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Non-destructive Evaluation Of Concrete Structures Using High Resolution Digital Image And Infrared Thermography Technology

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NON-DESTRUCTIVE EVALUATION OF CONCRETE STRUCTURES USING HIGH RESOLUTION DIGITAL IMAGE AND INFRARED THERMOGRAPHY TECHNOLOGY

by

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ABSTRACT

As existing bridge structures age, they are susceptible to the effects of deterioration, damage and other deleterious processes. These effects hamper the capacity and efficiency of transportation networks and adversely impact local, regional and national economic growth. As a result, bridge authorities and other professionals have become more sensitive to maintenance issues related to this aging infrastructure. While highway bridge condition have been monitored by visual inspection, non-destructive evaluation (NDE) technologies have also been developing and they are expected to be utilized for effective management of highway bridges or other civil infrastructure systems. Efficient use of these technologies saves time spent or bridge inspections, and also helps the bridge authorities for management decision-making. One of the NDE technologies is the image-based technology. In this thesis research, image-based technologies using high resolution digital images (HRDI) and infrared thermography image (IRTI) are introduced, described and implemented.

First, a review of the mechanisms of these technologies is presented. Due to the specific engineering utilization and recent technological development, there is a need to validate effectiveness of HRDI and IRTI for their practical use for engineering purpose. For this reason, a pilot project using these technologies was conducted at an in-service bridge and a parking structure with the support of Florida Department of Transportation District 5 and the results are presented in this thesis.

Secondly, in order to explore and enhance the usability of infrared thermography technology (IRTI), experiments on campus and on another bridge were conducted to determine the best time to test bridges and the sensitivity of IRTI to delamination volume. Since the accuracy of damage detection using infrared thermography technology is greatly affected by daily temperature variation, it is quite important to estimate an appropriate duration for infrared thermography inspection prior to the inspection. However, in current practice, the way to estimate the duration is to monitor the temperature of the concrete surface. Since the temperature varies depending on the area or region, there is a need to visit the bridge before the actual test and monitor the temperature variation. This requires additional visits to the bridge site and also access to the bridge for measuring concrete temperature. Sometimes, this can be a practical issue. In this research, in order to estimate an appropriate duration without visiting bridges, a practical method is explored by monitoring and analyzing variation of concrete surface temperature at one location and projected to another location by also incorporating other factors that affect the concrete temperature, such as air temperature and humidity. For this analysis, specially-designed concrete plates of a few types of thickness and shapes are used and the regression analysis is employed to establish a relationship between environmental effects and temperature variation between two different sites. The results have been promising for this research study and it is shown that HRDI and IRTI are excellent technologies for assessing concrete structures in a very practical manner.

ACKNOWLEDGMENTS

The author would first like to thank Dr. F. Necati Catbas for his support and guidance with this research study associated with developing this overall thesis: He always provides telling clues about this research study.

I would also like to thank my colleagues in Dr. Catbas's research group for their advice, contribution, support with experiments and encouraging me to work. Their names in no particular order are: Evan Prado, Tung Khuc, Masoud Malekzadeh, Travis Henriques, Martisa Washington, and Keke Peng. I wish to also thank Juan Cruz for his support with manufacturing and setting up equipment. It was not able to conducted experiments without him.

I also would like to thank my colleagues in NEXCO-West USA, Inc. and members in Florida Department of Transportation for their support and help with the project in Florida. They provided me with valuable experience at the field.

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CHAPTER ONE: INTRODUCTION

Various non-destructive evaluation (NDE) technologies have been developing all over the world. NDE technologies range from hammer sounding test to advanced technologies such as Ground Penetrating Radar (GPR). Traditionally, highway bridge conditions have been monitored by visual inspection such as hammer sounding test by qualified engineers and inspectors. This visual inspection is time-consuming and can present potential danger to the inspector because the inspector needs to be close to the object. One of the innovative technologies to make up for these negative elements of the inspection is the technology using images. This research focuses on non-destructive evaluation technology using images.

These images are high resolution digital image and infrared thermography image. High resolution digital images are taken by motion-controlled digital camera from the fixed locations, or high definition video cameras through mobile carriers such as the inspectors, vehicles, or boats. These images, which show surface of the concrete bridge elements, are analyzed by image processing including gradation analysis and line featuring analysis to detect cracks. In addition, delamination and spalling at subsurface concrete are detected by measuring the difference in surface temperature that exists between sound condition area and damaged area under a certain environmental conditions using infrared camera. As a result, this research explored future application availability of these technologies. These NDE technologies using image are innovative and have the potential to be used widely. However, the studied crack detection technology is quite new, therefore, there is a need to show the reliability of this technology. Meanwhile, IR technology has a certain limitation. Because the accuracy of damage identification using infrared image is greatly affected by ambient temperature variation, suitable temperature condition to enable detection is essential. However, the ambient temperature condition cannot be controlled, therefore, this research explores the relationship between the ambient environmental condition and the temperature of concrete surface to estimate the duration with appropriate environmental condition for the inspection using IR technology.

Purpose

NDE technologies using image are innovative, so need to be easy to be install. Basically cracks on the images are detected by the software automatically and damages in subsurface of concrete on thermal images are filtered by the software, and it can be said the result is objective. In order to show the reliability of these technologies, a pilot project using these technologies was conducted and the result was shown in this research.

As for the infrared thermal image, because the accuracy of damage identification using infrared image is greatly affected by ambient temperature variation, suitable temperature condition to enable detection is essential. However, the ambient temperature condition cannot be controlled, therefore, ambient temperature data and concrete temperature data are collected and special concrete plates that is simulating a delamination at subsurface of the concrete bridge element is attached to the object and the temperature data of the concrete plates is collected prior to the inspection. However, it takes extra time and the data cannot be collected as long as someone doesn’t go to the location where is inspected. This is inconvenient in the case that there are a number of bridges to inspect and bridges are far away from a maintenance office. Therefore, this research explores the relationship between the ambient environmental condition and the temperature of concrete surface so that it makes possible to estimate the duration with appropriate environmental condition for the inspection using IR technology.

Objectives

The goal of this research is to show the utility of innovative image based non-destructive evaluation technologies and improve the usability of infrared thermography technology by exploring the way to estimate appropriate duration for inspection. In order to achieve the goal, the objectives of this research are as follows:

-Investigate the reliability of image-based technologies using high resolution digital images (HRDI) and infrared thermography image (IRTI) by investigating the variability of analyzed data.

-Develop a method to estimate the duration with appropriate environmental condition for infrared bridges inspection.

Approach

In order to show the reliability of these technologies, a pilot project using these technologies was conducted and the result was shown in this research.

In addition to that, as for the infrared thermography technology, since the accuracy of damage identification using infrared image is greatly affected by ambient temperature variation, suitable temperature condition to enable detection is essential. However, the ambient temperature condition cannot be controlled, therefore, this research explores the relation between environmental temperature condition and concrete surface temperature to estimate the appropriate duration for infrared inspection.

The primary environmental factors believed to affect the heat transfer from the environment into the concrete include:

-Ambient Temperature

-Humidity

-Dew Point

-Pressure

-Wind Speed

To evaluate the effect of these parameters on the ability of infrared inspection to detect delamination or spalling, concrete plates, which simulate concrete subsurface delamination were installed. (Figure. 1) The detail of these concrete plates is mentioned in chapeter2. These concrete plates were attached to selected concrete bridges elements with temperature measurement devices and concrete surface temperature was collected.

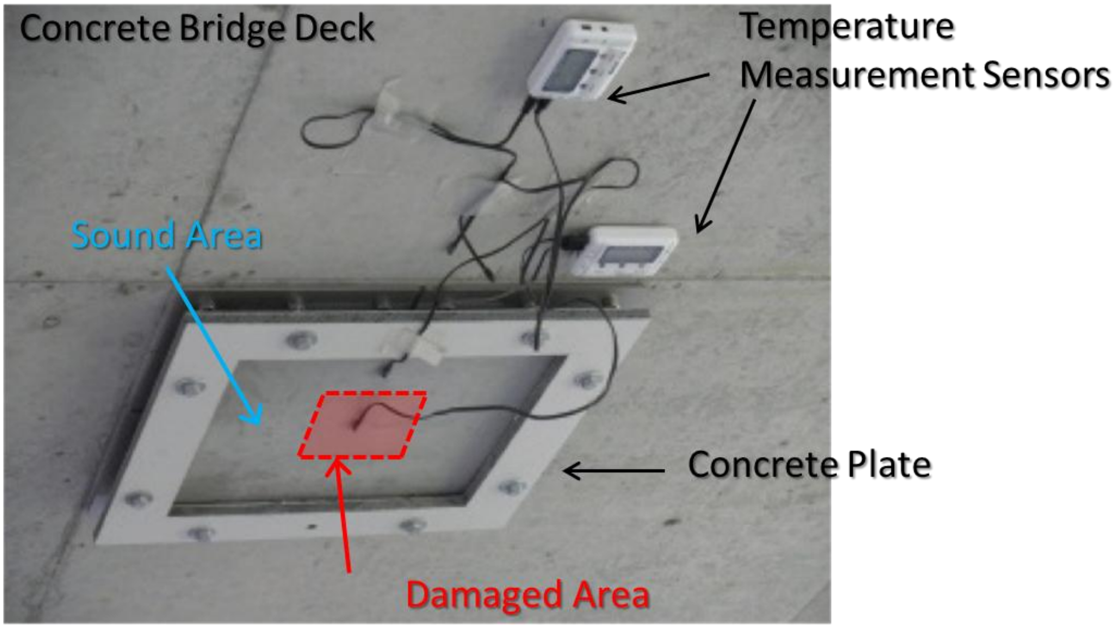


Figure 1: Concrete Plates with Temperature Measurement Sensors

CHAPTER TWO: IR AND HRDI NON-DESTRUCTIVE EVALUATION TECHNOLOGIES

Innovative bridge condition assessment technologies that applied in this research are introduced here. These technologies have been developed by NEXCO-West, one of major toll road operators in Japan.

Infrared Thermography Image Technology

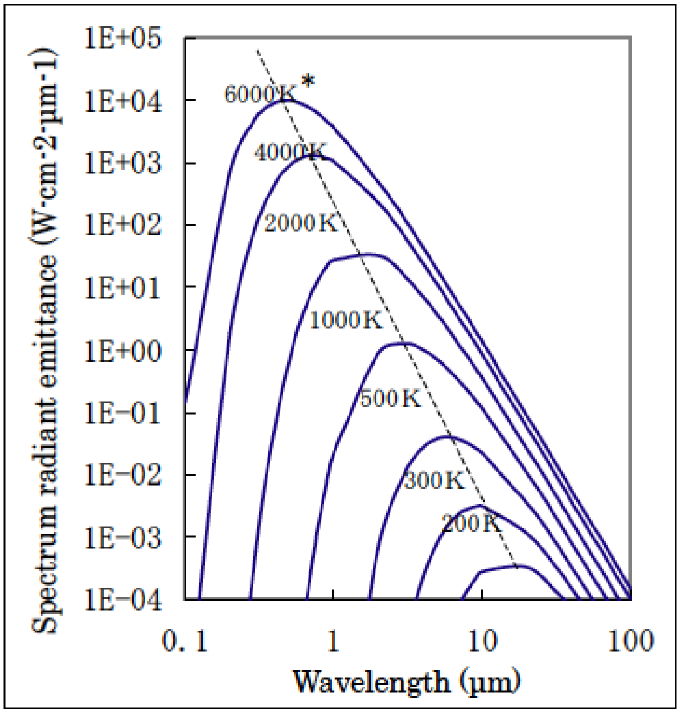
Infrared thermography image technology in this thesis is a non-destructive evaluation technology to locate possible delamination and spalling of concrete subsurface through the monitoring of temperature variations on concrete surface using high-end infrared camera (Figure 2). The camera used in this technology is FLIR SC5600. The advantage of this IR technology is to enable inspectors to identify likely delaminated, spalled and inner void areas from a distance of up to 60 meters. Due to this advantage, there is no need for inspectors to move closer to objects using ladders or snooper trucks. Moreover, the result of the thermography images, which are screening of potential concrete defects on concrete subsurface, reduce the amount of time to inspect compared to sounding test, since there is no need to inspect spot by spot.

Figure 2: Infrared Camera

Infrared Rays

Infrared thermography technology is a technology based on collecting the surface radiant temperature of an object and converting that measured temperature into a thermal infrared image. In general, all bodies that are not at absolute zero emit energy as electromagnetic radiation at various wavelengths and strengths. Figure 3 shows the temperature of a body and radiant emittance at each wavelength. As shown in this figure, energy emitted from a body is released as visible emissions like incandescence from a metal rolling mill, i.e. light when the body becomes hot, since it contains elements within the visible spectrum range (0.38μm to 0.75μm).
Usually, a body where the temperature is 500°C or less will release all energy as infrared emissions, and the released amount is closely related to the surface temperature of the body. The

infrared camera fetches the amount of infrared rays within a certain wavelength range and measure the temperature of the body by using this amount as a function.



*K indicates Kelvin

Figure 3: Spectrum Radiant Emittance of Black Body

Infrared Camera

In general, a wavelength range of infrared rays that can be captured with an infrared camera is about 1.5μm to 14μm. The infrared camera is composed of a lens, a scanning mechanism, and a detector incorporating elements for detecting electromagnetic waves within a certain infrared area only. (Figure 4) Thus, the infrared camera only captures infrared rays emitted from the subject structure passively, but emits nothing. As shown in Figure 5, temperatures measured with the infrared camera are influenced by not only the temperature of the subject structure to be measured but also by the constant thermal reflection of the surrounding structures (facing surface) and the emissions from the atmosphere even if they are quite small. The greater the difference in the temperature of the subject surface to be measured and the surrounding structures (facing surface), the more difficult it is to measure the temperature accurately.

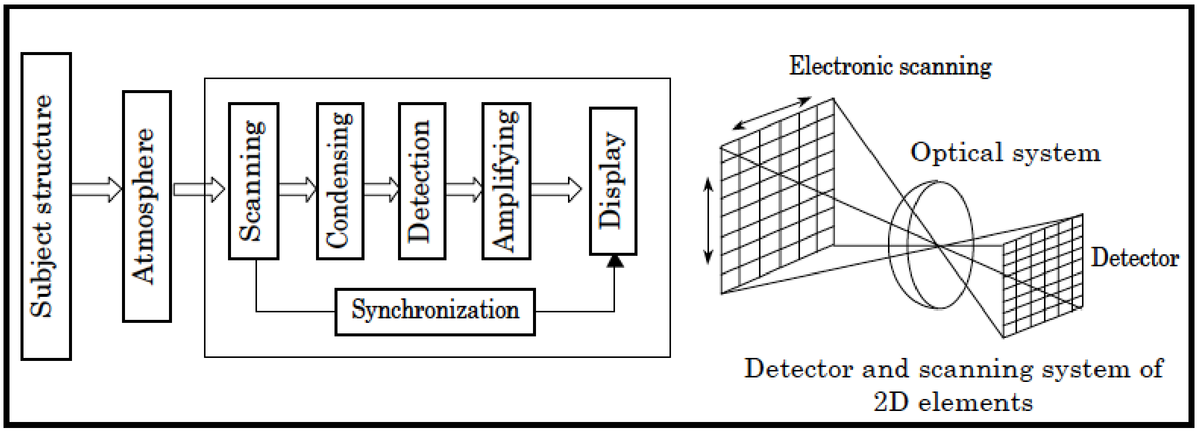


Figure 4: Configuration Outlines of the Infrared Camera

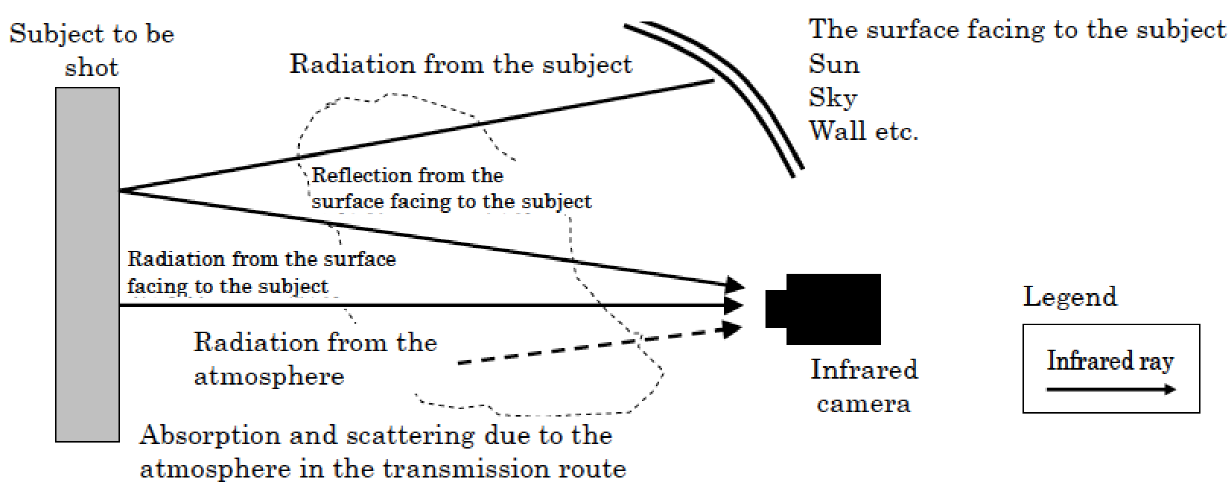


Figure 5: Infrared Radiation Energy Transmission Route for Outdoor Shooting

In this case, the emissivity (Figure 6) is the ratio of the amount of infrared rays emitted from the subject to be measured to the amount of the infrared rays reflected on the surface subject to the measurement. Materials with higher emissivity are less influenced by the ambient thermal environment.

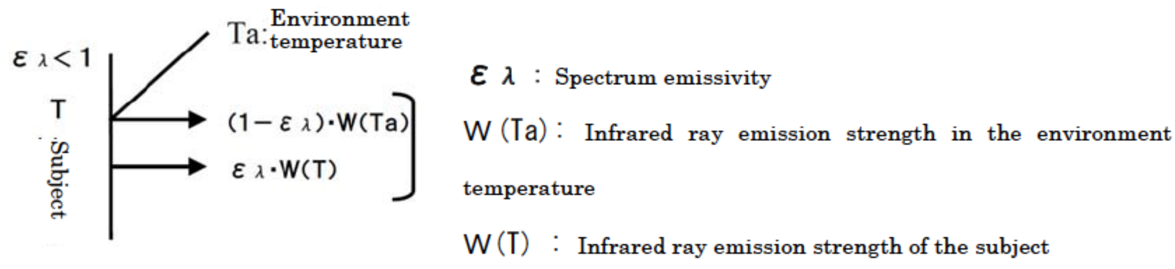


Figure 6: Relation between Emissivity and Reflectance in the Temperature Measurement with Infrared Rays

Infrared Method

The infrared camera simply photographs temperature distributions on the surface of the subject, but is not transmissive into the subject. The infrared method will estimate internal defects by using the fact that the changing speed of the surface temperature of a body varies with the materials composing the body and its thermal properties (specific heat, heat conductivity etc.) In the case of concrete structures, peeling or exfoliation around the concrete surface contains air with low heat conductivity, thus differences in the surface temperature between these portions and sound sections may occur due to changes in the temperature, such as atmospheric temperature, as shown in Figure 7. The infrared method described in this research is a noncontact method for observing temperature differences between the sound sections and changed sections using an infrared camera similar to an ordinary video camera.

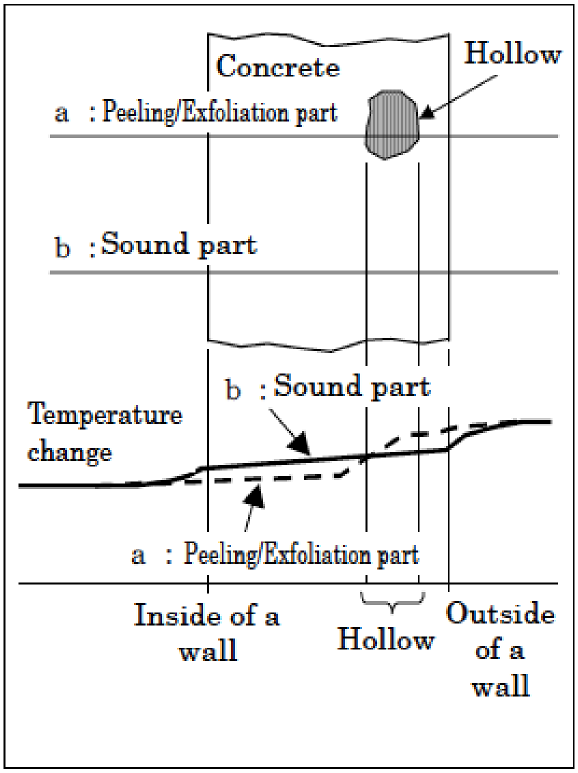


Figure 7: Temperature Change in a Concrete Structure

As mentioned above, the infrared method is a technology that detects defects through differences in the speed of temperature changes in the subject to be measured, i.e. temperature differences for a certain duration. However, it is impossible to detect defects in an environment with a constant temperature since there is no temperature change. Thus, temperature changes in the subject to be measured are indispensable for detecting defects with the infrared method. It is possible to classify this method into the active type and the passive type according to the method of changing temperatures. The infrared method described in this research is the passive type.

-Active type: This method artificially heats or cools the subject to be measured to force a temperature change on the surface of the subject to be measured, and then detects the changed sections by observing the temperature change.

-Passive type: This method does not forcibly heat the subject to be measured but captures the naturally occurring temperature changes due to changes in the atmospheric temperature.

In the passive-type infrared method, the peeling, exfoliation and internal defects sections of a concrete structure show different temperature distributions than the sound sections as a result of natural temperature changes, such as insolation and atmospheric temperature, as shown in Figure 8. In this method, the temperature distribution is captured by an infrared camera, and the infrared images is displayed in an appropriate temperature range so that the changed section can be identified easily, and then the inspector detects some sections where the temperature has changed.

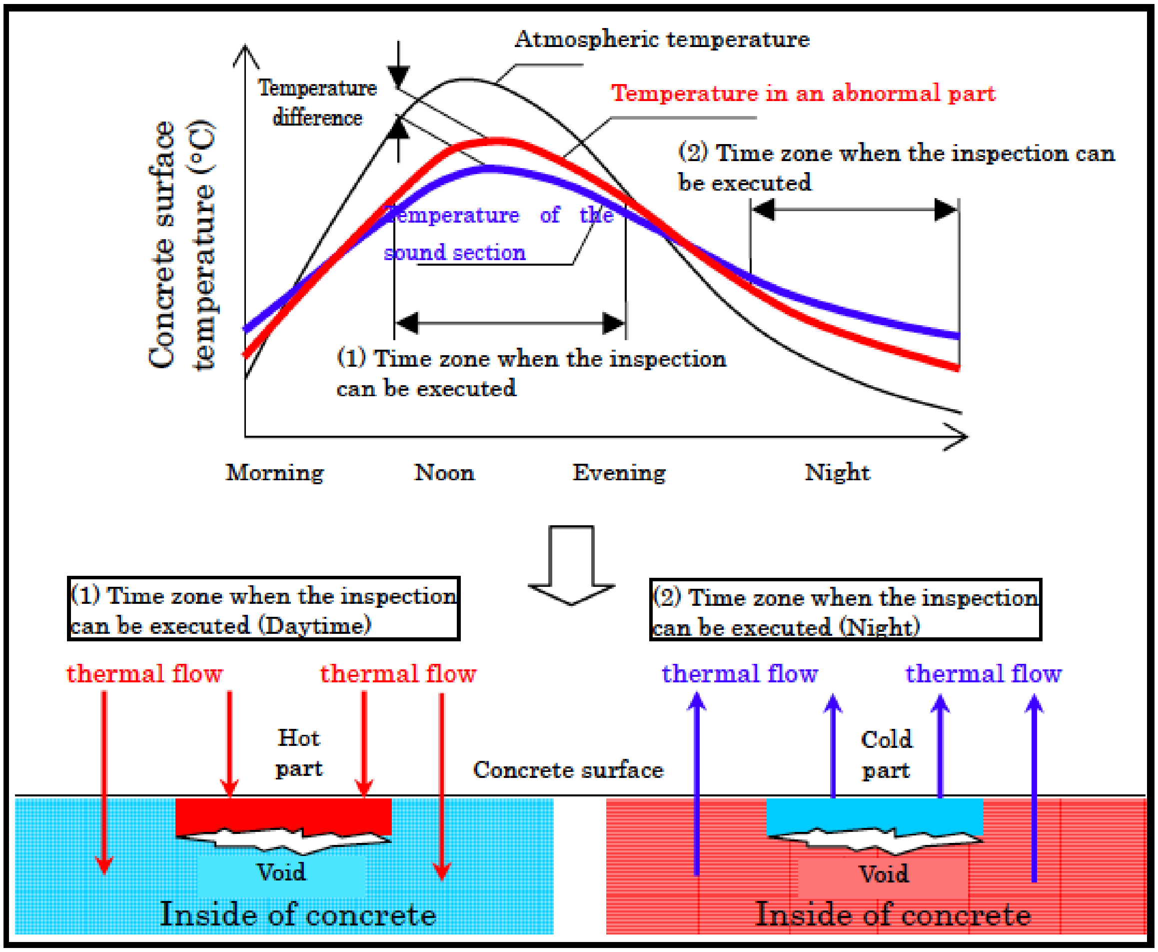


Figure 8: Inspection Duration Example of the Infrared Method

It is not always possible to detect delamination of concrete only from the color variation of infrared imagery since the concrete structure itself tends to have a temperature gradient depending on location and orientation with respect to the sun. Akashi et al. performed the statistical and analytical study on the relationship between characteristics of temperature variation and inherent damage of the concrete from the historical inspection database, and developed an automatic damage classification system that can classify the damage rate into three categories; the classification categories being "Critical" (crack caused by delamination reaches on concrete surface and immediate attention is required), "Caution" (crack exists within 2cm from the concrete surface and close monitoring is recommended) and "Indication" (Currently satisfactory) (Figure 9). Raw infrared (IR) image data is filtered and rated into three categories by the software to indicate and evaluate the severity of subsurface defects in concrete structures. The monitor shows the raw, filtered and rated IR images at an inspection site in real time.

