a-period separated values actually represents the average moisture content of the day.

A secondary finding was learned on the moisture behavior due to rainfall and cracking at the same time. We learned that surface cracking definitely caused a leap of changes in moisture value of the base layer. The level of drastic changes was most likely depending on the amount of rainfall on the day. In comparison, pavement with no crack has a lot smaller escalation (1%) in moisture value of the base layer. Moreover, by comparing the moisture reading on rainfall condition between surface with the crack and the one without crack, it was noticeable that the descending trend of moisture behavior in cracked condition looks more drastic, and takes a shorter time. Without crack on the surface, the draining process takes longer time (days)

In conclusion, moisture sensor such as Thetaprobe and SM300 is a good option to conduct moisture monitoring for a long term period. The quality of the reading is good, easy to use and the operation is flexible, and the price is quite reasonable. The drawback of measurement using such equipment on road structure is that some difficulties might occur when attempting to insert the sensor into the ground since road layers are harder to penetrate compared to soil generally.

5.2 Limitation of the Study

One of the limitations of this study is the quantity of moisture sensor used to monitor the behavior. It would be a lot more advantageous to have more installation on the same road section. The fact that there was only one moisture sensor installed at one point might not give us highly strong notion about the moisture behavior.

Supporting equipment would be the other limitation since it is necessary to have additional observation tools to record some parameters that might explain the findings. It was not possible to explain some of the findings in this study due to the unavailability of further parameters in the field, such as rainfall and water pressure measurement. Regarding the methodology, at the moment the findings related to moisture behavior inside the base layer are only limited to no-rainfall situation, which may only happen often in tropical country with a longer summer season. This limitation encourages further study to make use of the sensor to analyze the effect of seasonal variation as well in the future.

5.3 Recommendation for Further Studies

Based on the findings of this study, further studies to explore the effect of heat transfer inside the base layer on the moisture movement itself would be very much needed in order to gain knowledge of how the moisture behaves inside the base layer. Moreover, additional equipment should be integrated in the monitoring process to capture seasonal variations that are highly possible influencing the moisture behavior.

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APPENDIX

TECHNICAL SPECIFICATION OF ML2X THETAPROBE, SM150, AND SM300

Specification	ML2x Theta probe	SM150	SM300
Accuracy	±0.01 $m^3.m^{-3}$, 0 to 40°C, ±0.02 $m^3.m^{-3}$, 40 to 70°C,	±3.0% vol over 0 to 70 % vol and 0-60°C	±2.5% vol over 0 to 50% vol and 0-60°C
Measurement range	Accuracy figures apply from 0.05 to 0.6 $m^3.m^{-3}$, Full range is from 0.0 to 1.0 $m^3.m^{-3}$	0 to 100% vol but less accurate above 70%vol	0 to 100% vol with reduced accuracy
Salinity error	±0.05 $m.m^{-3}$, 0 to 70°C	±5% vol over 100 to 1000 $mS.m^{-1}$ and 0-60% vol	≤3.5%vol over 50 to 1000 $mS.m^{-1}$ and 0-40% vol
Sampling volume	40mm diameter; 60mm long	55 x 70mm diameter	55 x 70mm diameter
Output signal	0-1V DC for 0-0.5 $m^3.m^{-3}$	0-1 V differential ≈ 0 to 60% nominal	0-1V differential ≈ 0 to 60% vol nominal
Output compatible with		HH150, HH2, GP1, GP2, DL6, DL2e	GP1, GP2, DL6, DL2e, HH2
Maximum cable length	100m	1m (HH150 meter) 100m (GP1, GP2, DL6 and DL2e data loggers)	100m (GP1,GP2 & DL6 data loggers) 100m (DL2e: water content measurement)

Specification	ML2x Theta probe	SM150	SM300
Power requirement	5-15V DC unregulated	5-14VDC, 18mA for 1s	5-14VDC, 18mA for 0.5 to 1s
Operating range		-20 to +60°C	-20 to +60°C
Environment	IP68	IP68	IP68
Dimensions/Weight	112 x 40 mm diameter/ 350 gm with 5m cable	143 x 40 mm diameter/ 0.1 kg	143 x 40 mm diameter/ 77gm

VITA

Reynaldo (Siahaan) was born in Medan, North Sumatera Province of Republic of Indonesia, on August 12 in 1990. He received Bachelor of Science (B.S.) in Civil Engineering degree from Bandung Institute of Technology (ITB) in 2011. He spent several months after graduation helping some research work in Transportation Division in ITB. He was then awarded the AUN/SEED-Net scholarship in 2012, and continued his study by pursuing Master of Engineering (M.Eng) degree in Civil Engineering Department of Chulalongkorn University with specialization in Transportation Engineering Division.