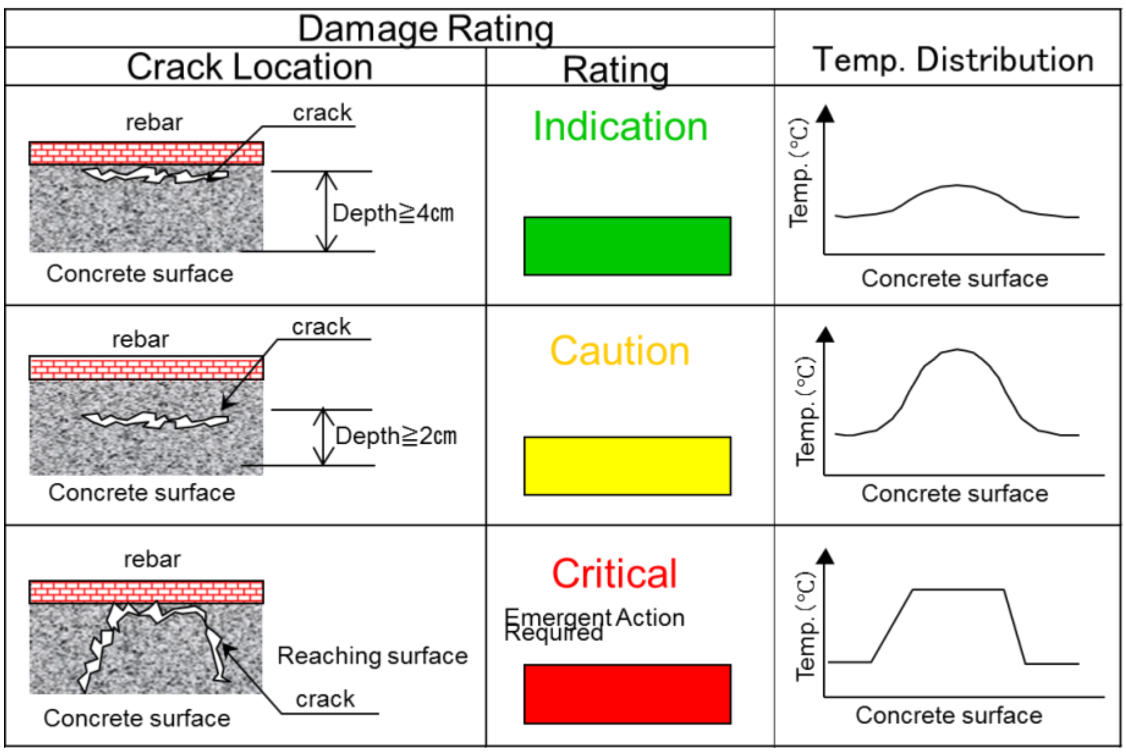


Figure 9: Damage Rating by Infrared Thermography Technology

High Resolution Digital Imaging (HRDI) Technology

This technology is a non-destructive evaluation technology to detect cracks on concrete surface using high quality digital image and image processing software. Sections of the concrete bridge elements are photographed by motion-controlled digital camera from the fixed locations (Automatic Camera System), or high definition video cameras through mobile carriers such as the inspectors, vehicles, or boats (HDV System). The digital camera used in this system is “Nikon D3s” and the high definition video camera is “Canon XH GIS (1440×1080). This technology enables inspectors to identify cracks on concrete on the photos taken even from a distance. Due to this, there is no need for inspectors to move closer to objects using ladders or snooper trucks. Figure 10 shows detectable crack width from each distance. Figure 11 shows the field data collection by high definition video cameras through mobile carriers. As shown in the picture, it is possible to detect cracks of a bridge over a river with the use of a boat. Figure 12 shows the field data collection by motion-controlled digital camera. Once the target area is set up using the software, the camera automatically takes images of that adjusting a focus and light quality. Once the field data collection process is finished, software stitches the images collected from different angles at different distances and presents normal views of all structural surfaces, usually arranged as a single high-resolution composite image of the combined individual frames. The composite digital image is analyzed by image processing to detect cracks on the concrete surface in terms of crack size, location and distribution. Innovative crack identification algorithms can identify concrete cracks as narrow as 0.008 inch or 0.2mm. This size exceeds FHWA criteria, since current FHWA inspection criteria for crack detection requires to 0.01inch, or 0.25mm. Additionally, the crack size and length are determined by computer software and these quantitative characteristics are summarized in spread sheet format. The obtained crack maps and supporting data are provided to engineers for their subsequent structural diagnosis and rehabilitation planning. A special advantage of this HRDI crack detection technology, with respect to crack identification and measurement, is the ease of maintaining a historical record of bridge cracks for use in monitoring crack propagation over time.

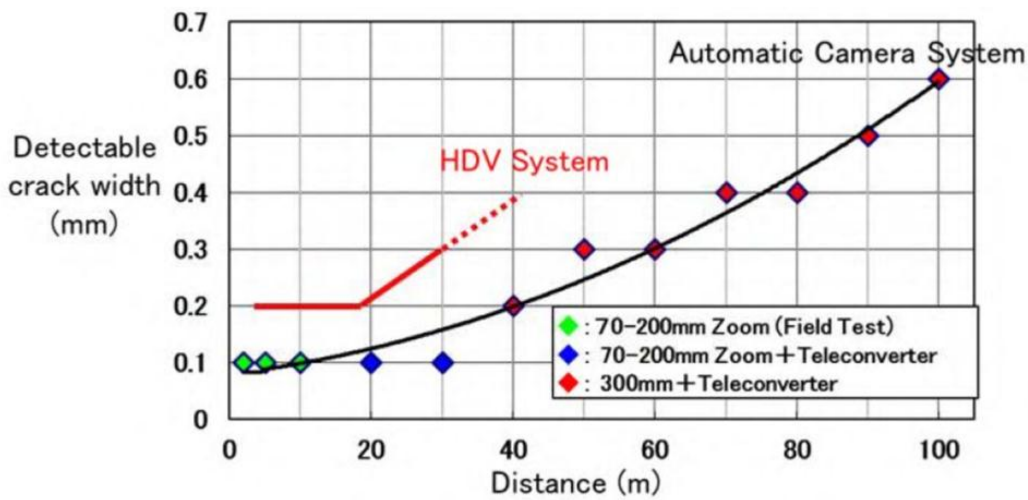


Figure 10: Detectable Crack Width

Figure 11: Bridge Inspection using High Definition Video Camera

Figure 12: Bridge Inspection using Motion-Controlled Digital Camera

Combination of HRDI and IR Technologies

As shown in Table 1, high resolution digital image technology detects cracks on concrete surface that generally obtained by close-up visual inspections. Meanwhile, infrared thermography technology detects voids, delamination and spalling of concrete subsurface condition that generally obtained by sounding test using a hammer. Therefore, it can be said that combination of these imaged based technologies covers the most of information obtained by visual inspection and sounding test. As mentioned in the previous section, there is no need to be close up to the object by using these technologies. It means that inspectors can reduce the time for inspection by using both technologies effectively. Additionally, these digital image data can be stored and monitored historically. Furthermore, these digital images help inspectors with identifying the areas that need close-up inspection and future monitoring. Therefore, the combination of HRDI and IR technologies improves the efficiencies in concrete structure inspection.

Table 1: Purpose of Innovative Inspection Technologies

	Purpose	Traditional Method
HRDI	Surface Cracks	Visual Inspection
IR	Inner Void, Delamintaion and Spalling	Hammer Sounding

CHAPTER THREE: PILOT PROJECT IN FLORIDA

A pilot project in order to validate the effectiveness and capability of high resolution digital image technology and infrared thermography technology was conducted at a bridge in Florida in cooperation with Florida Department of Transportation (FDOT) District 5 and NEXCO-West USA, Inc.

Objectives

The objective of the project is to investigate the capabilities of high resolution digital image technology and infrared thermography technology on a bridge in service by exploring the use of novel image based technologies in a way that the information generated with these technologies will provide useful data for the inspection and evaluation of civil infrastructure system.

Test Structures

FDOT District 5 provided some candidate concrete bridges and one of them was selected for the project ,since it is found that the bridge was deteriorated to some extent and there was enough space for the demonstration based on the field survey. The bridge is No.700006 on US-1 in Melbourne (Figure 13). The bridge was built in 1959 and reconstructed in 1990. The number of lanes is seven and the total length is 380 ft. They also provided their parking garage as a test structure (Figure 14).

Figure 13: Sample Bridge in Melbourne

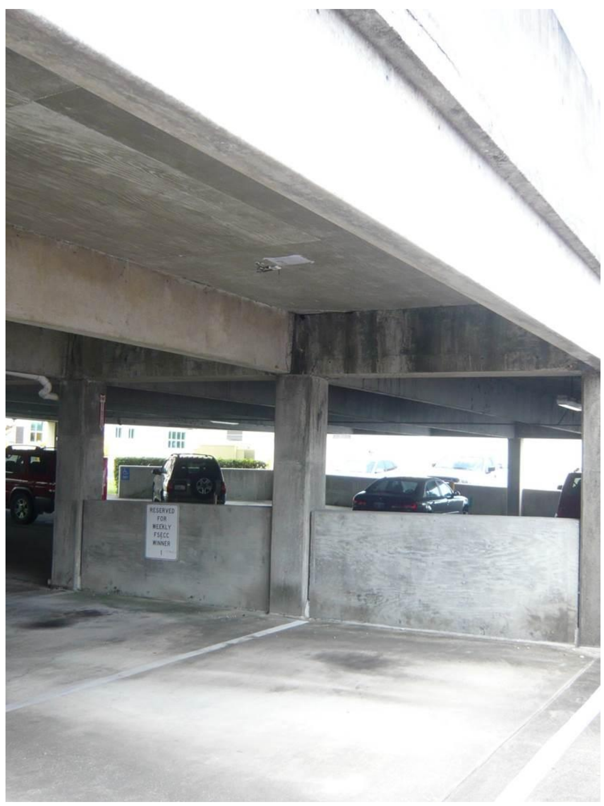


Figure 14: Sample Parking Garage at FDOT

Data Acquisition and Analysis

In this project, the underside of the concrete bridge deck (Figure 15) and parking garage at FDOT (Figure 16) were inspected using motion-controlled digital camera and infrared camera. The photographed images were analyzed using special software for these technologies. The detected cracks were categorized into three ranks depending on their widths (Rank 1: ≤0.010." (0.25mm), Rank 2: 0.010." (0.25mm) to 0.030." (0.76mm), Rank 3: 0.030." (0.76mm) or greater) (Figure 17). The detected inner voids, delamination, and spalling were categorized into three ranks (Critical (crack exists on concrete surface and immediate attention is required), Caution (crack exists within 2cm from the concrete surface and close monitoring is recommended) and Indication (Currently satisfactory)) (Figure 18).

Figure 15: Underside of the Bridge Deck

Figure 16: Ceiling at FDOT Parking Garage

	WIDE	>0.030"
	MEDIUM	0.010" to 0.030"
	NARROW	<0.010"

Figure 17: Crack Classification

	CRITICAL
	CAUTION
	INDICATION

Figure 18: Damage Classification

Result and Interpretation

Bridge Result

Figure 19-22 Show the result of the inspection using HRDI technology and IR technology. Table 2 and Table3 show the potential spall area obtained from IR technology software. After obtaining the result from both technologies, the FDOT certified bridge inspector provided the hands-on inspection using a crack width ruler and a hammer in order to evaluate the accuracy of the new bridge assessment method (Figure 23). Figure 24 shows the result measured by the inspector. It presented that the widths of cracks detected from the high resolution digital image matched with the actual hands-on measurement by crack width ruler for all the evaluated cracks. Additionally, after sounding test of one of the critical location, hidden plastic sheet appeared from beneath the mortar (Figure 25). The result indicates that the infrared thermography could successfully detect the subsurface defects which could not be seen from the concrete surface by regular visual inspection.

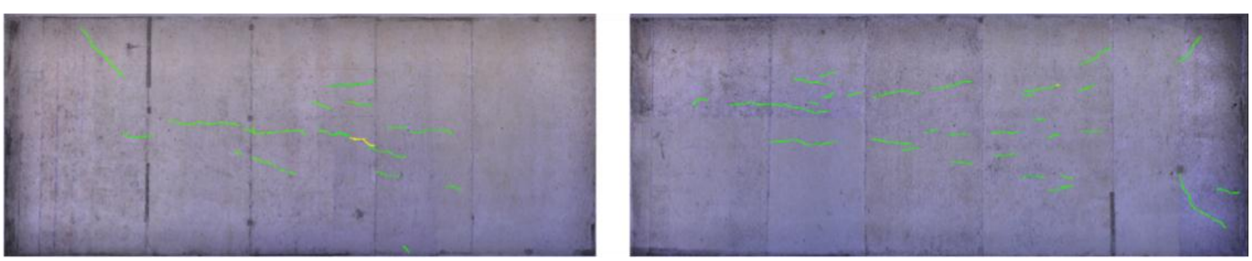


Figure 19: Crack Map (Deck-1)

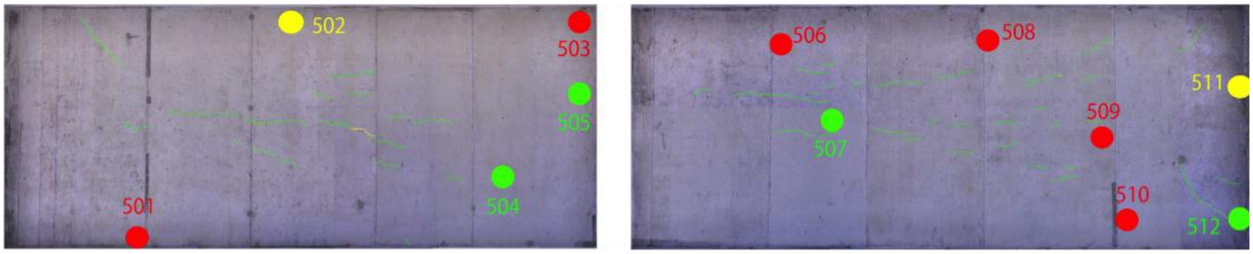


Figure 20: Potential Spall Area Map (Deck-1)

Table 2: Potential Spall Area (Deck-1)

ID #	Potential Spall Area		
	Critical	Caution	Observation
501	0.32		
502		0.86	
503	0.22		
504			1.51
505			1.29
506	0.11		
507			0.43
508	0.22		
509	0.54		
510	0.22		
511		0.22	
512			1.08
Total	1.61	1.08	4.31

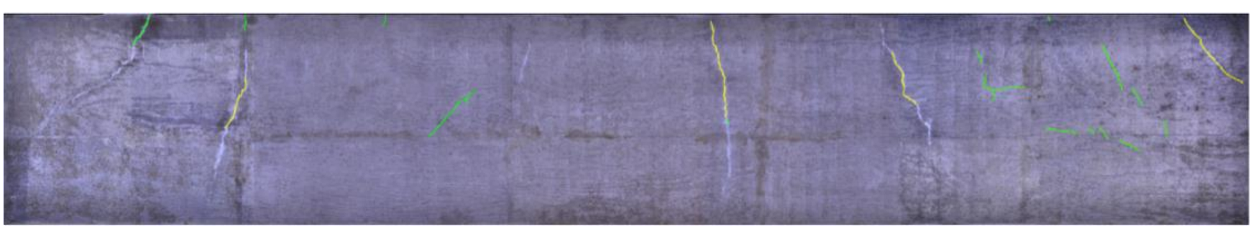


Figure 21: Crack Map (Deck-2)

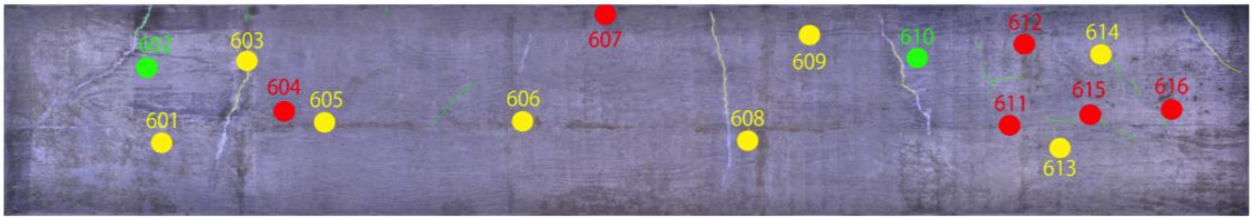


Figure 22: Potential Spall Area (Deck-2)

Table 3: Potential Spall Area (Deck-2)

ID #	Potential Spall Area		
	Critical	Caution	Observation
601		4.31	
602			1.94
603		1.51	
604	4.84		
605		2.15	
606		1.29	
607	0.11		
608		2.15	
609		0.54	
610			3.77
611	0.32		
612	1.29		
Total	6.57	11.95	5.70

Figure 23: Hammer Sounding by FDOT Qualified Inspector

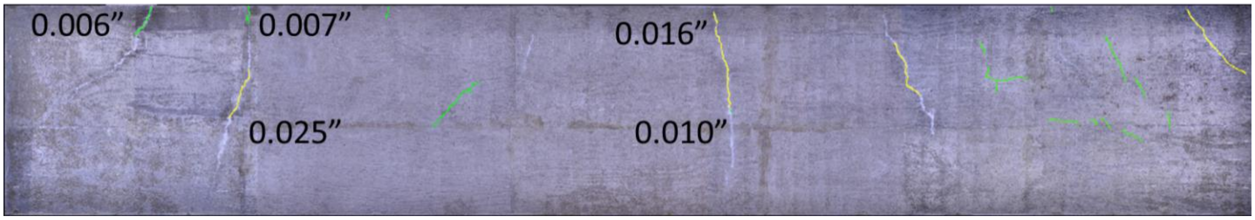


Figure 24: Result by Inspector (Deck-2)

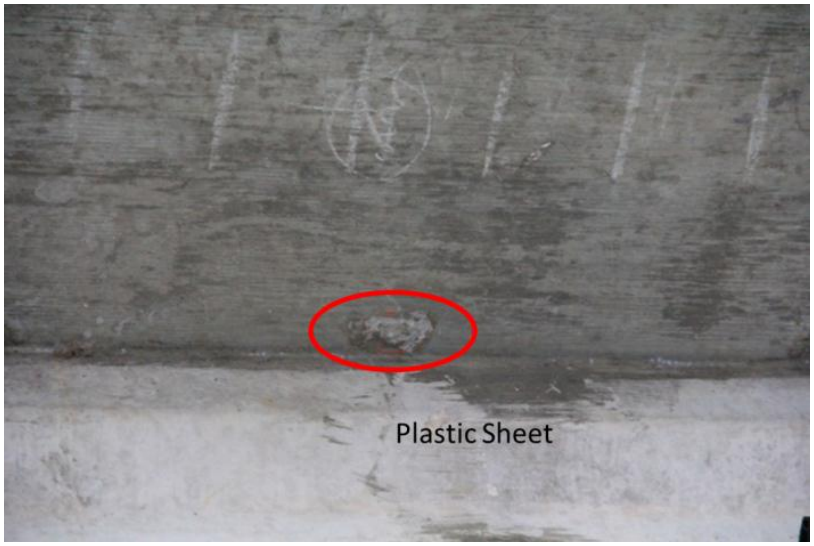


Figure 25: After Hammer Sounding Test

Parking Garage Result

Figure 26 shows the result of the inspection using HRDI technology. The color shows the classification of crack width. After this inspection, the FDOT certified bridge inspector measured the width of cracks. According to the inspector, the width of red cracks was 0.06 inches and the width of green cracks was 0.006 inches. It presented that the results of HRDI matched the results by the inspector. Figure 27 shows the results of the inspection using IRTI technology. The color shows the damage classification. After this inspection, the inspector provided hammer sounding test. Figure 28 show the result provided by the inspector. When comparing these two results, the results by IRTI covers critical damaged area shown by the inspector. Therefore, it can be said that these technologies detect cracks and subsurface defects.

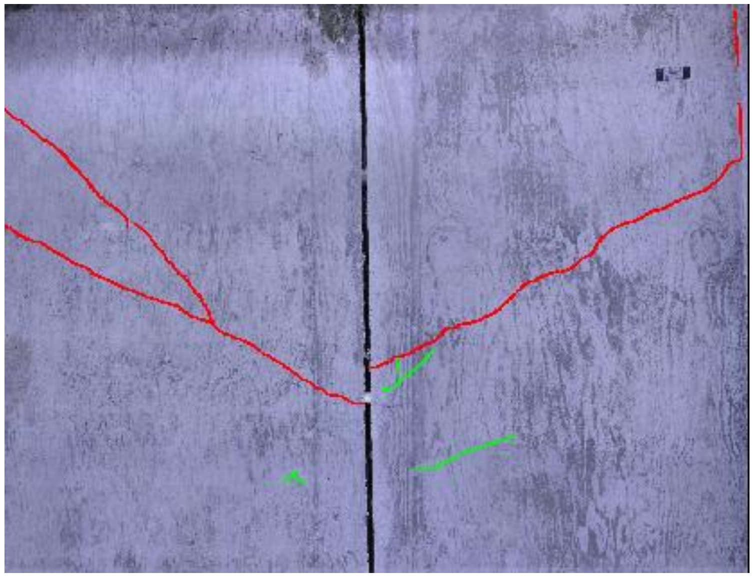


Figure 26: Crack Map (Ceiling)

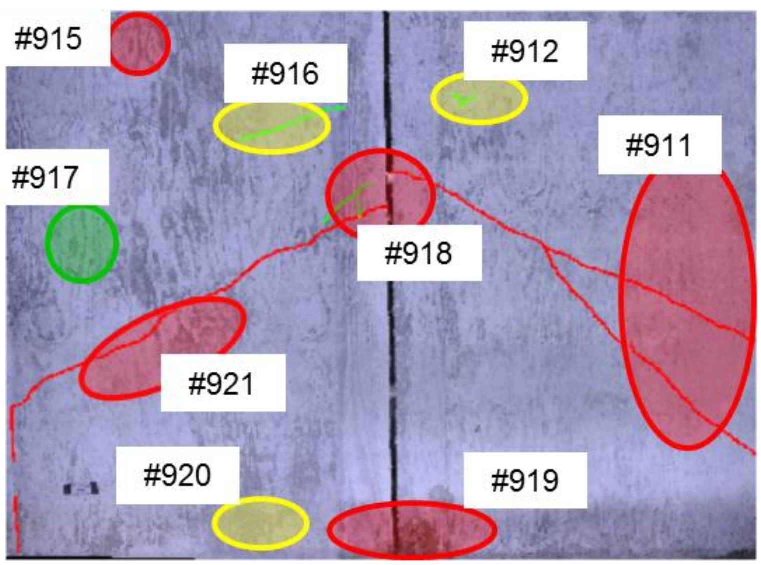


Figure 27: Infrared Inspection Result (Ceiling)

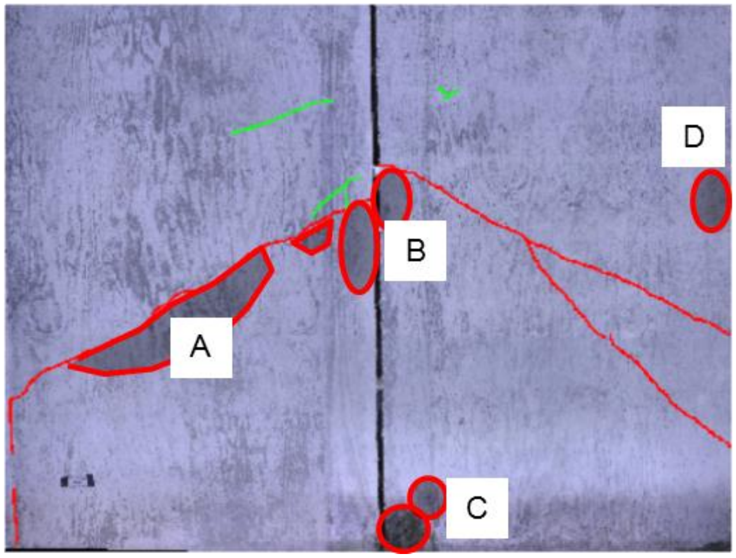


Figure 28: Hammer Sounding Test Result (Ceiling)

CHAPTER FOUR: PRACTICAL IMPLEMENTATION

As shown in chapter2, infrared thermography image technology is applicable during the periods when temperature differentials are detectable over time (Imagery period A and B in Figure 29). Since the accuracy of damage identification using infrared imagery is greatly affected by daily temperature variation, finding the appropriate periods is quite important. In current situation, in order to find out this period, equipment is used. Figure 30 shows the equipment “Concrete Test Piece” that is used to monitor the temperature condition on the concrete surface. 30cm×30cm size of concrete panel is attached to the bridge deck surface and simulated the subsurface cracks or delamination. Figure 31 shows the composition of the concrete test piece. The process to attach it to the bridge deck is first, fix the anchor plate with adhesive tapes, second, put the concrete panel inside the anchor plate and then, bolt the fixation plate. A temperature measurement sensor (Figure 32) is attached with the concrete plate for monitoring the concrete surface temperature of delaminated area, sound area and ambient temperature. It is necessary to monitor at least for twenty-four hours so that one-day temperature variation is obtained. The applicable condition is the periods there is 0.2 ºC temperature differentials between the delaminated concrete surface and sound concrete surface. In addition to that, 7 ºC diurnal range of temperature is ideal. In fact, inspection in pilot project, concrete test pieces were attached to the bridge deck to see if there was sufficient temperature difference between damaged and sound areas and when the period is prior to the inspection. However, this preparation work needs extra time and sometimes can be a difficulty, for example in case that the target bridge is quite far to go. Therefore, the way to estimate the appropriate period for the infrared inspection without visiting the target bridge is explored and developed in this research.

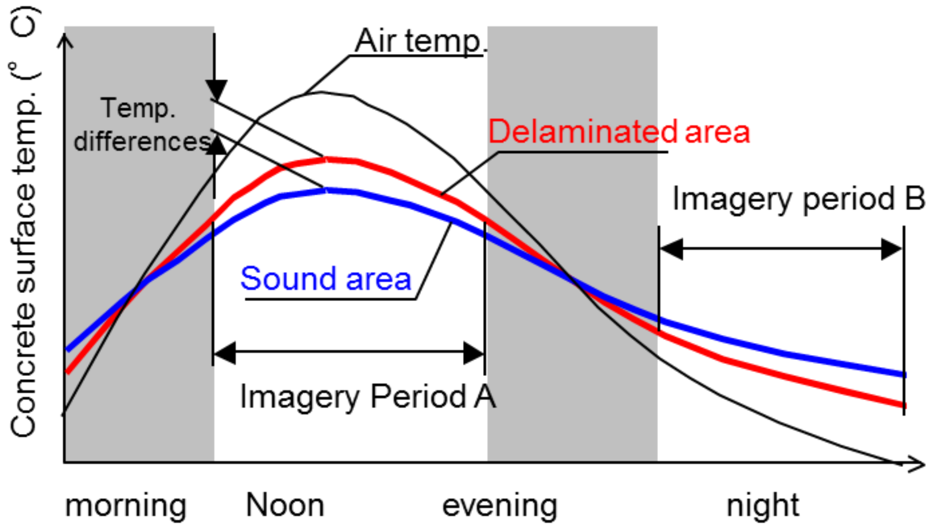


Figure 29: Temperature Variation of a Day

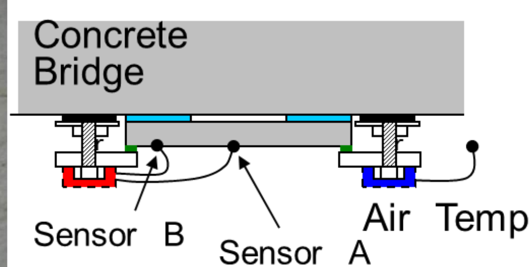



Figure 30: Concrete Test Piece for Temperature Monitoring

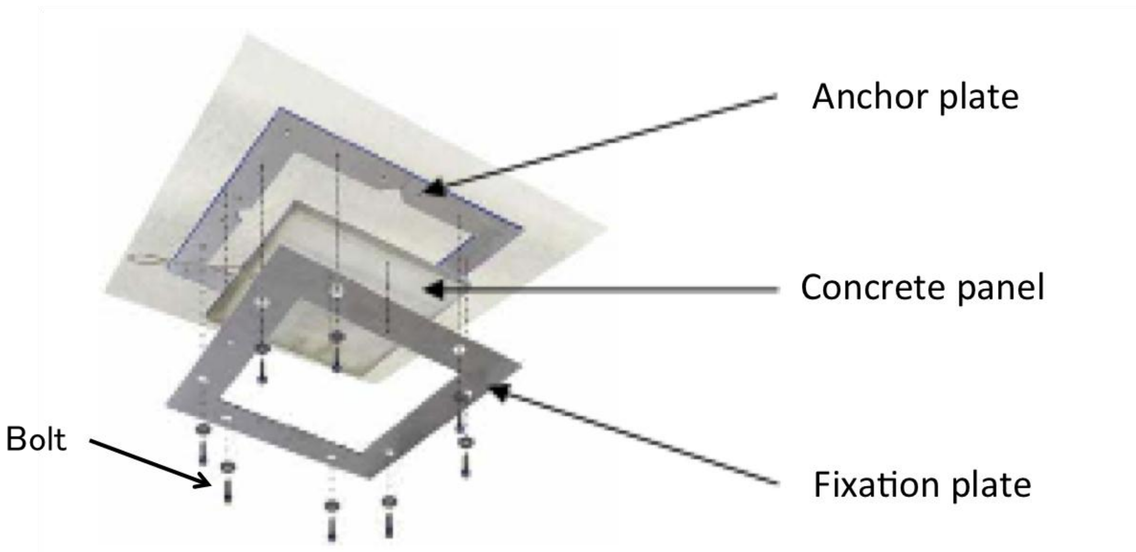


Figure 31: Composition of Concrete Test Piece

Figure 32: Temperature Measurement Sensor

Introduction

The main objective of this chapter is to find the way to estimate the appropriate period for the infrared inspection without visiting the target bridge. Even if it is impossible to visit the target bridge prior to the inspection, it is possible to monitor the temperature variation using concrete test piece in the neighborhood. Therefore, the method to estimate the temperature variation at the target bridge is investigated based on collected data using concrete test piece at the University of Central Florida and weather data around the university and bridge that is available from a website. Some experiments were conducted on the assumption that the bridge deck top and underside of the deck are inspected.

Field

The sample bridge in this experiment is No.180068 at I-75over SR44, which is provided for the experiment by FDOT District 5 (Figure 33-35). The bridge deck top and the underside of the deck were targeted for the experiment. Parking area paved with concrete at the university (Figure 36), which correspond in position to the bridge deck top, and the ceiling covered with concrete in the parking garage at the university (Figure 37), which correspond to the underside of the bridge deck were used to collect data.

Figure 33: Sample Bridge at I-75

Figure 34: Bridge Deck Top

Figure 35: Underside of Bridge Deck

Figure 36: Parking Area at University

Figure 37: Parking Garage at University

Equipment

Concrete test pieces in three different thicknesses were used. Each thickness is 1cm, 2cm and 3cm, which simulates delamination in the depth of 1.0cm, 2.0cm and 3.0cm from the concrete surface (Figure 38). In addition to that, concrete test pieces in three different depths of delamination were prepared to explore the difference of temperature variation in terms of the delamination volume (Figure 39). The delamination exists at 1cm from the concrete surface and each delamination depth is 0.5cm, 1.0cm and 1.5cm.

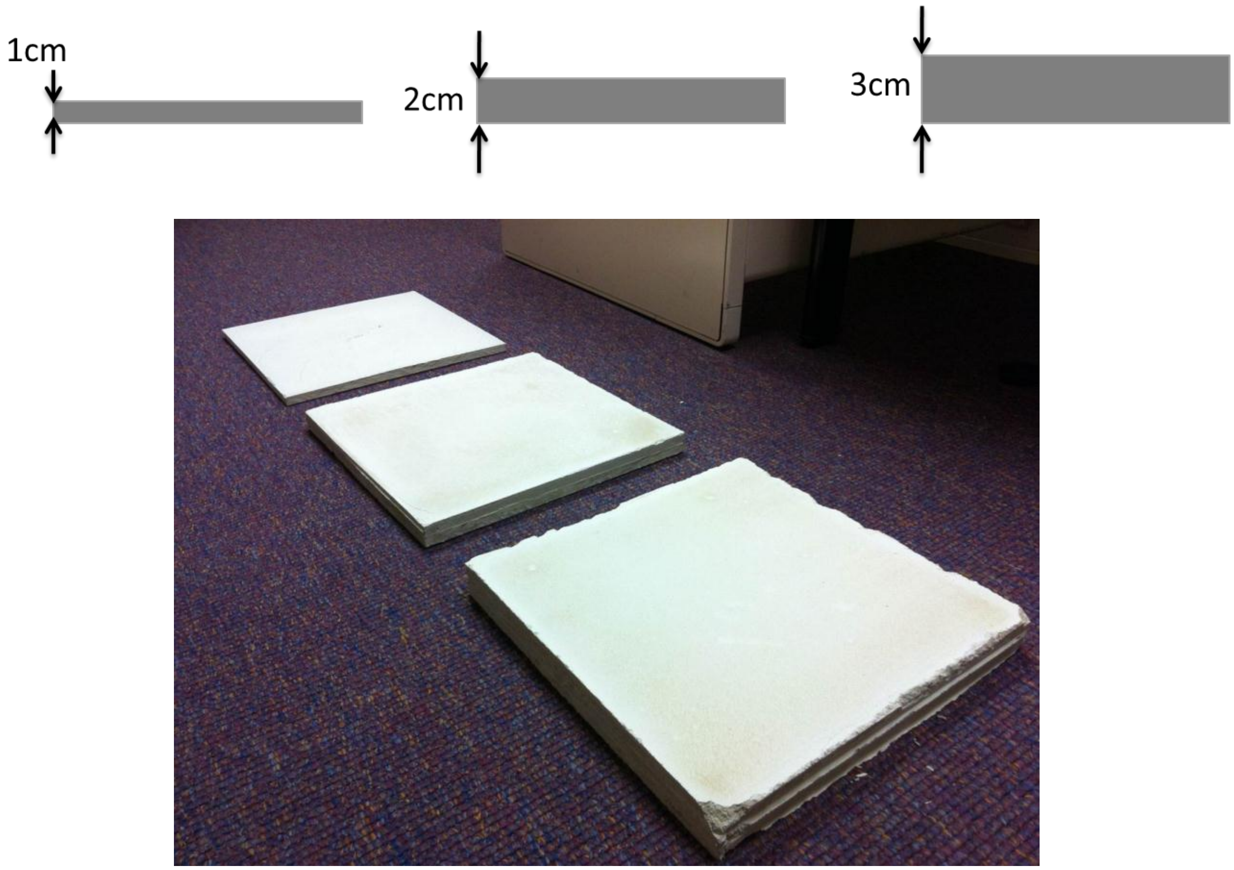


Figure 38: Concrete Test Pieces (Different Thickness)

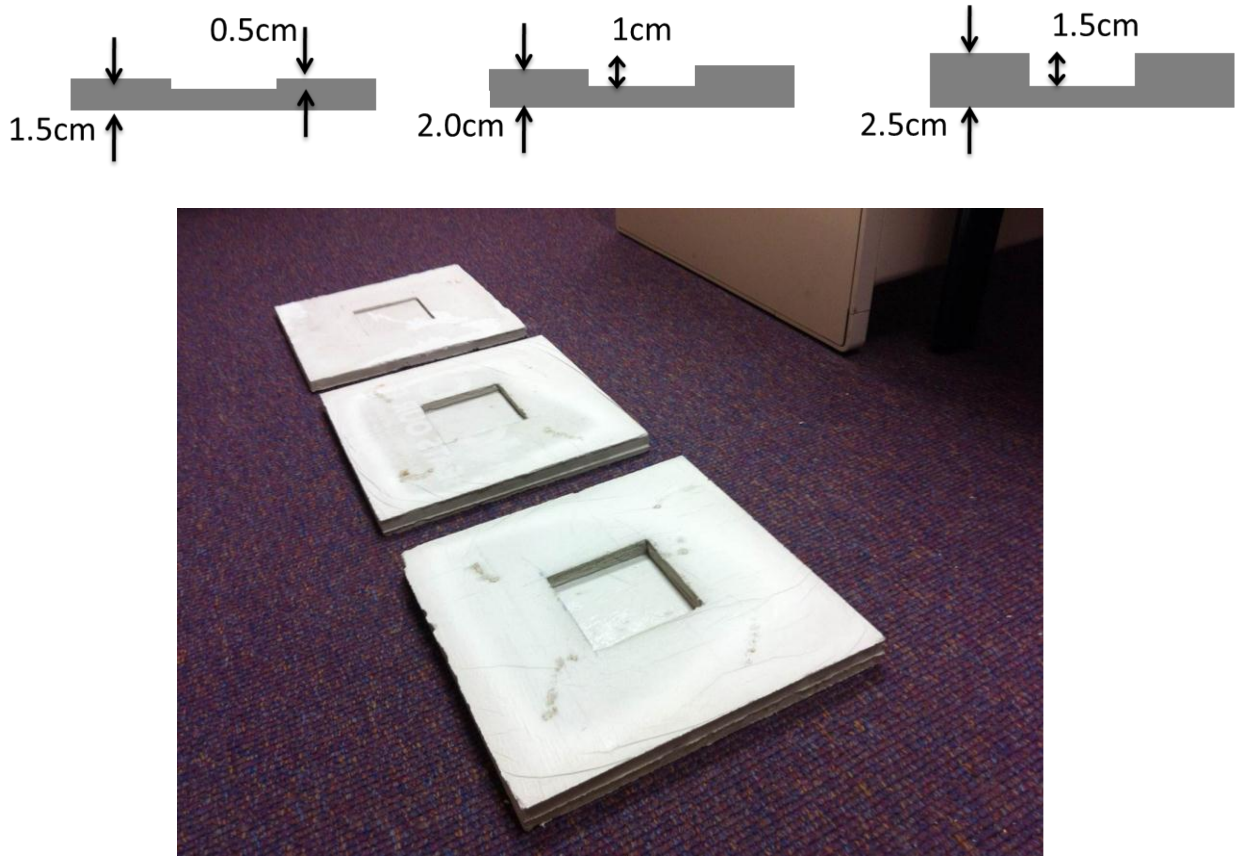


Figure 39: Concrete Test Pieces (Different Volume of Delamination)

Weather Station

The weather data used in this research is available from a website so that it can be used anytime if needed by anybody. The website is http://www.wunderground.com/. The data of 12:00 am, 6:00 am, 12:00 pm and 6:00 pm are accessible.

Data Acquisition

Figure 40 shows the data acquisition at each field. Concrete test pieces of three different thicknesses were attached to the surface of each target area and collected temperature variation for a certain period of time in March and April 2013. Concrete test pieces of three different volumes of delamination were placed at parking area in the university and explored the difference of temperature variation in terms of the delamination volume. Temperature measurement sensors were attached to the delaminated area and sound area on each concrete test piece, and the ambient air temperature was collected as well.

Bridge Deck Top

Underside of Bridge Deck

University Parking Area

University Parking Garage Ceiling

Figure 40: Data Acquisition

CAPTER FIVE: CALIBRATION APPROACHES FOR IR

Test Data

Table 4 shows the information on each data set. Concrete surface temperature of damaged area and sound area and ambient air temperature were collected at each location. Also the weather data at 0:00am, 6:00am, 12:00pm and 6:00pm at each location were obtained from a website. The obtained weather data are temperature, dew point, humidity, pressure, wind speed, wind direction, visibility, rainfall and clouds.

Table 4: Data Set

No.	Location	Date
1	UCF (Pavement at Parking Area), Orlando	3/19/2013-4/2/2013
2	Bridge (Deck Top), Wildwood	3/20/2013-4/3/2013
3	UCF (Ceiling at Parking Garage), Orlando	4/8/2013-4/15/2013
4	Bridge (Underside of Deck Top), Wildwood	4/3/2013-4/15/2013

*Bridge deck top (3cm, damaged) data is 3/20/2013-3/26/2013

Analysis

The analysis process is as follows. First, it was investigated which factors of weather data have affected the concrete surface temperature for each data set. However, it is assumed that temperature data from a website is always important factor. Additionally, since some factors, which are visibility, rainfall, didn't differ from day to day, and some factors, which are wind direction and clouds, are non-quantifiable factors, these factors were not chosen for analyses. Secondly, prediction formulae for concrete surface temperature variation were derived using the influential factors. Regression analysis method was used for this analysis. It begins by generating a linear model to describe the statistical relationship between some predictors (factors) and the response variable. Regression results indicate the statistical significance of the relationship between the predictors (factors) and the response variable. Then, as referring to the following variables, the analysis is conducted. P value for each predictor (factor) tests the null hypothesis that the coefficient is equal to zero, which means no effect. Therefore, low P values suggest that the predictor (factor) is a meaningful addition to the model. The coefficients (Coef) mean the numbers by which the variables in an equation are multiplied. Each coefficient estimates the change in the mean response per unit increase in X when all other predictors are held constant. Standard errors of coefficients (SE Coef) mean the standard deviation of the estimate of a regression coefficient. It measures how precisely the data can estimate the coefficient's unknown value. Its value is always positive, and smaller values indicate a more precise estimate. The standard error of the regression (S) is used as a measure of model fit in regression. The better the equation predicts the response, the lower the value of S. R-squared means the percentage of response variable variation that is explained by its relationship with some predictor (factor) variables. In general, the higher the R-squared, the better the model fits the data. Along with these variables, residual plots, which are histogram of the residuals, normal probability plot of residuals, residuals versus fitted values, and residuals versus order of data, are used to examine the goodness of model fit in regression. Residual is the difference between an observed value and its corresponding fitted value. Histogram of the residuals is an exploratory tool to show general characteristics of the residuals. As for the normal probability plot of residuals, the points should generally form a straight line if the residuals are normally distributed. As for the plot of residuals versus fitted values, it shows a random pattern of residuals on both sides of 0. There should not be any recognizable pattern in this plot. Residuals versus order of data is a plot of all residuals in the order that the data was collected and can be used to find non-random error, especially of time-related effects. The software used for regression analysis is Minitab 16. The process is summarized as follows.

1. To analyze the data on campus using all data to decide significant factors
2. To analyze the data on campus without insignificant factors
3. To analyze the data at the bridge using all data to decide significant factors
4. To analyze the data at the bridge without insignificant factors
5. To analyze the data at the bridge using both data on campus and at the bridge

Deck Top and Parking Area

In order to estimate the temperature variation of the bridge deck top, the collected temperature variation data using concrete test pieces which were placed on a parking area on campus, and the weather data at the location where the bridge and the campus locate.

1cm Thickness

Table 5-9 show the regression analysis results of 1cm thickness concrete test piece, damaged area. It is started by the first analysis with linear regression model. Table 5 shows the result on campus. The equation to calculate the concrete surface temperature of 1cm thickness, damaged area, or "Y" is presented. In this equation, all the factors are used to calculate the temperature variation. When looking at P value on the last line, the P value $\leq \alpha=0.05$, the linear model should be fine. Then, when looking at R-squared, it can be found if the model fits the data set. In general, the higher R-squared, the better the model fits the data. In this case, since the P value of this equation is 0, and the valued of R-squared is relative high, it can be said that the equation is fine and fits the data. However, when looking at P value of each factor (predictor), it can be found which factor affect to Y value. When the P value $\leq \alpha=0.05$, the factor should be significant. In this case, the P values of humidity, dew point and wind speed are relative high compared to $\alpha=0.05$. Therefore, it can be said that these factors are not significant. Figure 41 shows the residual plots for this model.

Table 5: Regression Analysis Result of 1cm Damaged Area on Campus with All Data

The regression equation					
$y = -364 + 1.41x^1 - 0.296x^2 + 0.53x^3 + 0.048x^4 + 12.1x^5 + 0.0263x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.40805	0.08347	16.87	0.000
x^2	Temperature from Website in Orlando	-0.2957	0.2420	-1.22	0.228
x^3	Humidity from Website in Orlando	0.529	7.777	0.07	0.946
x^4	Dew Point from Website in Orlando	0.0481	0.2526	0.19	0.850
x^5	Pressure from Website in Orlando	12.068	2.349	5.14	0.000
x^6	Wind Speed from Website in Orlando	0.02631	0.07321	0.36	0.721
S=2.05024					
R-Sq=95.9%					
P=0.000					

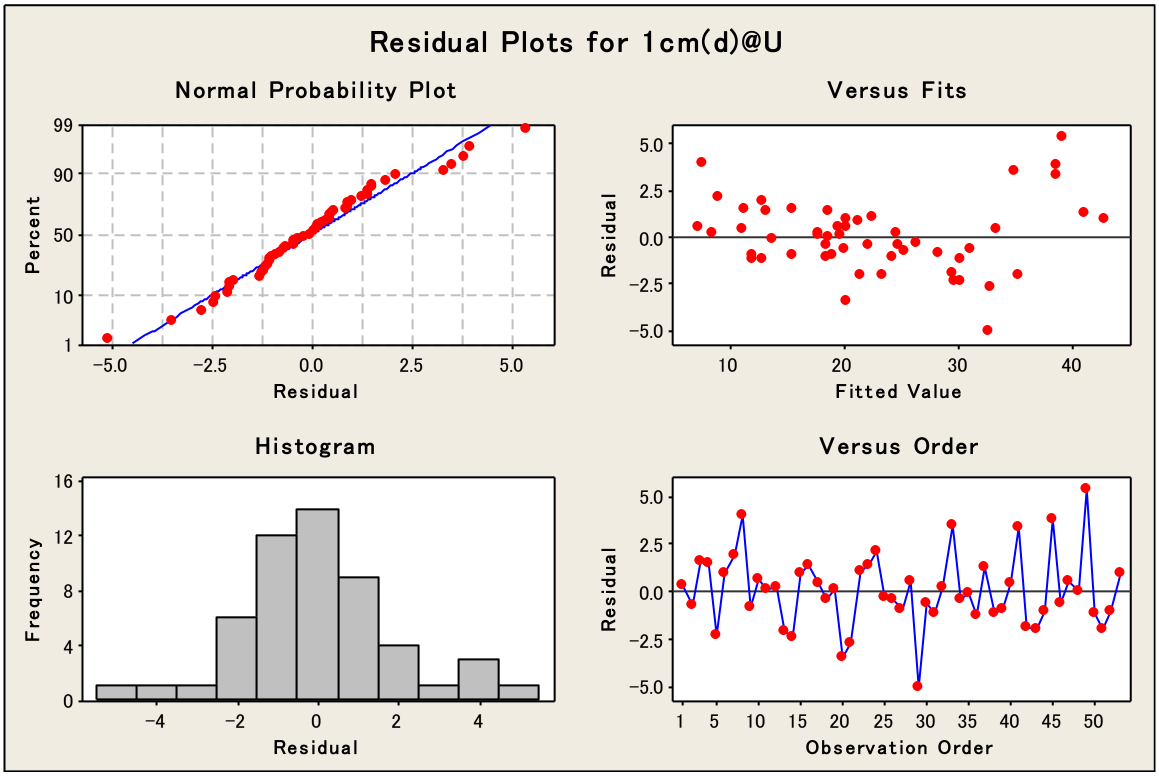


Figure 41: Residual Plots for 1cm Damaged Area on Campus with All Data

Secondly, the analysis without factors of humidity, dew point and wind speed was conducted, since these factors are not significant. Table 6 shows the result on campus without these three factors. When looking at R-squared, the value is not changed from the previous analysis. However, compared to the previous analysis, this equation has smaller number of factors, it is simpler than the previous one and it should be more reasonable. Since when looking at P value of each factor (predictor) and they are less than α=0.05, they are significant. Also when looking at the P value of this equation, it is 0 and it can be said that this equation is appropriate. Figure 42 shows the residual plots for this model.

Table 6: Regression Analysis Result of 1cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -316 + 1.39 x^1 - 0.259 x^2 + 10.5 x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.39015	0.07531	18.46	0.000
x^2	Temperature from Website in Orlando	-0.2588	0.1079	-2.40	0.020
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	10.475	1.826	5.74	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=2.02364					
R-Sq=95.7%					
P=0.000					

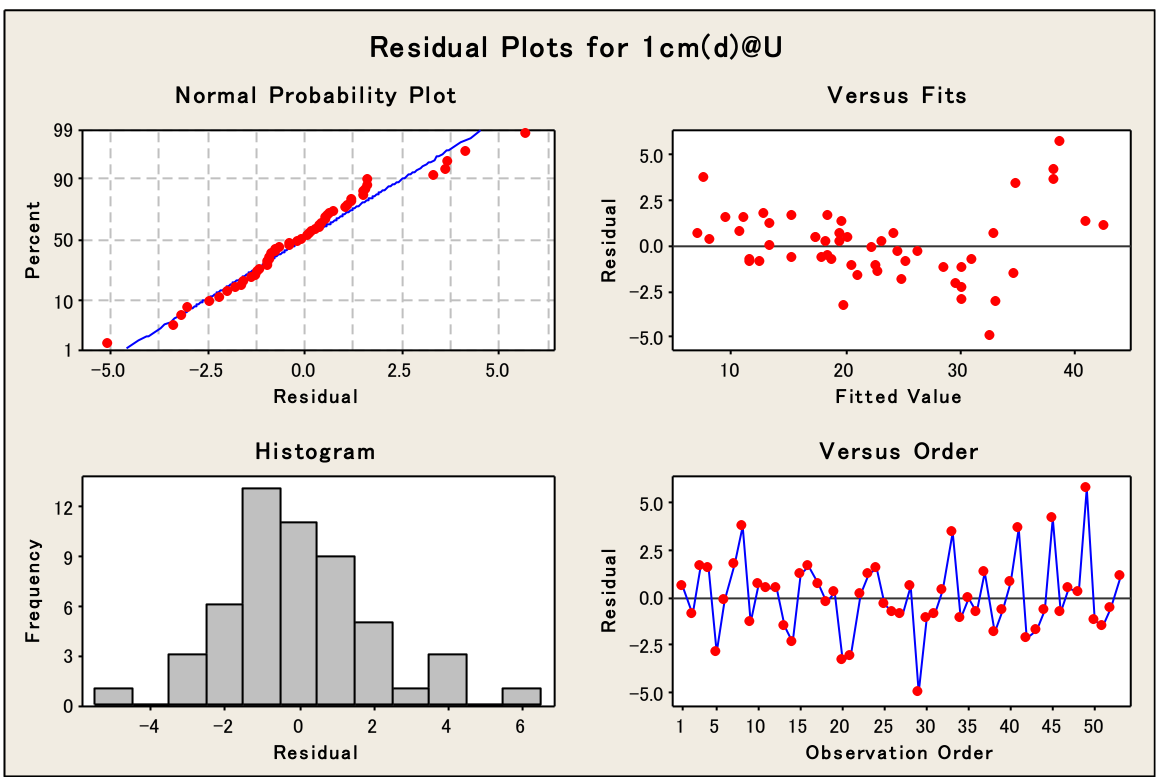


Figure 42: Residual Plots for 1cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

From previous two analyses, it is found that the equation using factors of ambient temperature, temperature and pressure from a website is applicable to estimate the temperature variation. Since those results are the temperature variation on campus, it is proceeded to the analysis at the bridge in Wildwood. The first analysis to decide significant factors is conducted. Table 7 shows the result at the bridge. The equation is to calculate the concrete surface temperature of 1cm, damaged area, which placed at the bridge. As mentioned above, this analysis is to decide the significant factors, in this analysis, all the factors are used to calculate the temperature variation as the first analysis of the data on campus. In this case, since the P value of this equation is 0, and the valued of R-squared is relative high, it can be said that the equation is fine and fits the data. However, when looking at P value of each factor (predictor), it can be found which factor affect to Y value. When the P value $\leq \alpha=0.05$, the factor should be significant. In this case, the P values of humidity, dew point and wind speed are relative high compared to $\alpha=0.05$. Therefore, it can be said that these factors are not significant. These findings are the same as the result of the data on campus.

Figure 43 shows the residual plots for this model.

Table 7: Regression Analysis Result of 1cm Damaged Area at Bridge with All Data

The regression equation					
$y = -96.5 + 1.16 x^1 - 0.173 x^2 - 2.01 x^3 + 0.041 x^4 + 3.30 x^5 + 0.0361 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.16094	0.04861	23.89	0.000
x^2	Temperature from Website in Wildwood	-0.1732	0.1271	-1.36	0.179
x^3	Humidity from Website in Wildwood	-2.015	3.472	-0.58	0.565
x^4	Dew Point from Website in Wildwood	0.0406	0.1164	0.35	0.729
x^5	Pressure from Website in Wildwood	3.303	1.233	2.68	0.010
x^6	Wind Speed from Website in Wildwood	0.03608	0.03683	0.98	0.332
S=1.03123					
R-Sq=98.8%					
P=0.000					

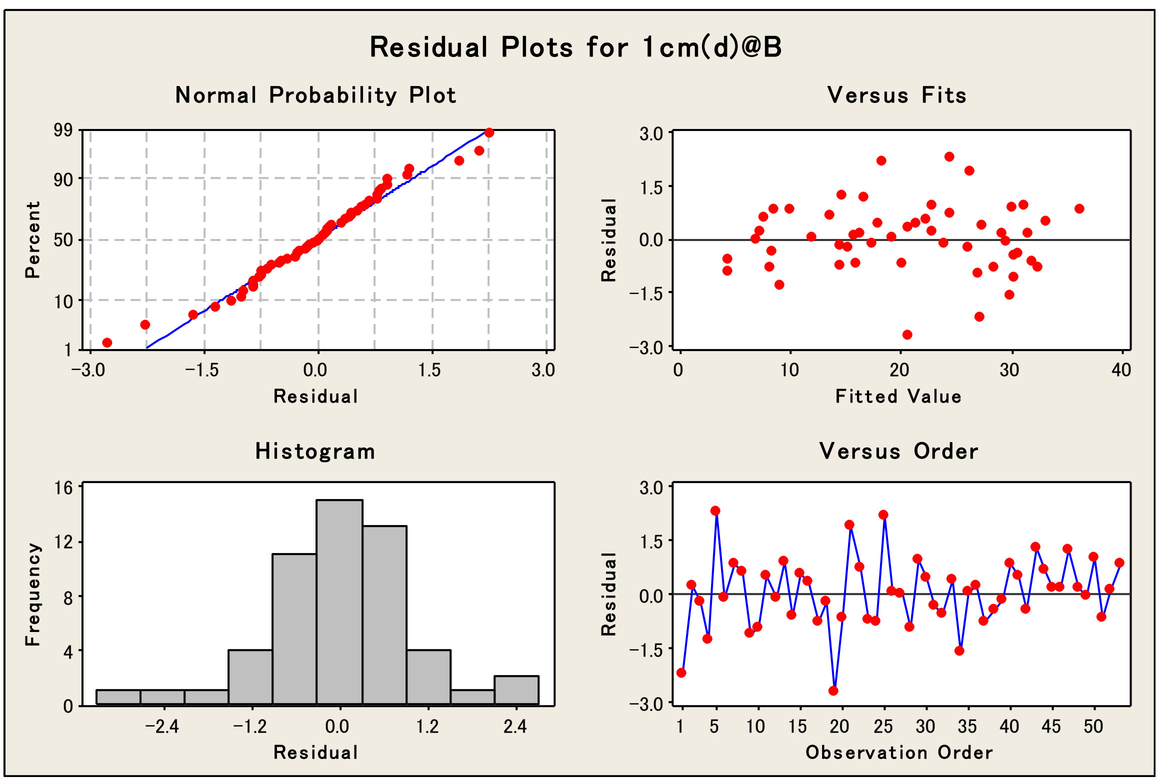


Figure 43: Residual Plots for 1cm Damaged Area at Bridge with All Data

Since insignificant factors are found in the first analysis, next analysis without insignificant factors, which are humidity, dew point and wind speed was conducted. Table 8 shows the result of the data at the bridge without these three factors. When looking at R-squared, the value is not changed from the previous analysis. However, compared to the previous analysis, this equation has smaller number of factors, it is simpler than the previous one and it should be more reasonable. Since when looking at P value of each factor (predictor) and they are less than α=0.05, it is found that they are significant. Also when looking at the P value of this equation, it is 0 and it can be said that this equation is appropriate. Figure 44 shows the residual plots for this model.

Table 8: Regression Analysis Result of 1cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -107 + 1.19x^1 - 0.138x^2 + 3.59x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.19147	0.04325	27.55	0.000
x^2	Temperature from Website in Wildwood	-0.13797	0.05752	-2.40	0.020
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	3.5928	0.9403	3.82	0.000
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=1.03617					
R-Sq=98.7%					
P=0.000					

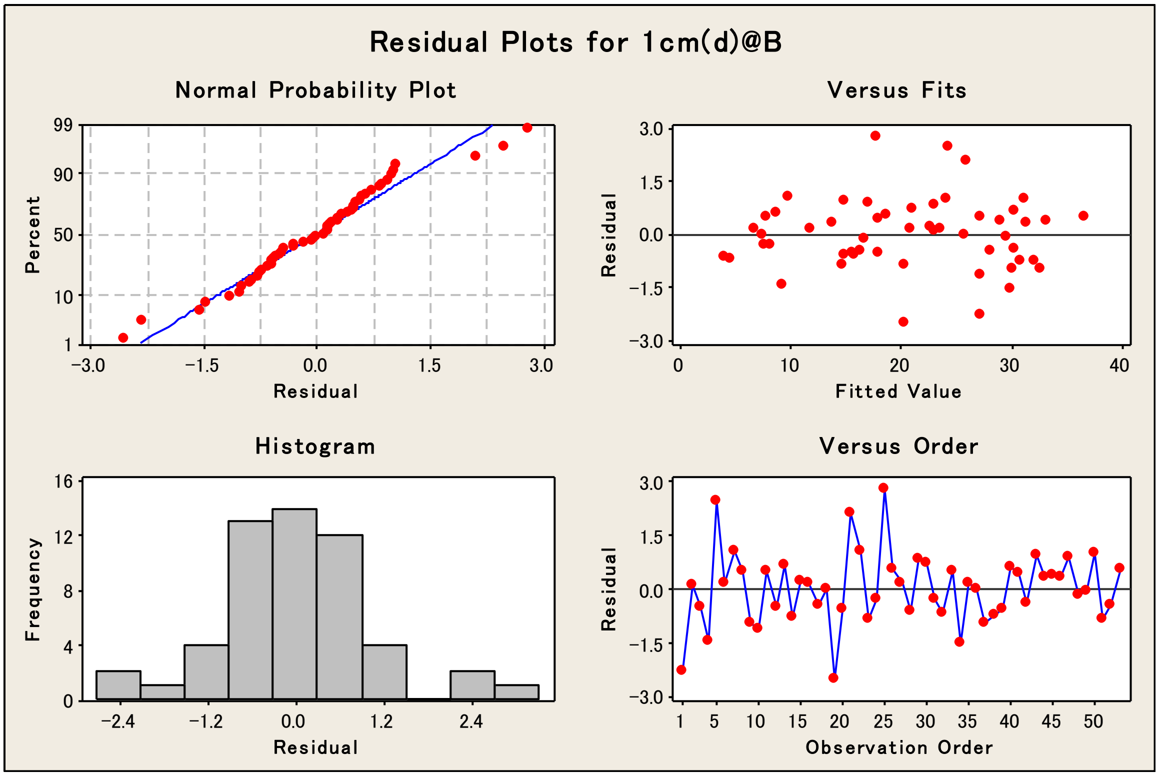


Figure 44: Residual Plots for 1cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

From the result of both on campus and at the bridge, it is found that ambient air temperature, temperature and pressure from a website affect the temperature of concrete surface. The final analysis is to calculate the concrete surface temperature of 1cm thickness, damaged area at the bridge using combination of data of both on campus and at the bridge. The factors used in this analysis are concrete temperature of 1cm, damaged area on campus, collected ambient temperature on campus, temperature and pressure in Orlando and Wildwood from a website. As a result, the equation was derived as shown in Table 9. In this result, since P value of this equation is 0 and the R-squared is relative high, it can be said that the equation is appropriate, although the P values of each factors are bigger than α=0.05.

Table 9: Regression Analysis Result of 1cm Damaged Area at Bridge (Final)

The regression equation					
$y = - 335 - 0.284\ x^1 + 1.11\ x^2 + 0.246\ x^3 + 10.8\ x^4 + 0.259\ x^5 + 0.24\ x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 1cm Damaged Area at UCF	-0.2839	0.1730	-1.64	0.108
x^2	Ambient Air Temperature at UCF	1.1112	0.2573	4.32	0.000
x^3	Temperature from Website in Orlando	0.2459	0.2138	1.15	0.256
x^4	Pressure from Website in Orlando	10.762	6.542	1.65	0.107
x^5	Temperature from Website in Wildwood	0.2595	0.1721	1.51	0.138
x^6	Pressure from Website in Wildwood	0.244	6.430	0.04	0.970
S=2.44796					
R-Sq=93.2%					
P=0.000					

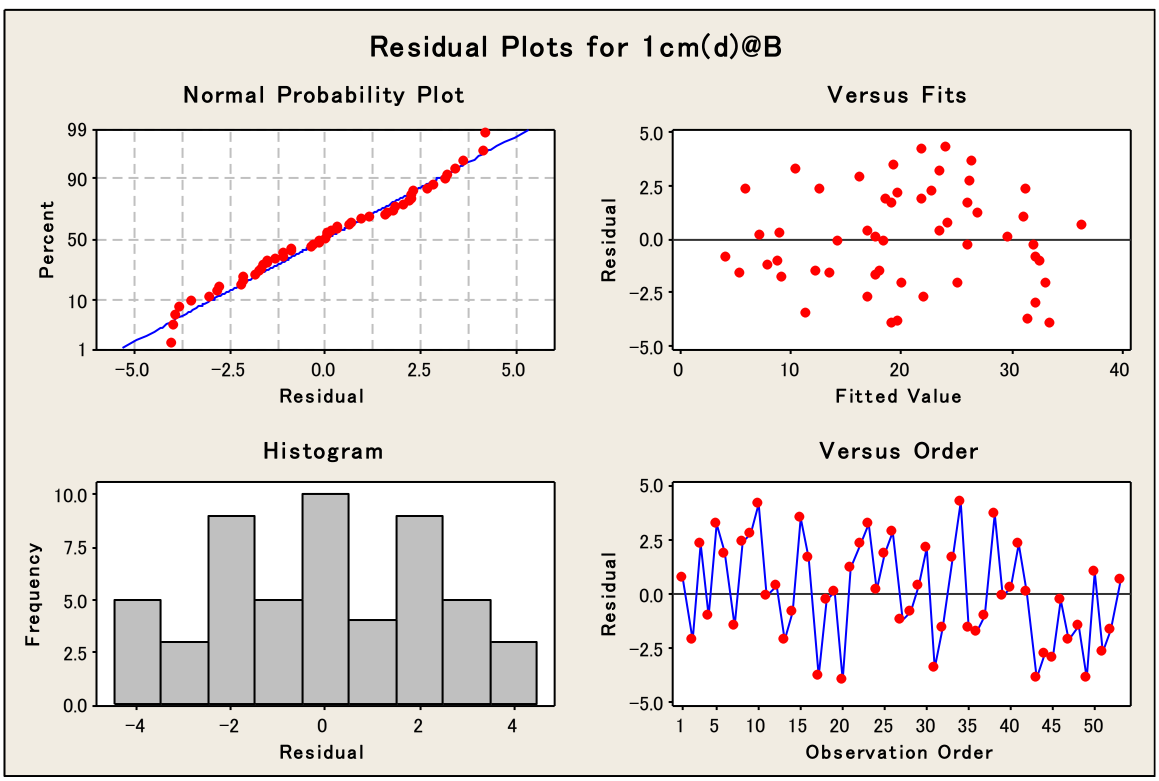


Figure 45: Residual Plots for 1cm Damaged Area at Bridge (Final)

Same analyses as that of damaged area were conducted for sound area. The process is as follows.

1. To analyze the data on campus using all data to decide significant factors

2. To analyze the data on campus without insignificant factors

3. To analyze the data at the bridge using all data to decide significant factors

4. To analyze the data at the bridge without insignificant factors

5. To analyze the data at the bridge using both data on campus and at the bridge

Tables 10-14 and Figures 46-50 show the results of each step. In these analyses, the same finding as that of damaged area was obtained. That is to say, both on campus and at the bridge, factors of humidity, dew point and wind speed are not significant to calculate the concrete surface temperature.

Table 10: Regression Analysis Result of 1cm Sound Area on Campus with All Data

The regression equation					
$y = - 231 + 1.43 x^1 - 0.404 x^2 - 0.71 x^3 + 0.036 x^4 + 7.72 x^5 + 0.0265 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.43008	0.08539	16.75	0.000
x^2	Temperature from Website in Orlando	-0.4037	0.2476	-1.63	0.11
x^3	Humidity from Website in Orlando	-0.714	7.956	-0.09	0.929
x^4	Dew Point from Website in Orlando	0.036	0.2584	0.14	0.89
x^5	Pressure from Website in Orlando	7.721	2.403	3.21	0.002
x^6	Wind Speed from Website in Orlando	0.02649	0.07489	0.35	0.725
S=2.09725					
R-Sq=95.6%					
P=0.000					

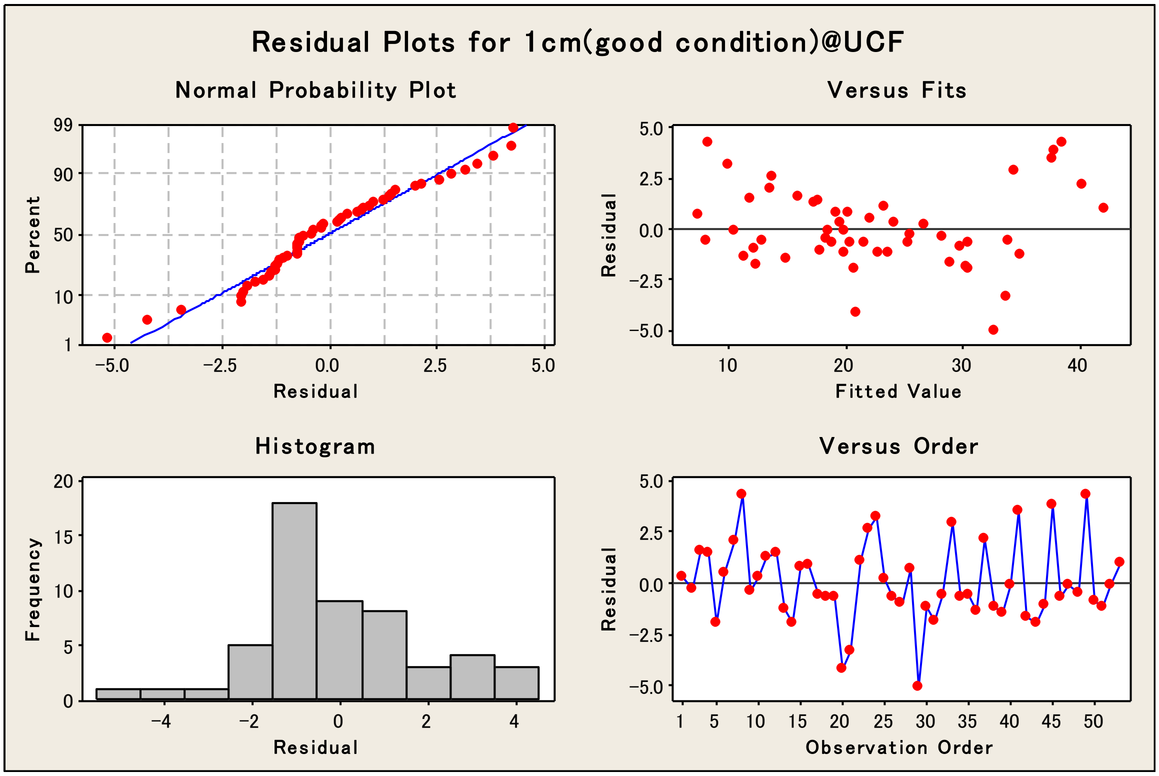


Figure 46: Residual Plots for 1cm Sound Area on Campus with All Data

Table 11: Regression Analysis Result of 1cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -217 + 1.44\ x^1 - 0.377\ x^2 + 7.23\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.43635	0.07581	18.95	0.000
x^2	Temperature from Website in Orlando	-0.3773	0.1086	-3.47	0.001
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	7.232	1.838	3.93	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=2.03708					
R-Sq=95.6%					
P=0.000					

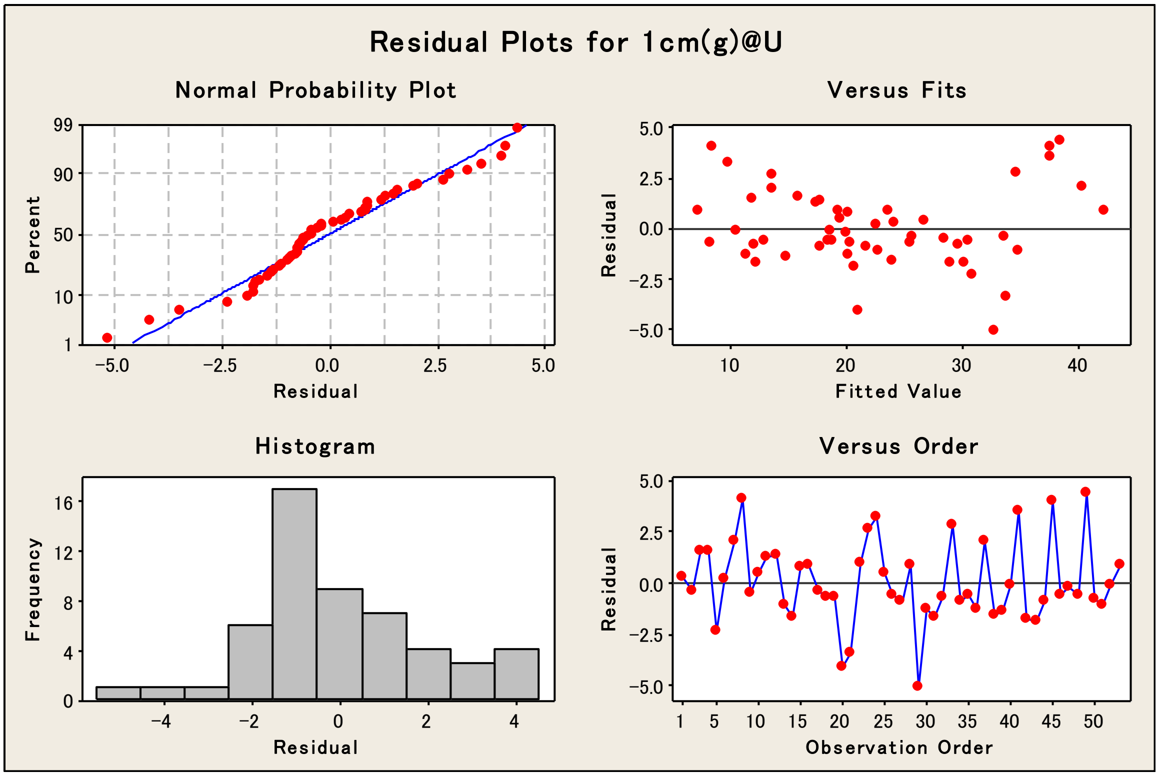


Figure 47: Residual Plots for 1cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

Table 12: Regression Analysis Result of 1cm Sound Area at Bridge with All Data

The regression equation					
$y = -64.4 + 1.14x^1 - 0.239x^2 - 3.33x^3 + 0.049x^4 + 2.32x^5 + 0.0397x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.14035	0.04815	23.68	0.000
x^2	Temperature from Website in Wildwood	-0.2392	0.1259	-1.90	0.064
x^3	Humidity from Website in Wildwood	-3.331	3.440	-0.97	0.338
x^4	Dew Point from Website in Wildwood	0.0487	0.1153	0.42	0.675
x^5	Pressure from Website in Wildwood	2.323	1.221	1.90	0.063
x^6	Wind Speed from Website in Wildwood	0.03966	0.03648	1.09	0.283
S=1.02159					
R-Sq=98.7%					
P=0.000					

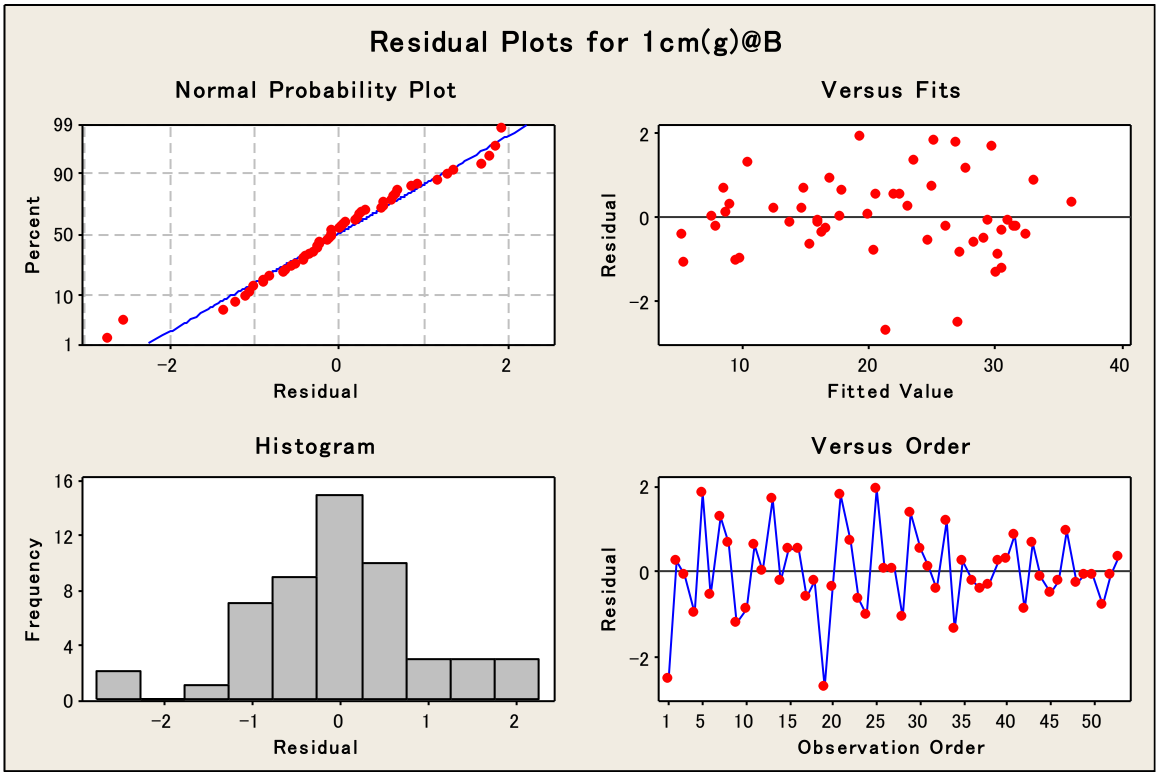


Figure 48: Residual Plots for 1cm Sound Area at Bridge with All Data

Table 13: Regression Analysis Result of 1cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -97.0 + 1.20\,x^1 - 0.203\,x^2 + 3.31\,x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.19919	0.04535	26.45	0.000
x^2	Temperature from Website in Wildwood	-0.20275	0.06031	-3.36	0.002
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	3.3063	0.9859	3.35	0.002
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=1.08636					
R-Sq=98.5%					
P=0.000					

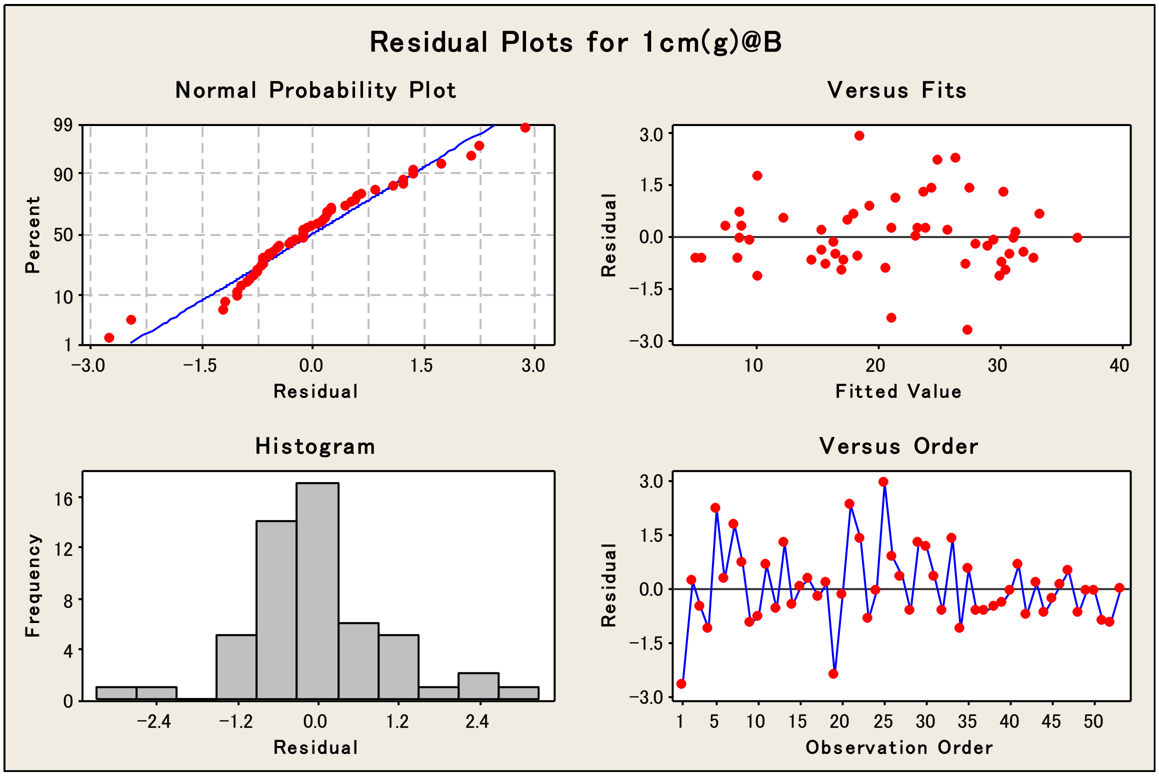


Figure 49: Residual Plots for 1cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

Table 14: Regression Analysis Result of 1cm Sound Area at Bridge (Final)

The regression equation					
$y = -249 - 0.120\, x^1 + 0.911\, x^2 + 0.148\, x^3 + 6.30\, x^4 + 0.286\, x^5 + 1.90\, x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 1cm Sound Area at UCF	-0.1198	0.1844	-0.65	0.519
x^2	Ambient Air Temperature at UCF	0.9115	0.2825	3.23	0.002
x^3	Temperature from Website in Orlando	0.1483	0.2342	0.63	0.530
x^4	Pressure from Website in Orlando	6.296	6.884	0.91	0.365
x^5	Temperature from Website in Wildwood	0.2860	0.1846	1.55	0.128
x^6	Pressure from Website in Wildwood	1.904	6.904	0.28	0.784
S=2.62843					
R-Sq=91.6%					
P=0.000					

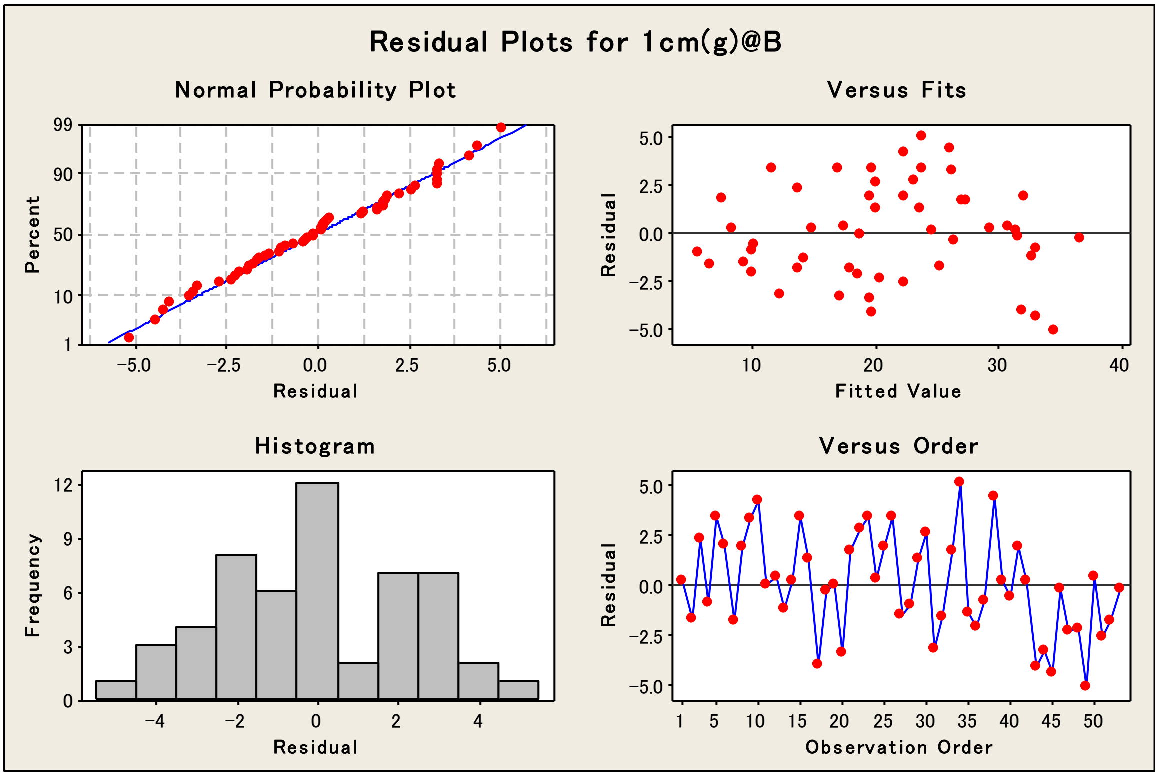


Figure 50: Residual Plots for 1cm Sound Area at Bridge (Final)

2cm Thickness

Same analyses as that of 1cm thickness concrete test piece were conducted for 2cm thickness concrete test piece. The process is as follows and these analyses were conducted for damaged area and sound area.

1. To analyze the data on campus using all data to decide significant factors

2. To analyze the data on campus without insignificant factors

3. To analyze the data at the bridge using all data to decide significant factors

4. To analyze the data at the bridge without insignificant factors

5. To analyze the data at the bridge using both data on campus and at the bridge

Tables 15-19 and Figures 51-55 show the results of each step for damaged area. Tables 20-24 and Figures 56-60 show the results of each step for sound area. In these analyses, the same finding as that of 1cm thickness concrete test piece was obtained. That is to say, for both damaged and sound area, both on campus and at the bridge, factors of humidity, dew point and wind speed are not significant to calculate the concrete surface temperature.

Table 15: Regression Analysis Result of 2cm Damaged Area on Campus with All Data

The regression equation					
$y = - 311 + 1.22 x^1 - 0.025 x^2 + 2.77 x^3 - 0.053 x^4 + 10.2 x^5 + 0.0064 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.22187	0.07478	16.34	0.000
x^2	Temperature from Website in Orlando	-0.0249	0.2168	-0.12	0.909
x^3	Humidity from Website in Orlando	2.770	6.967	0.40	0.693
x^4	Dew Point from Website in Orlando	-0.0534	0.2263	-0.24	0.814
x^5	Pressure from Website in Orlando	10.222	2.104	4.86	0.000
x^6	Wind Speed from Website in Orlando	0.00644	0.06559	0.10	0.922
S=1.83670					
R-Sq=96.2%					
P=0.000					

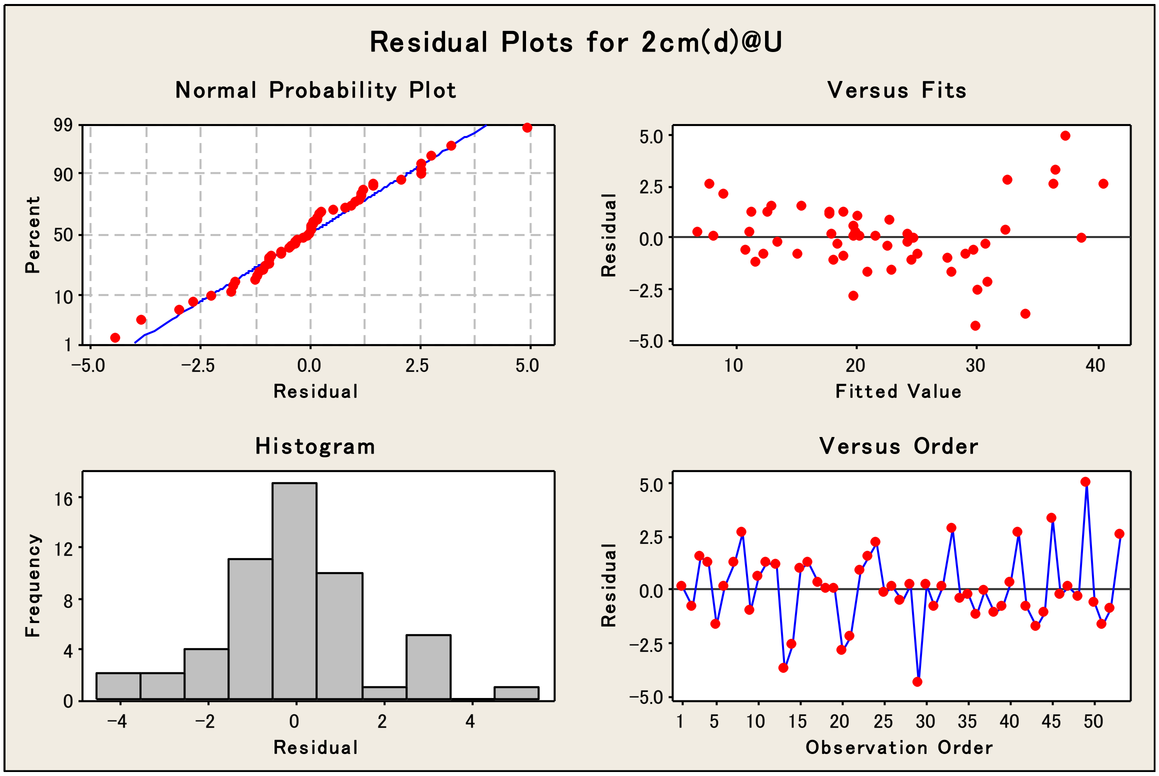


Figure 51: Residual Plots for 2cm Damaged Area on Campus with All Data

Table 16: Regression Analysis Result of 2cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -281 + 1.20x^1 - 0.0705x^2 + 9.31x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.20046	0.06679	17.97	0.000
x^2	Temperature from Website in Orlando	-0.07046	0.09569	-0.74	0.465
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	9.309	1.620	5.75	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=1.79470					
R-Sq=96.2%					
P=0.000					

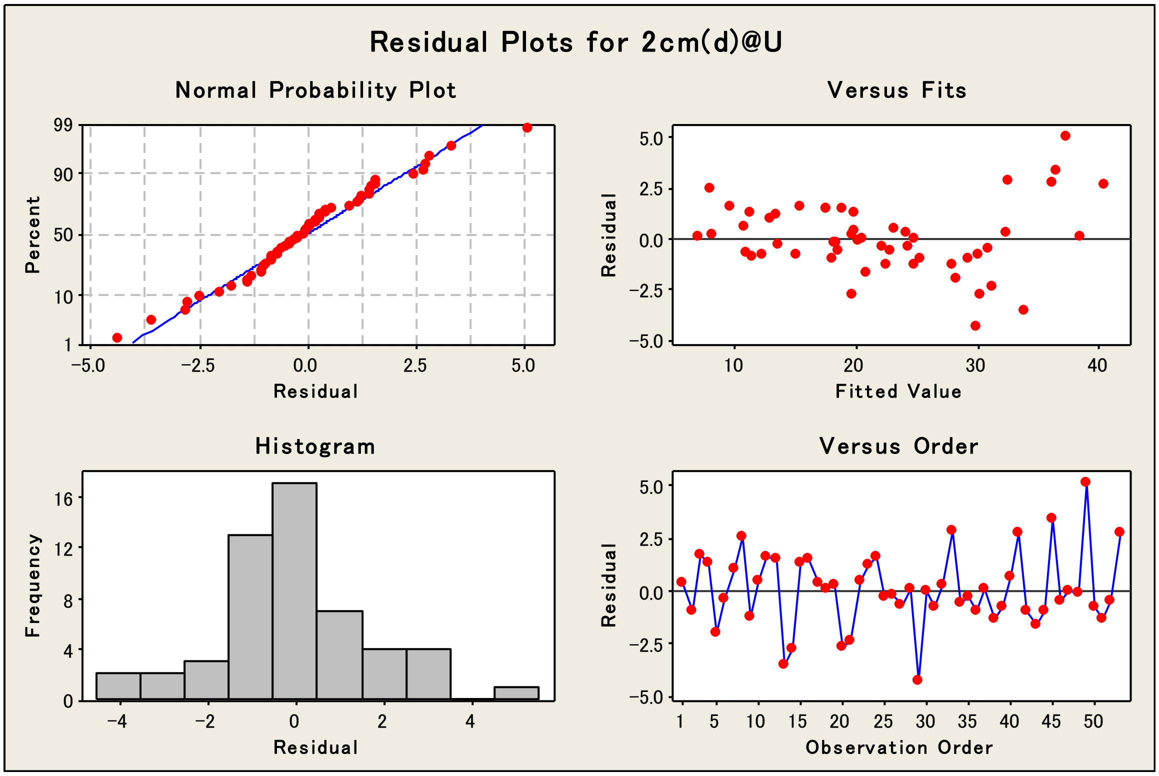


Figure 52: Residual Plots for 2cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

Table 17: Regression Analysis Result of 2cm Damaged Area at Bridge with All Data

The regression equation					
$y = -75.2 + 1.17x^1 - 0.174x^2 - 2.73x^3 + 0.026x^4 + 2.62x^5 + 0.0200x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.16665	0.05560	20.98	0.000
x^2	Temperature from Website in Wildwood	-0.1743	0.1454	-1.20	0.237
x^3	Humidity from Website in Wildwood	-2.728	3.972	-0.69	0.496
x^4	Dew Point from Website in Wildwood	0.0265	0.1332	0.20	0.843
x^5	Pressure from Website in Wildwood	2.618	1.410	1.86	0.070
x^6	Wind Speed from Website in Wildwood	0.01999	0.04213	0.47	0.637
S=1.17963					
R-Sq=98.5%					
P=0.000					

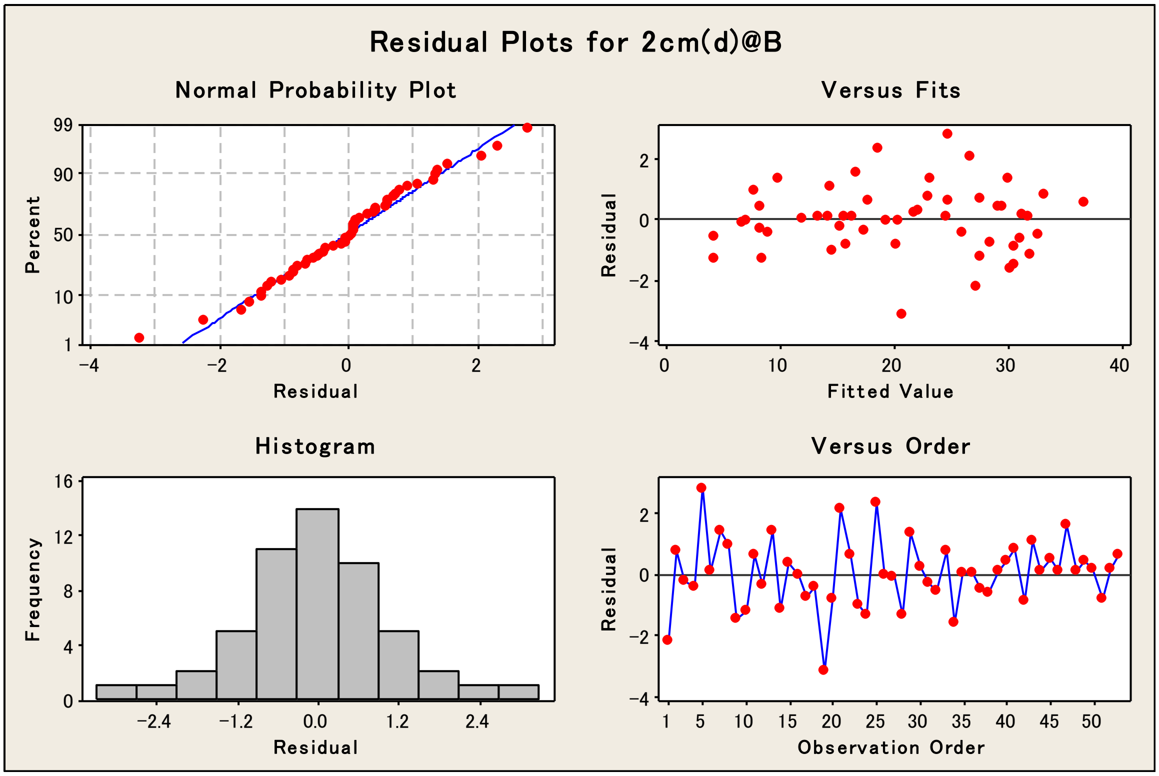


Figure 53: Residual Plots for 2cm Damaged Area at Bridge with All Data

Table 18: Regression Analysis Result of 2cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -112 + 1.22\ x^{1} - 0.160\ x^{2} + 3.77\ x^{5}$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.22147	0.05033	24.27	0.000
x^2	Temperature from Website in Wildwood	-0.16020	0.06693	-2.39	0.021
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	3.773	1.094	3.45	0.001
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=1.20568					
R-Sq=98.3%					
P=0.000					

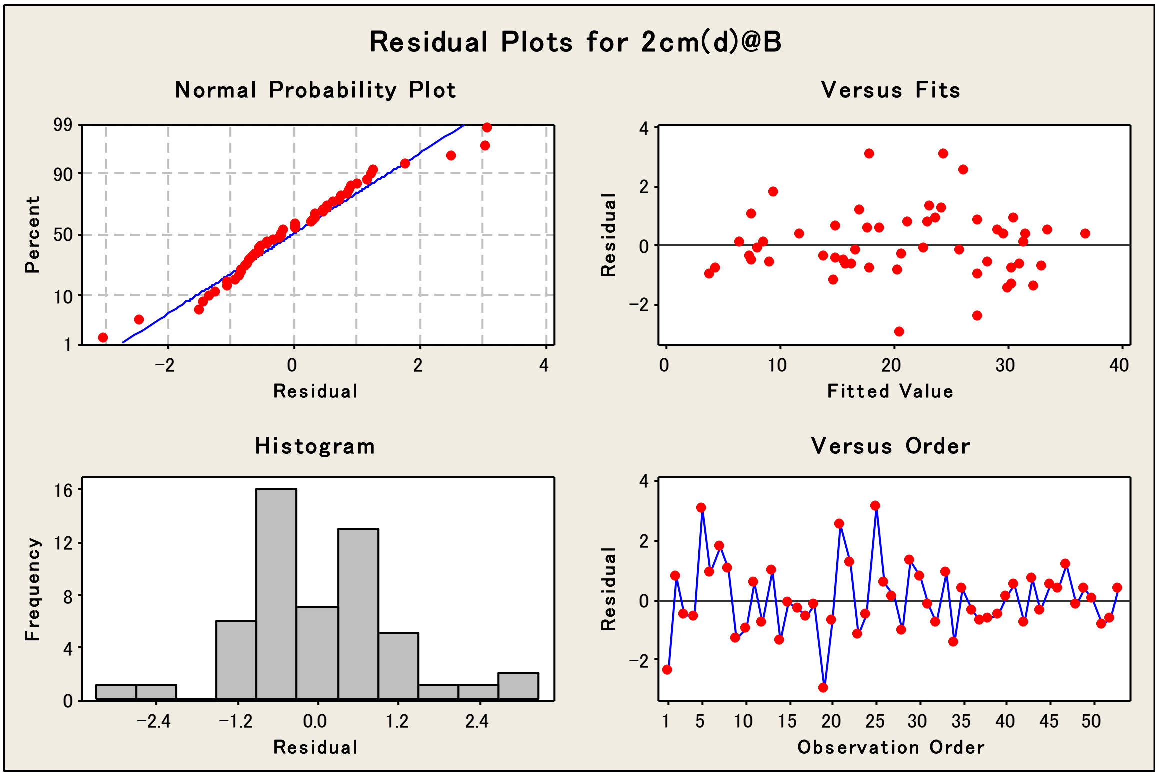


Figure 54: Residual Plots for 2cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

Table 19: Regression Analysis Result of 2cm Damaged Area at Bridge (Final)

The regression equation					
$y = -287 - 0.162 x^1 + 0.964 x^2 + 0.222 x^3 + 9.25 x^4 + 0.287 x^5 + 0.16 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 2cm Damaged Area at UCF	-0.1621	0.2066	-0.78	0.437
x^2	Ambient Air Temperature at UCF	0.9641	0.2658	3.63	0.001
x^3	Temperature from Website in Orlando	0.2221	0.2208	1.01	0.320
x^4	Pressure from Website in Orlando	9.251	6.906	1.34	0.187
x^5	Temperature from Website in Wildwood	0.2867	0.1821	1.57	0.122
x^6	Pressure from Website in Wildwood	0.159	6.794	0.02	0.981
S=2.58644					
R-Sq=92.6%					
P=0.000					

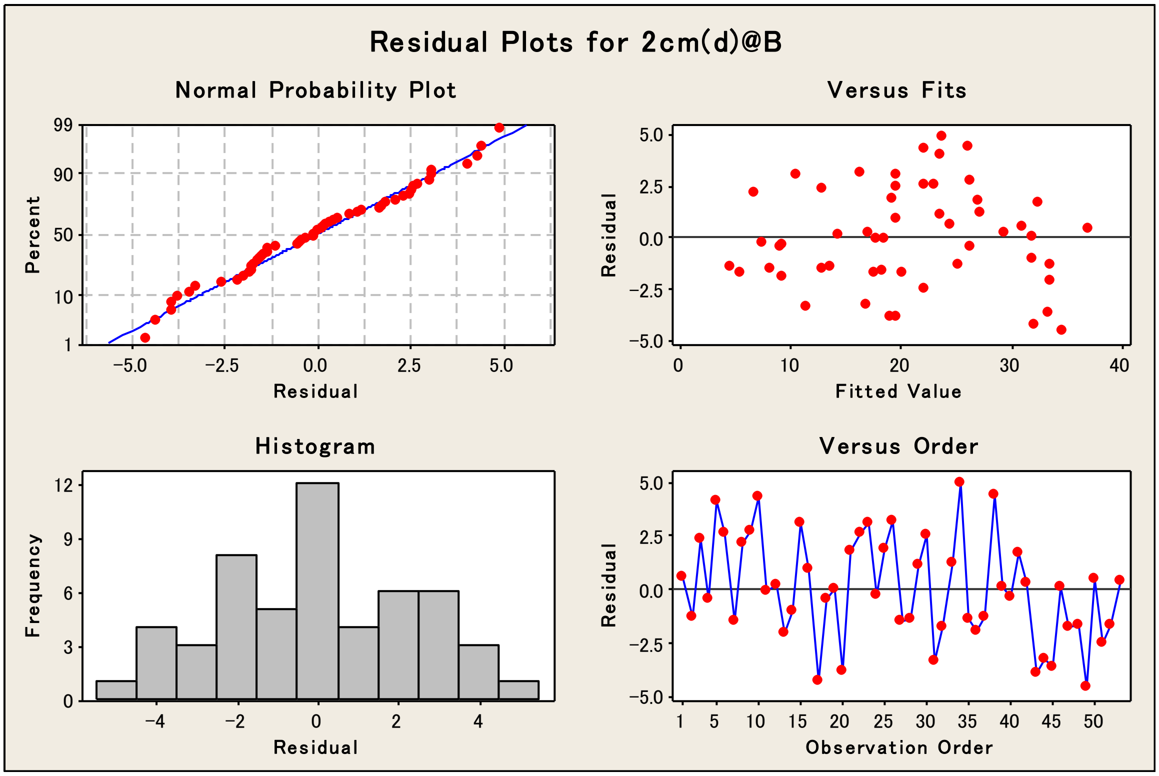


Figure 55: Residual Plots for 2cm Damaged Area at Bridge (Final)

Table 20: Regression Analysis Result of 2cm Sound Area on Campus with All Data

The regression equation					
$y = -215 + 1.11\,x^1 - 0.077\,x^2 - 1.08\,x^3 + 0.028\,x^4 + 7.18\,x^5 + 0.0131\,x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.11261	0.05054	22.01	0.000
x^2	Temperature from Website in Orlando	-0.0768	0.1465	-0.52	0.603
x^3	Humidity from Website in Orlando	-1.078	4.709	-0.23	0.820
x^4	Dew Point from Website in Orlando	0.0281	0.1530	0.18	0.855
x^5	Pressure from Website in Orlando	7.182	1.422	5.05	0.000
x^6	Wind Speed from Website in Orlando	0.01308	0.04433	0.30	0.769
S=1.24134					
R-Sq=98.0%					
P=0.000					

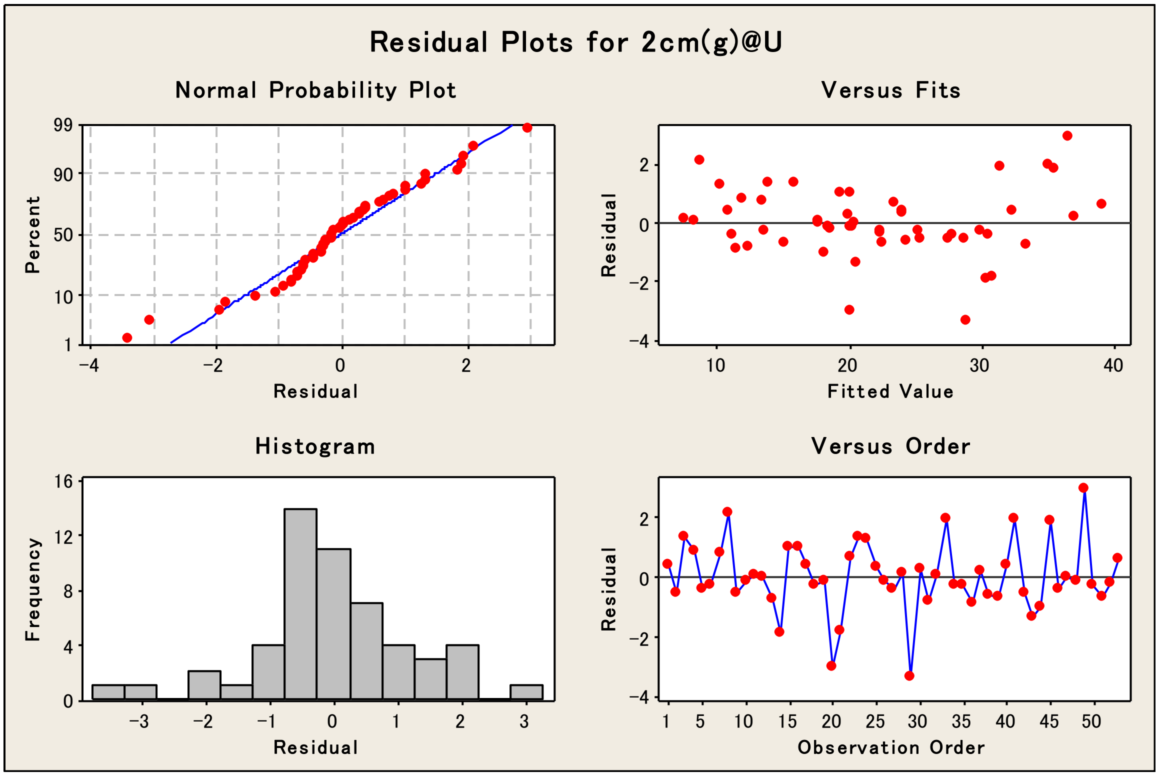


Figure 56: Residual Plots for 2cm Sound Area on Campus with All Data

Table 21: Regression Analysis Result of 2cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -217 + 1.12\,x^1 - 0.0552\,x^2 + 7.24\,x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.12325	0.04490	25.02	0.000
x^2	Temperature from Website in Orlando	-0.05517	0.06433	-0.86	0.395
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	7.237	1.089	6.65	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=1.20652					
R-Sq=98.0%					
P=0.000					

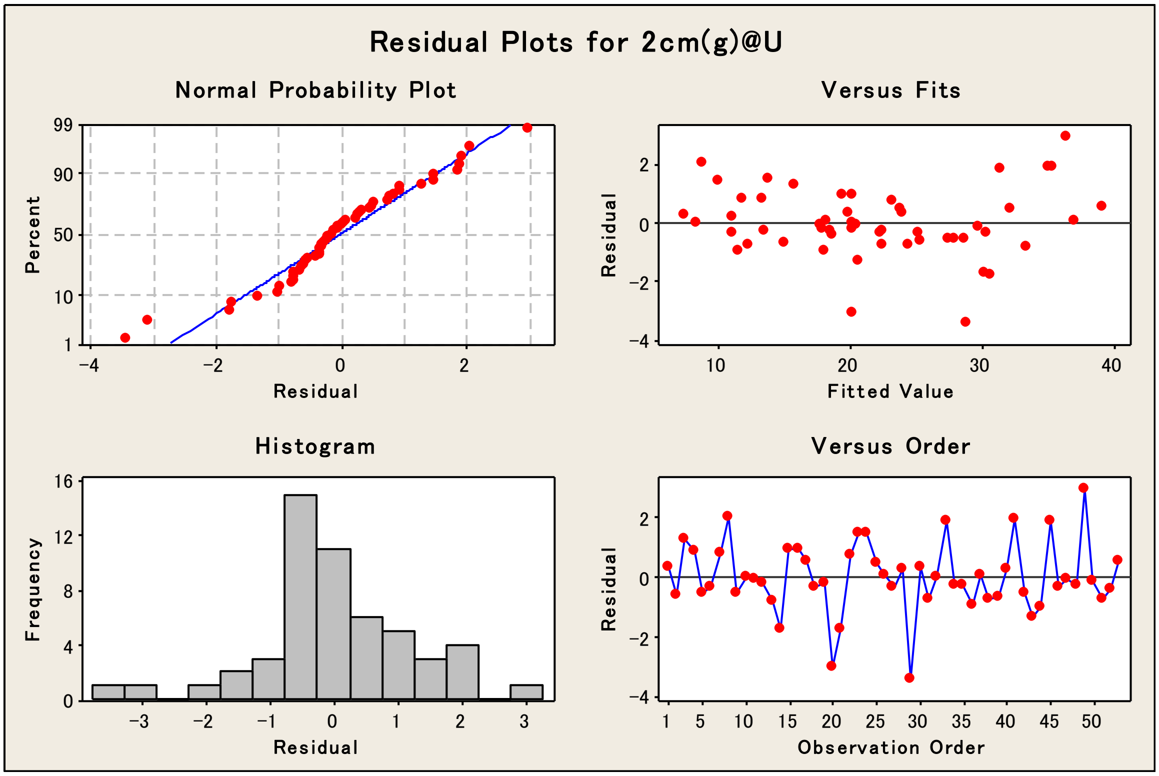


Figure 57: Residual Plots for 2cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

Table 22: Regression Analysis Result of 2cm Sound Area at Bridge with All Data

The regression equation					
$y = -43.1 + 1.01\ x^1 + 0.034\ x^2 - 0.53\ x^3 - 0.0710\ x^4 + 1.50\ x^5 - 0.0030\ x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.01043	0.04084	24.74	0.000
x^2	Temperature from Website in Wildwood	0.0336	0.1068	0.31	0.754
x^3	Humidity from Website in Wildwood	-0.533	2.918	-0.18	0.856
x^4	Dew Point from Website in Wildwood	-0.07104	0.09782	-0.73	0.471
x^5	Pressure from Website in Wildwood	1.505	1.036	1.45	0.153
x^6	Wind Speed from Website in Wildwood	-0.00301	0.03094	-0.10	0.923
S=0.866449					
R-Sq=99.1%					
P=0.000					

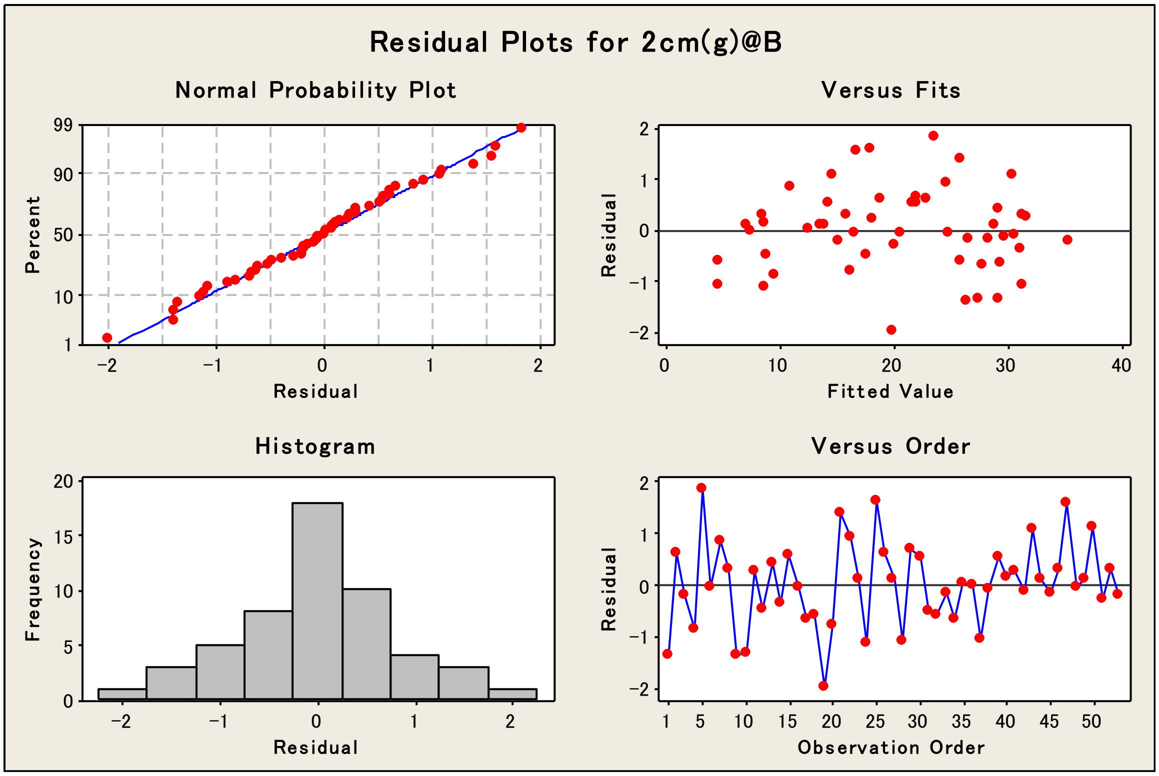


Figure 58: Residual Plots for 2cm Sound Area at Bridge with All Data

Table 23: Regression Analysis Result of 2cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -95.6 + 1.08\,x^1 - 0.0518\,x^2 + 3.23\,x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.07553	0.03929	27.37	0.000
x^2	Temperature from Website in Wildwood	-0.05182	0.05226	-0.99	0.326
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	3.2302	0.8543	3.78	0.000
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.941322					
R-Sq=98.8%					
P=0.000					

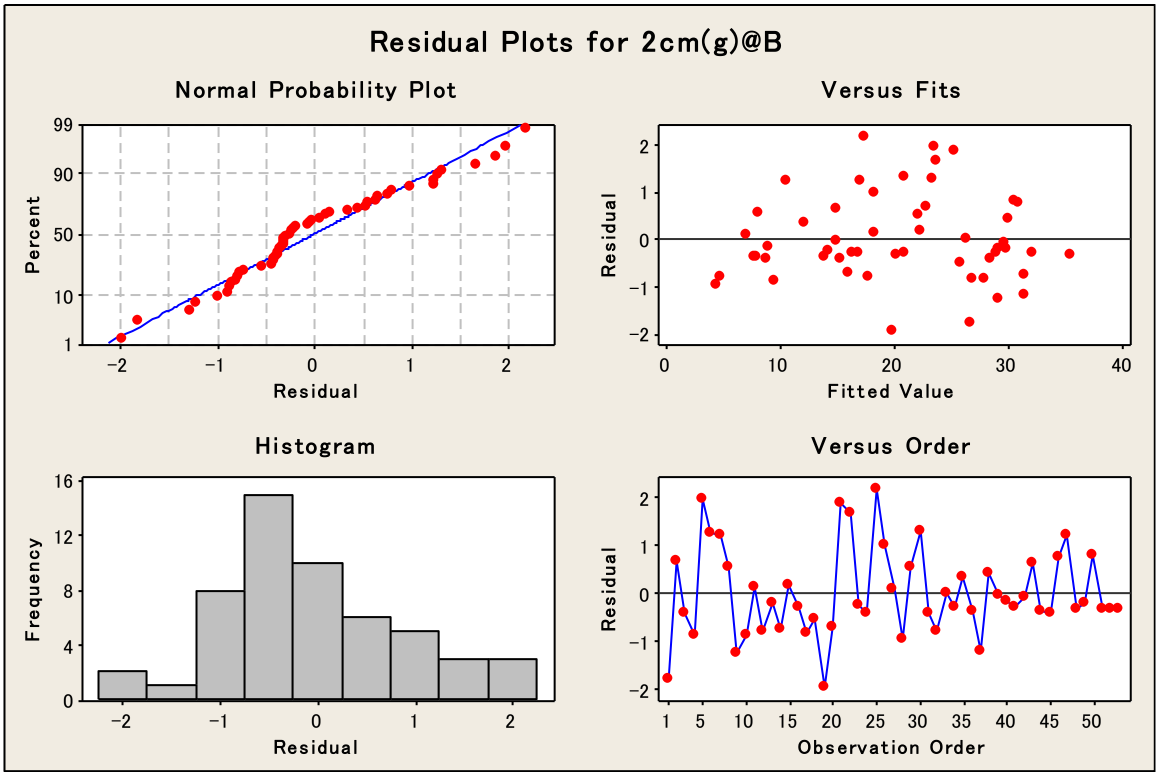


Figure 59: Residual Plots for 2cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

Table 24: Regression Analysis Result of 2cm Sound Area at Bridge (Final)

The regression equation					
$y = -245 - 0.048x^1 + 0.639x^2 + 0.350x^3 + 5.78x^4 + 0.322x^5 + 2.27x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 2cm Sound Area at UCF	-0.0477	0.2958	-0.16	0.873
x^2	Ambient Air Temperature at UCF	0.6392	0.3447	1.85	0.070
x^3	Temperature from Website in Orlando	0.3500	0.2124	1.65	0.106
x^4	Pressure from Website in Orlando	5.783	6.694	0.86	0.392
x^5	Temperature from Website in Wildwood	0.3218	0.1754	1.84	0.073
x^6	Pressure from Website in Wildwood	2.271	6.562	0.35	0.731
S=2.49571					
R-Sq=92.1%					
P=0.000					

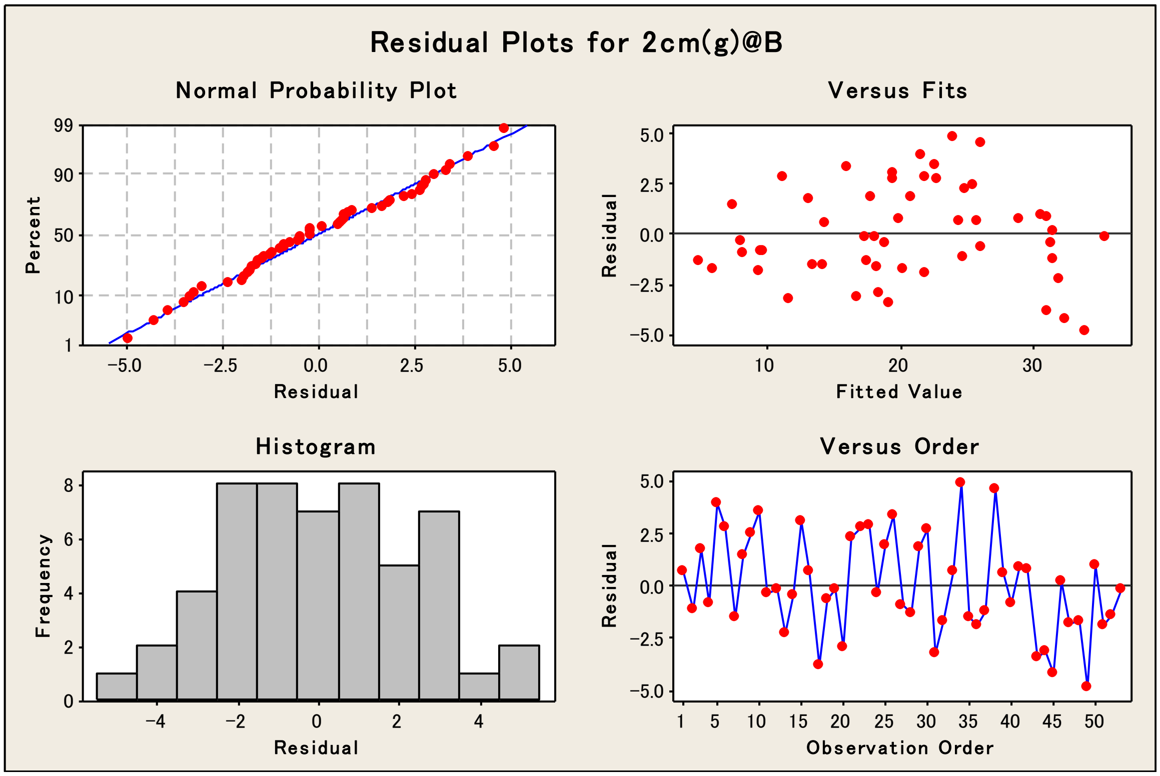


Figure 60: Residual Plots for 2cm Sound Area at Bridge (Final)

3cm Thickness

Same analyses as that of 1cm and 2cm thickness concrete test pieces were conducted for 3cm thickness concrete test piece. The process is as follows and these analyses were conducted for damaged area and sound area.

1. To analyze the data on campus using all data to decide significant factors

2. To analyze the data on campus without insignificant factors

3. To analyze the data at the bridge using all data to decide significant factors

4. To analyze the data at the bridge without insignificant factors

5. To analyze the data at the bridge using both data on campus and at the bridge

Tables 25-29 and Figures 61-65 show the results of each step for damaged area. For damaged area on campus, almost same result was obtained. That is to say, humidity, dew point and wind speed are not significant factors. As shown in Table 25, although the P value of pressure is larger than α=0.05, it is relative small compared to other factors. Therefore, pressure was adopted as a significant factor. However, as shown in Table 27, for damaged area at the bridge, the P value of the factor of pressure is not quite different from that of others. One of the reasons is because the damaged data at the bridge is not enough volume due to the failure of temperature measurement sensor. Although the P value of pressure is not quite different from that of others, it is the smallest. Therefore, the factor of pressure was adopted as a significant factor at the bridge as well. Then, using significant factors from analysis on campus and at the bridge, the final analysis to calculate the concrete surface temperature of damaged area at the bridge was derived as shown in Table 29. Tables 30-34 and Figures 66-70 show the results of each step for sound area. As the previous analyses, pressure is adopted as a significant factor, although P value of other factors are smaller than that of pressure factor. However, the R-square is still high.

Table 25: Regression Analysis Result of 3cm Damaged Area on Campus with All Data

The regression equation					
$y = - 157 + 1.37 x^1 + 0.009 x^2 + 11.0 x^3 - 0.372 x^4 + 4.92 x^5 + 0.101 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.3707	0.1016	13.49	0.000
x^2	Temperature from Website in Orlando	0.0095	0.2946	0.003	0.974
x^3	Humidity from Website in Orlando	10.971	9.466	1.16	0.252
x^4	Dew Point from Website in Orlando	-0.3721	0.3075	-1.21	0.232
x^5	Pressure from Website in Orlando	4.922	2.859	1.72	0.092
x^6	Wind Speed from Website in Orlando	0.10102	0.08911	1.13	0.263
S=2.49531					
R-Sq=93.7%					
P=0.000					

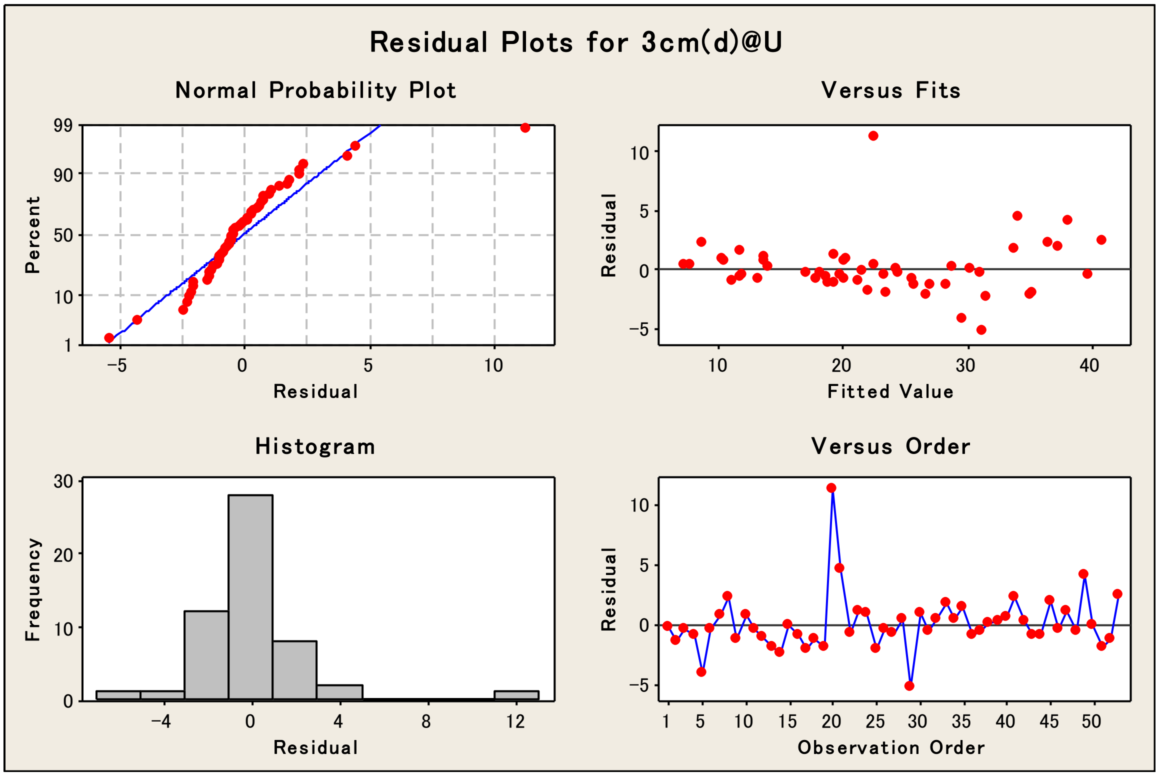


Figure 61: Residual Plots for 3cm Damaged Area on Campus with All Data

Table 26: Regression Analysis Result of 3cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = -113 + 1.37x^1 - 0.317x^2 + 3.79x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.37091	0.09203	14.90	0.000
x^2	Temperature from Website in Orlando	-0.3175	0.1318	-2.41	0.020
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	3.792	2.232	1.70	0.096
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=2.47285					
R-Sq=93.4%					
P=0.000					

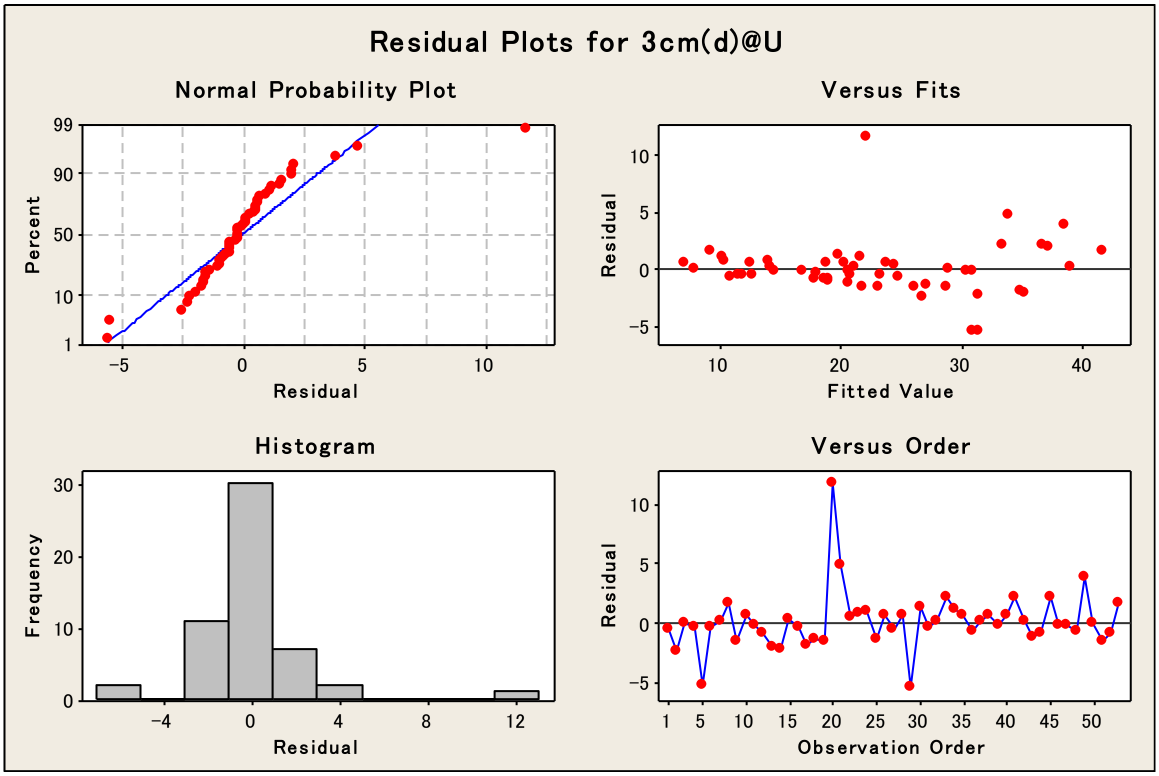


Figure 62: Residual Plots for 3cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

Table 27: Regression Analysis Result of 3cm Damaged Area at Bridge with All Data

The regression equation					
$y = 62 + 1.03\ x^1 - 0.099\ x^2 - 3.54\ x^3 + 0.011\ x^4 - 1.92\ x^5 - 0.0010\ x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.03215	0.07298	14.14	0.000
x^2	Temperature from Website in Wildwood	-0.0993	0.2433	-0.41	0.689
x^3	Humidity from Website in Wildwood	-3.539	6.848	-0.52	0.612
x^4	Dew Point from Website in Wildwood	0.0113	0.2207	0.05	0.960
x^5	Pressure from Website in Wildwood	-1.920	3.295	-0.58	0.568
x^6	Wind Speed from Website in Wildwood	-0.00098	0.06099	-0.02	0.987
S=1.03156					
R-Sq=98.3%					
P=0.000					

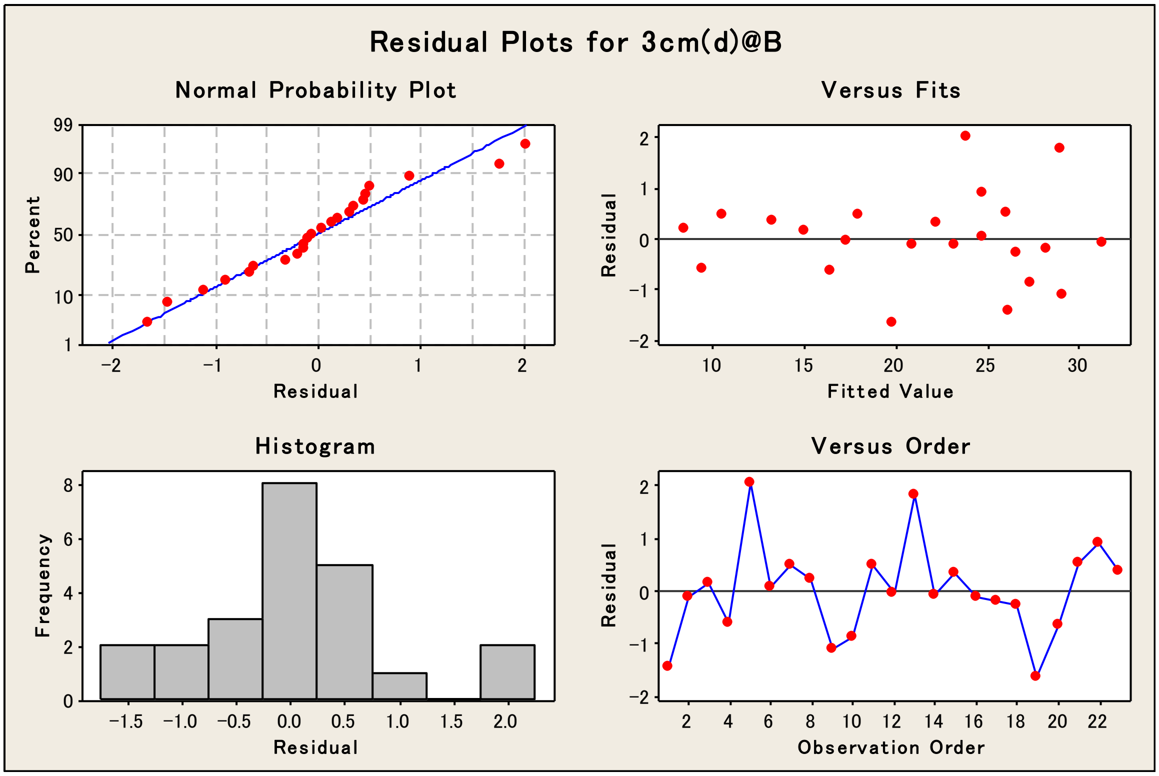


Figure 63: Residual Plots for 3cm Damaged Area at Bridge with All Data

Table 28: Regression Analysis Result of 3cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = - 35.3 + 1.10 x^1 - 0.0807 x^2 + 1.22 x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.09765	0.07033	15.61	0.000
x^2	Temperature from Website in Wildwood	-0.08068	0.09031	-0.89	0.383
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	1.220	2.416	0.51	0.619
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=1.09769					
R-Sq=97.7%					
P=0.000					

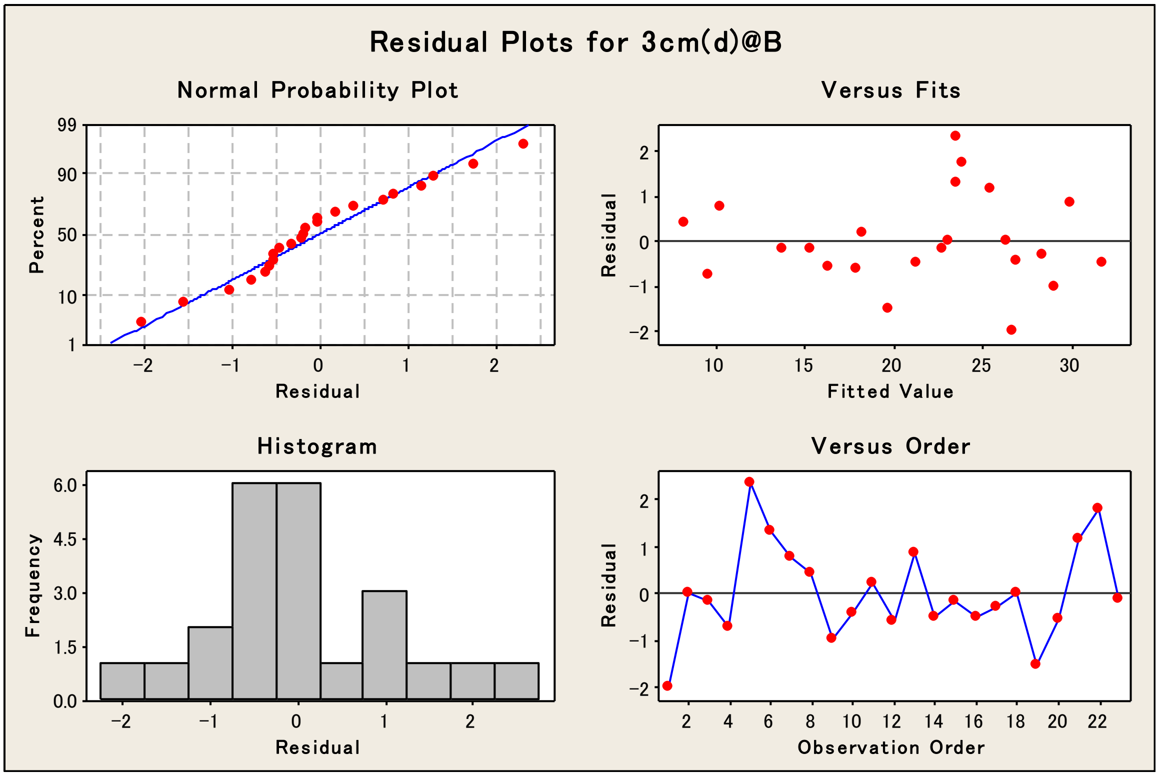


Figure 64: Residual Plots for 3cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

Table 29: Regression Analysis Result of 3cm Damaged Area at Bridge (Final)

The regression equation					
$y = -464 - 0.101 x^1 + 0.724 x^2 + 0.606 x^3 + 18.8 x^4 + 0.051 x^5 - 3.42 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 3cm Damaged Area at UCF	-0.1014	0.1500	-0.68	0.509
x^2	Ambient Air Temperature at UCF	0.7236	0.2603	2.78	0.013
x^3	Temperature from Website in Orlando	0.6060	0.3123	1.94	0.070
x^4	Pressure from Website in Orlando	18.783	7.130	2.63	0.018
x^5	Temperature from Website in Wildwood	0.0509	0.1995	0.26	0.802
x^6	Pressure from Website in Wildwood	-3.423	6.533	-0.52	0.608
S=2.06247					
R-Sq=93.3%					
P=0.000					

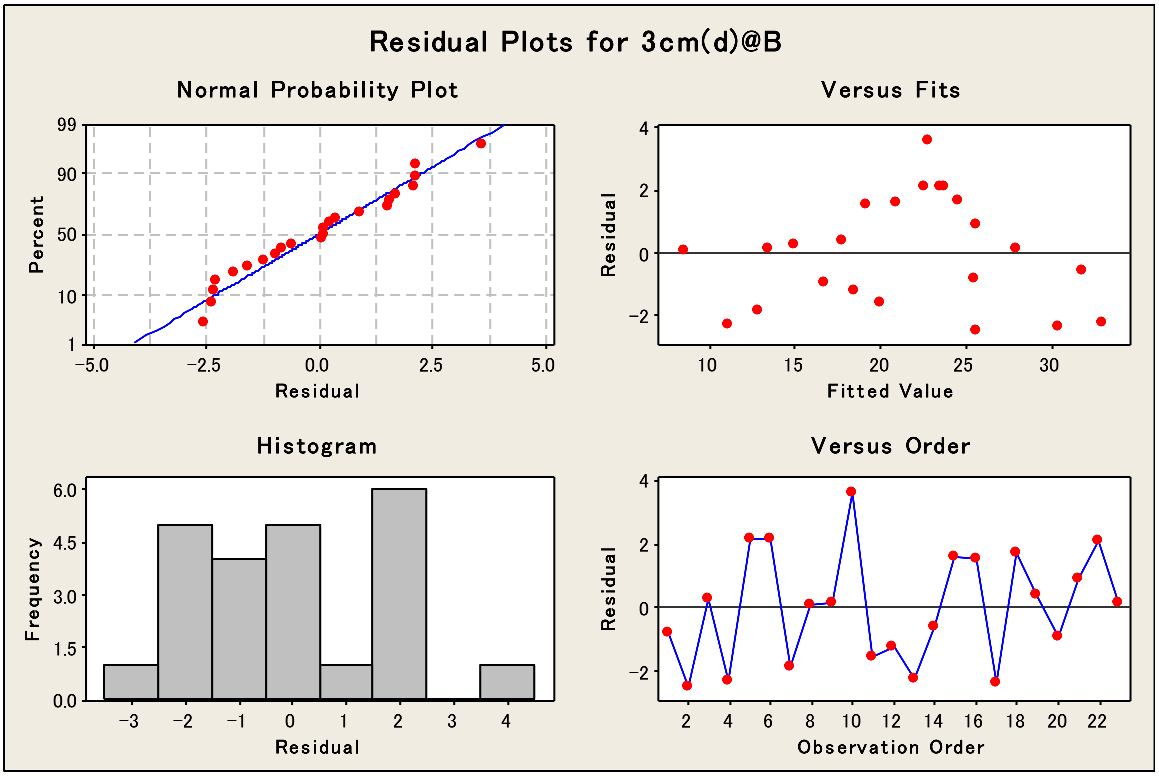


Figure 65: Residual Plots for 3cm Damaged Area at Bridge (Final)

Table 30: Regression Analysis Result of 3cm Sound Area on Campus with All Data

The regression equation					
$y = -89 + 1.43x^1 + 0.043x^2 + 16.8x^3 - 0.517x^4 + 2.53x^5 + 0.086x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.4294	0.1282	11.15	0.000
x^2	Temperature from Website in Orlando	0.0433	0.3717	0.12	0.908
x^3	Humidity from Website in Orlando	16.78	11.94	1.40	0.167
x^4	Dew Point from Website in Orlando	-0.5170	0.3880	-1.33	0.189
x^5	Pressure from Website in Orlando	2.527	3.608	0.70	0.487
x^6	Wind Speed from Website in Orlando	0.0862	0.1124	0.77	0.447
S=3.14881					
R-Sq=90.0%					
P=0.000					

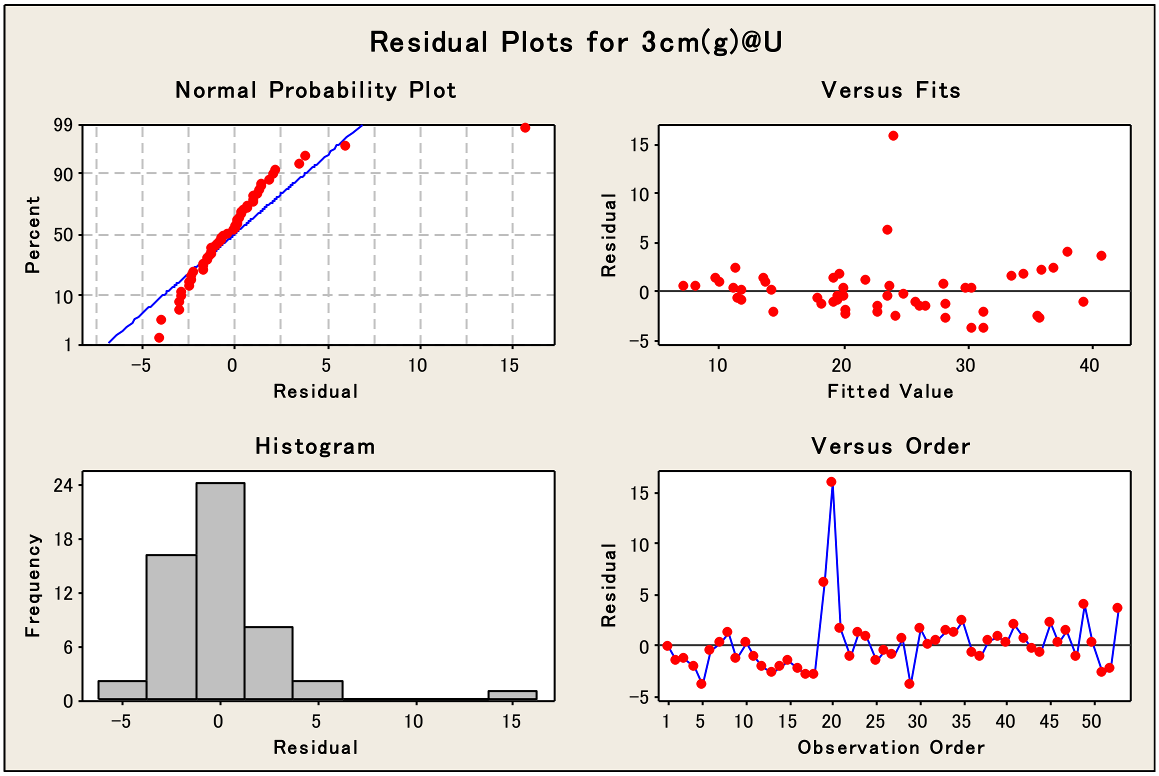


Figure 66: Residual Plots for 3cm Sound Area on Campus with All Data

Table 31: Regression Analysis Result of 3cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = - 10.3 + 1.39 x^1 - 0.403 x^2 + 0.42 x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	1.3880	0.1161	11.96	0.000
x^2	Temperature from Website in Orlando	-0.4028	0.1663	-2.42	0.019
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	0.424	2.815	0.15	0.881
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=3.11896					
R-Sq=89.6%					
P=0.000					

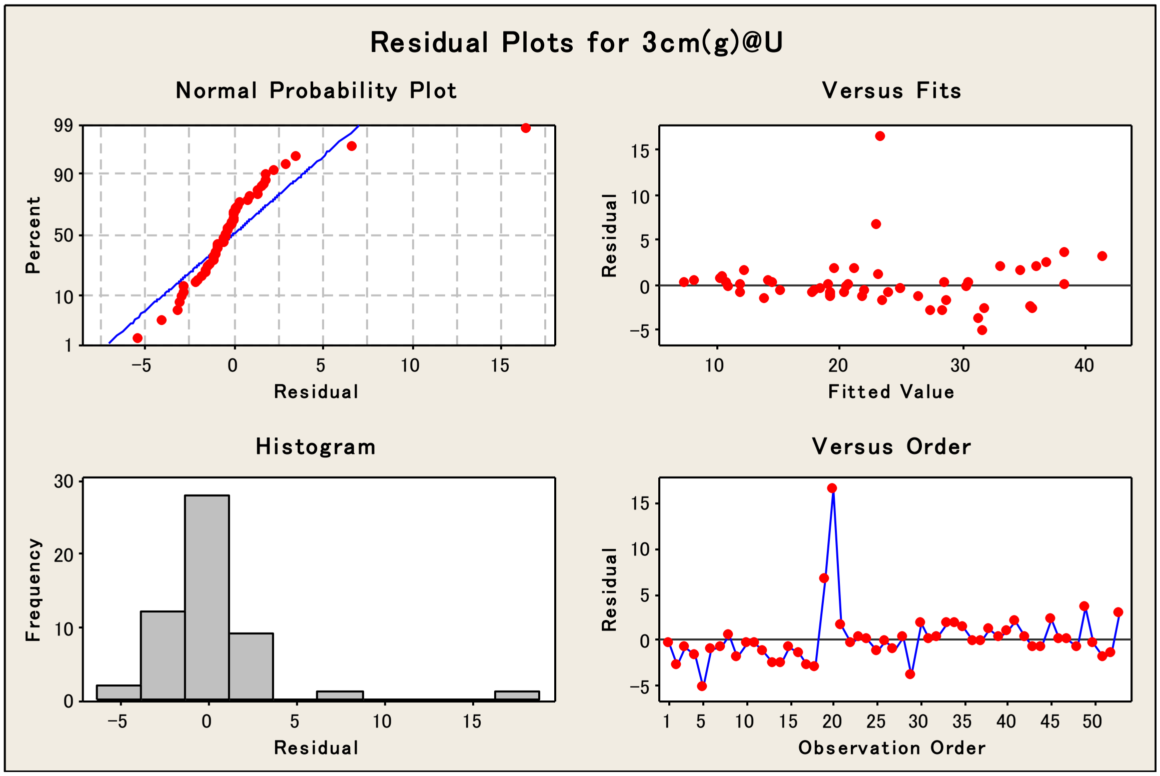


Figure 67: Residual Plots for 3cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

Table 32: Regression Analysis Result of 3cm Sound Area at Bridge with All Data

The regression equation					
$y = 74.0 + 1.03 x^1 - 0.180 x^2 - 7.27 x^3 + 0.181 x^4 - 2.15 x^5 - 0.0532 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.03344	0.09648	10.71	0.000
x^2	Temperature from Website in Wildwood	-0.1799	0.2523	-0.71	0.479
x^3	Humidity from Website in Wildwood	-7.272	6.893	-1.06	0.297
x^4	Dew Point from Website in Wildwood	0.1807	0.2311	0.78	0.438
x^5	Pressure from Website in Wildwood	-2.153	2.447	-0.88	0.383
x^6	Wind Speed from Website in Wildwood	-0.05325	0.07311	-0.73	0.470
S=2.04705					
R-Sq=95.3%					
P=0.000					

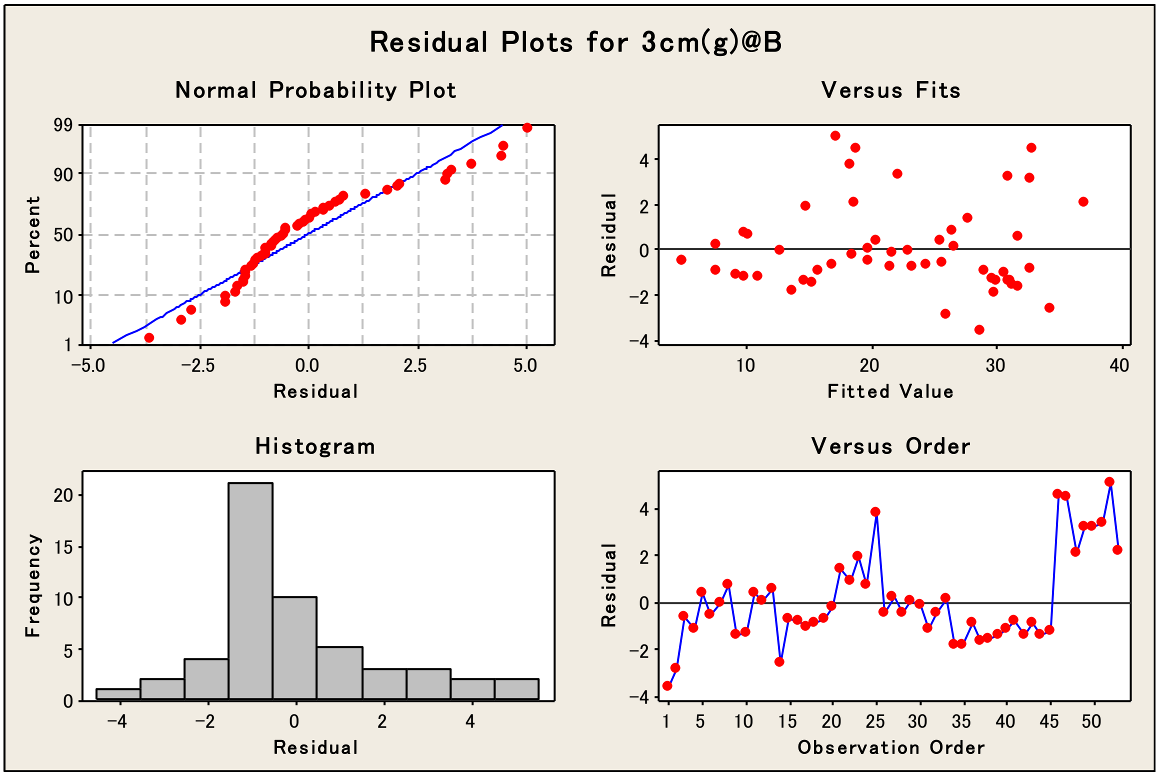


Figure 68: Residual Plots for 3cm Sound Area at Bridge with All Data

Table 33: Regression Analysis Result of 3cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 13.0 + 1.07\ x^1 - 0.018\ x^2 - 0.35\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	1.07062	0.08440	12.68	0.000
x^2	Temperature from Website in Wildwood	-0.0183	0.1123	-0.16	0.871
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-0.347	1.835	-0.19	0.851
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=2.02210					
R-Sq=95.1%					
P=0.000					

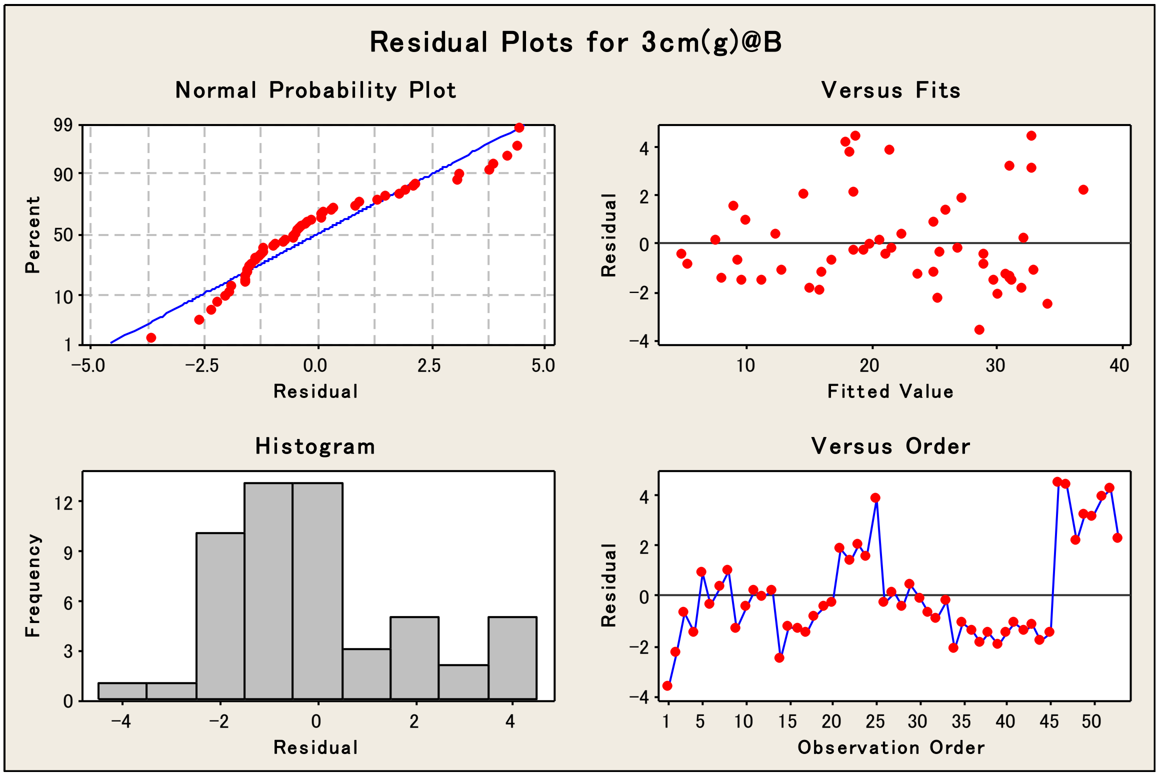


Figure 69: Residual Plots for 3cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

Table 34: Regression Analysis Result of 3cm Sound Area at Bridge (Final)

The regression equation					
$y = -126 - 0.097 x^1 + 0.743 x^2 + 0.341 x^3 - 2.43 x^4 + 0.323 x^5 + 6.55 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 3cm Sound Area at UCF	-0.0974	0.1276	-0.76	0.449
x^2	Ambient Air Temperature at UCF	0.7435	0.2011	3.70	0.001
x^3	Temperature from Website in Orlando	0.3412	0.2382	1.43	0.159
x^4	Pressure from Website in Orlando	-2.431	7.131	-0.34	0.735
x^5	Temperature from Website in Wildwood	0.3229	0.1910	1.69	0.098
x^6	Pressure from Website in Wildwood	6.553	7.316	0.90	0.375
S=2.70056					
R-Sq=91.9%					
P=0.000					

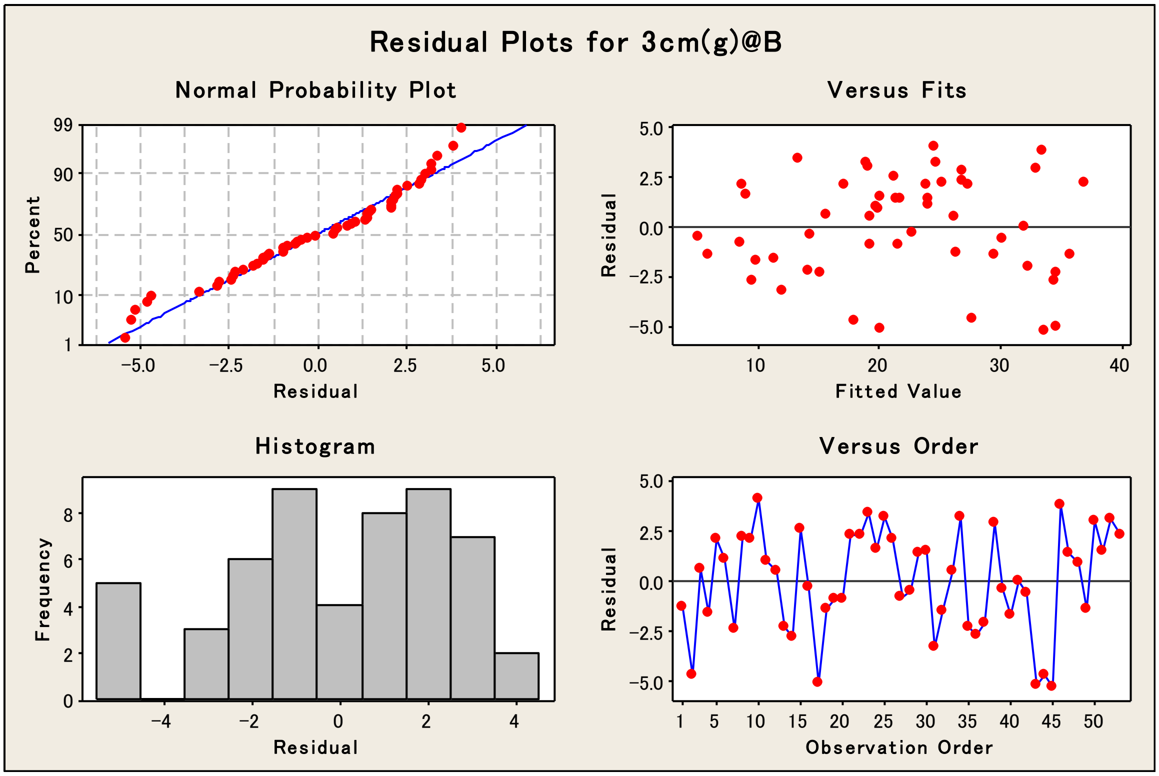


Figure 70: Residual Plots for 3cm Sound Area at Bridge (Final)

Underside of Deck and Parking Garage Ceiling

In order to estimate the temperature variation of the underside of the bridge deck, the collected temperature variation data using concrete test pieces which were attached to the ceiling of a parking garage on campus, and the weather data at the location where the bridge and the campus locate.

Analyses as that of bridge deck top were conducted for the underside of bridge deck. The process is as follows and these analyses were conducted for damaged area and sound area.

1. To analyze the data on campus using all data to decide significant factors

2. To analyze the data on campus without insignificant factors

3. To analyze the data at the bridge using all data to decide significant factors

4. To analyze the data at the bridge without insignificant factors

5. To analyze the data at the bridge using both data on campus and at the bridge

1cm Thickness

The first is about the results of damaged area. Table 35 and Figure 71 show the result on campus with all factors. As the past results, it shows that the factor of pressure is significant, since the P value of the pressure is 0. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 36 and Figure 72 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 35: Regression Analysis Result of 1cm Damaged Area on Campus with All Data

The regression equation					
$y = 171 + 0.644 x^1 - 0.152 x^2 - 2.31 x^3 + 0.049 x^4 - 5.26 x^5 - 0.0324 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.64362	0.09184	7.01	0.000
x^2	Temperature from Website in Orlando	-0.1517	0.2348	-0.65	0.524
x^3	Humidity from Website in Orlando	-2.312	5.012	-0.46	0.649
x^4	Dew Point from Website in Orlando	0.0490	0.2159	0.23	0.822
x^5	Pressure from Website in Orlando	-5.259	1.057	-4.97	0.000
x^6	Wind Speed from Website in Orlando	-0.03243	0.02068	-1.57	0.130
S=0.392722					
R-Sq=93.2%					
P=0.000					

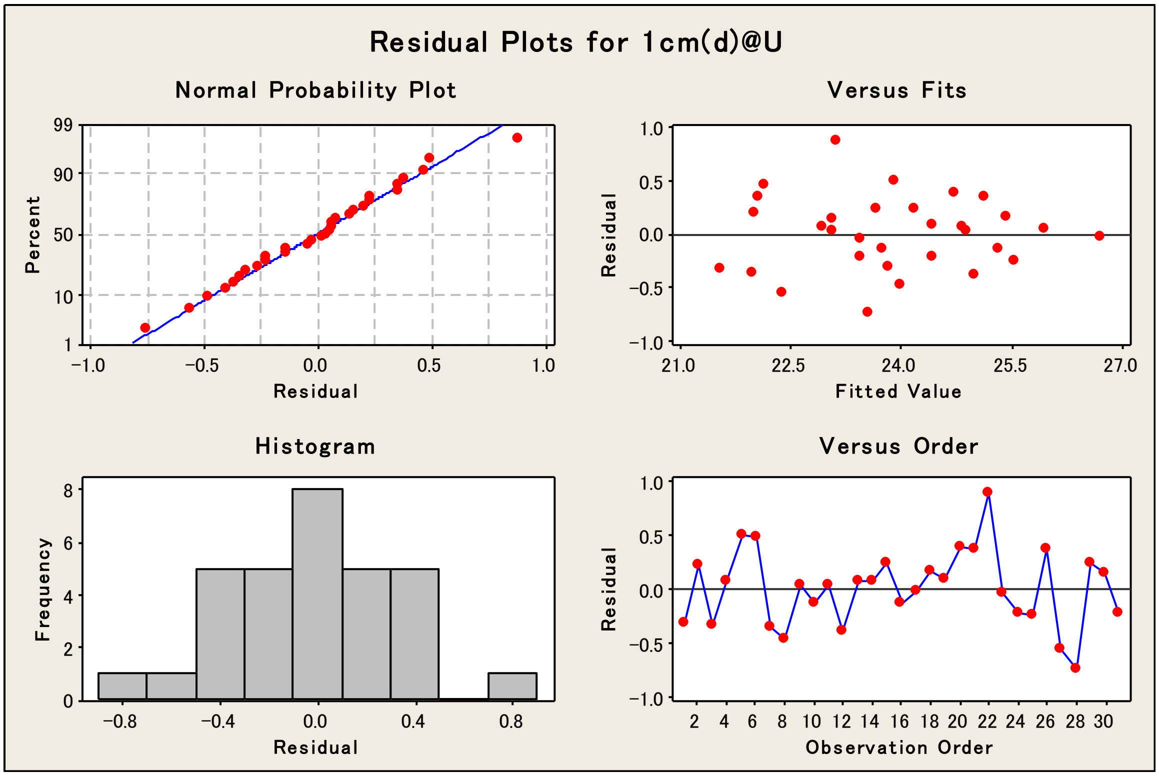


Figure 71: Residual Plots for 1cm Damaged Area on Campus with All Data

Table 36: Regression Analysis Result of 1cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 142 + 0.660\ x^1 - 0.0826\ x^2 - 4.40\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.66035	0.08549	7.72	0.000
x^2	Temperature from Website in Orlando	-0.08258	0.04447	-1.86	0.074
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	-4.4000	0.7963	-5.53	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=0.401149					
R-Sq=92.0%					
P=0.000					

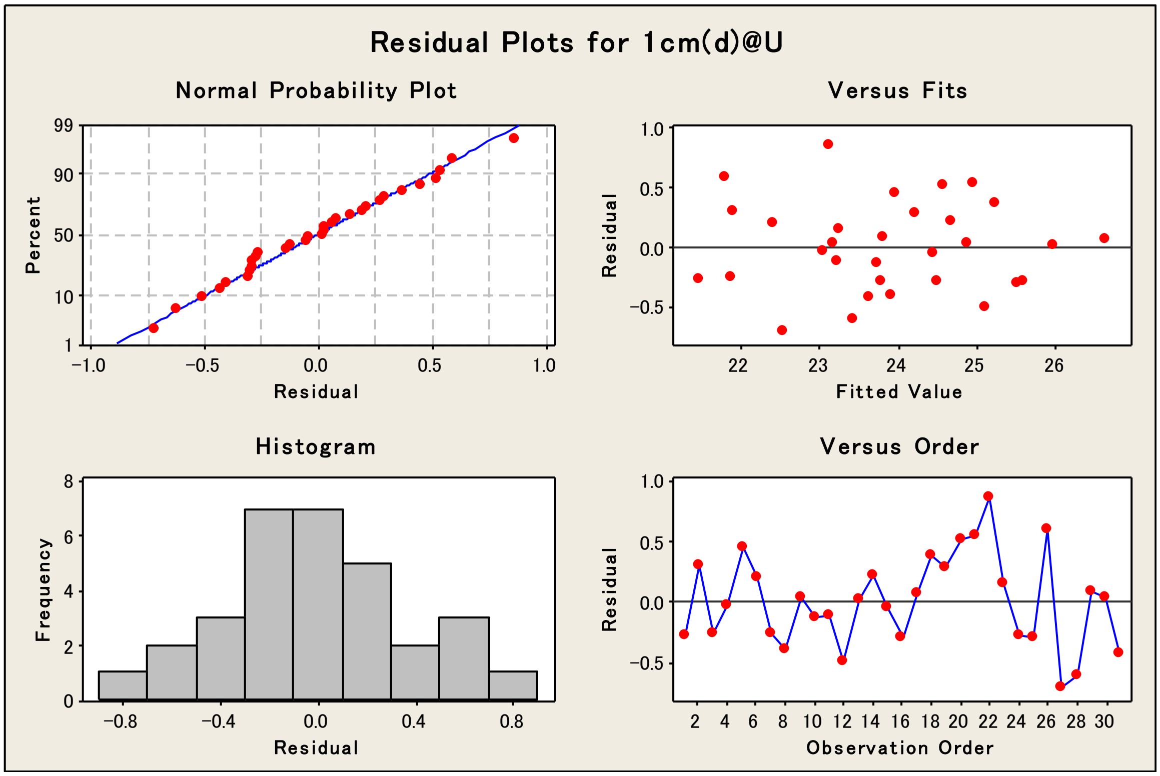


Figure 72: Residual Plots for 1cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

Next, the analysis for the bridge is conducted. Table 37 and Figure 73 show the results at the bridge. From the result, it is found that the factor of pressure is significant, since the P value is less than α=0.05. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 38 and Figure 74 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 37: Regression Analysis Result of 1cm Damaged Area at Bridge with All Data

The regression equation					
$y = 75.5 + 0.591 x^1 + 0.119 x^2 + 3.80 x^3 - 0.133 x^4 - 2.28 x^5 + 0.0071 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.59061	0.07775	7.60	0.000
x^2	Temperature from Website in Wildwood	0.1187	0.1362	0.87	0.392
x^3	Humidity from Website in Wildwood	3.800	3.094	1.23	0.231
x^4	Dew Point from Website in Wildwood	-0.1330	0.1165	-1.14	0.265
x^5	Pressure from Website in Wildwood	-2.2798	0.9231	-2.47	0.021
x^6	Wind Speed from Website in Wildwood	0.00707	0.03467	0.20	0.840
S=0.439298					
R-Sq=95.2%					
P=0.000					

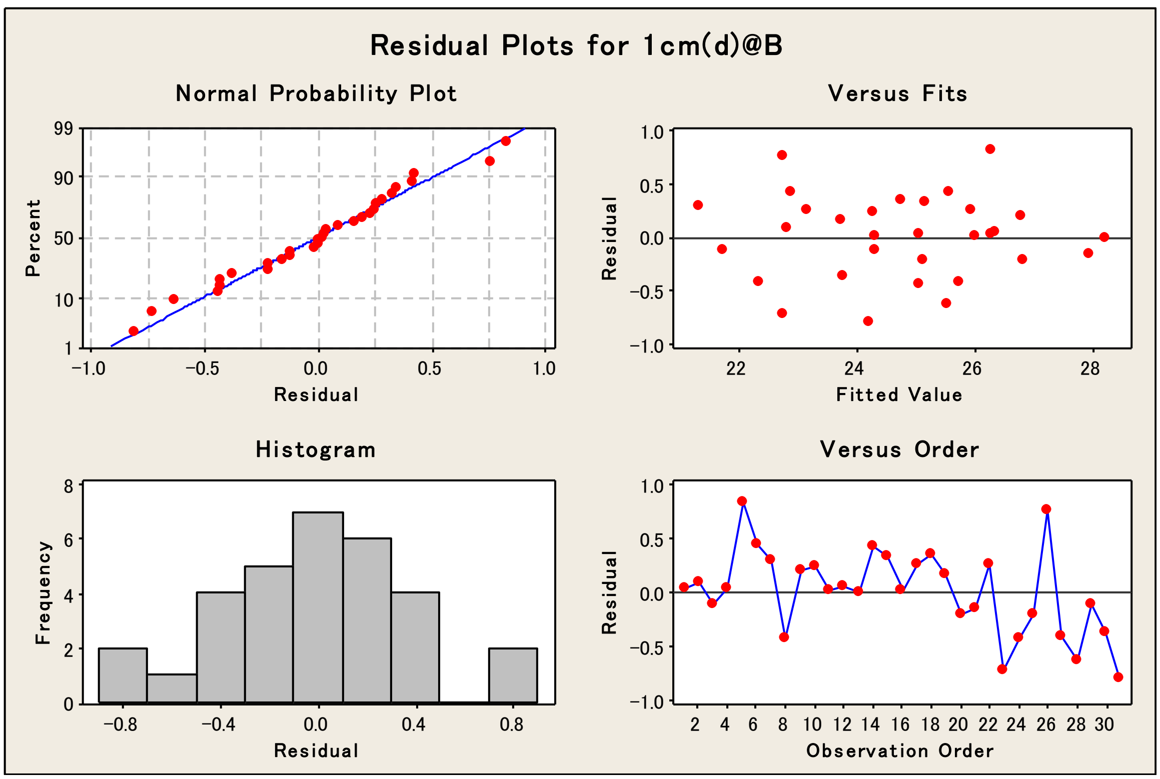


Figure 73: Residual Plots for 1cm Damaged Area at Bridge with All Data

Table 38: Regression Analysis Result of 1cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 88.9 + 0.611\ x^1 - 0.0400\ x^2 - 2.60\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.61123	0.06574	9.30	0.000
x^2	Temperature from Website in Wildwood	-0.03995	0.04377	-0.91	0.369
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-2.6034	0.7882	-3.30	0.003
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.428872					
R-Sq=94.8%					
P=0.000					

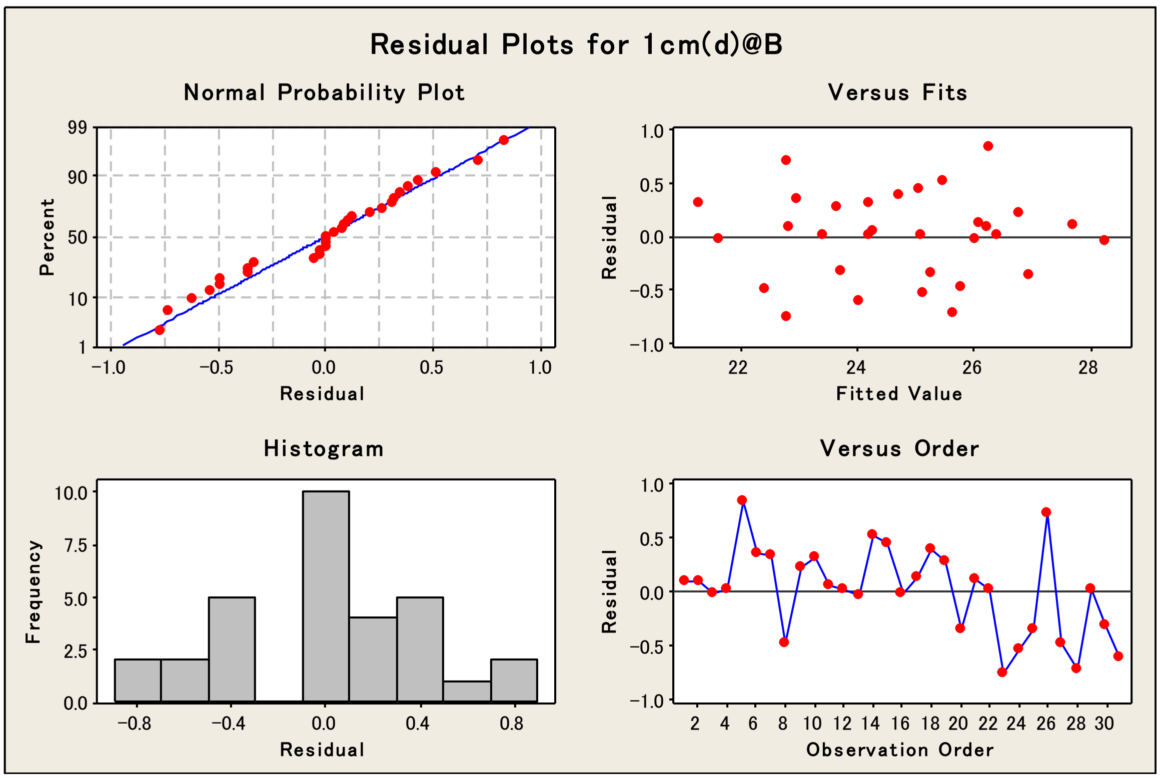


Figure 74: Residual Plots for 1cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

Finally, the equation to calculate the concrete surface temperature at the bridge was developed using significant factors from the results of campus and the bridge. Table 39 and Figure 75 show the results.

Table 39: Regression Analysis Result of 1cm Damaged Area at Bridge (Final)

The regression equation					
$y = -26.3 + 0.631 x^1 + 0.116 x^2 - 0.115 x^3 - 0.06 x^4 + 0.290 x^5 + 1.03 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 1cm Damaged Area at UCF	0.6309	0.3617	1.74	0.094
x^2	Ambient Air Temperature at UCF	0.1162	0.2848	0.41	0.667
x^3	Temperature from Website in Orlando	-0.1147	0.1666	-0.69	0.498
x^4	Pressure from Website in Orlando	-0.056	5.443	-0.01	0.992
x^5	Temperature from Website in Wildwood	0.2896	0.1136	2.55	0.018
x^6	Pressure from Website in Wildwood	1.027	5.240	0.20	0.846
S=0.732765					
R-Sq=86.6%					
P=0.000					

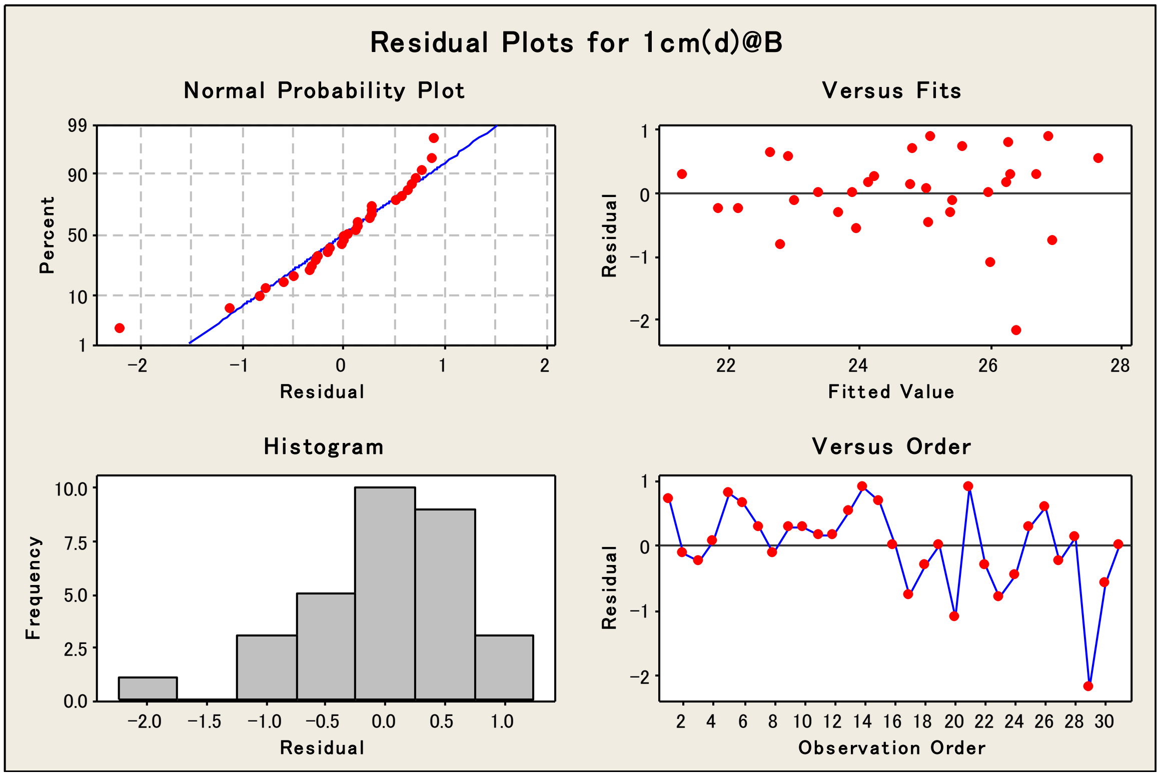


Figure 75: Residual Plots for 1cm Damaged Area at Bridge (Final)

Next is about the results of sound area. Table 40 and Figure 76 show the result on campus with all factors. It also shows that the factor of pressure is significant, since the P value of the pressure is 0. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 41 and Figure 77 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 40: Regression Analysis Result of 1cm Sound Area on Campus with All Data

The regression equation					
$y = 164 + 0.643\ x^1 - 0.125\ x^2 - 1.99\ x^3 + 0.049\ x^4 - 5.06\ x^5 - 0.0323\ x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.64346	0.08863	7.26	0.000
x^2	Temperature from Website in Orlando	-0.1246	0.2266	-0.55	0.588
x^3	Humidity from Website in Orlando	-1.990	4.837	-0.41	0.684
x^4	Dew Point from Website in Orlando	0.0486	0.2084	0.23	0.817
x^5	Pressure from Website in Orlando	-5.058	1.020	-4.96	0.000
x^6	Wind Speed from Website in Orlando	-0.03231	0.01995	-1.62	0.119
S=0.378973					
R-Sq=94.0%					
P=0.000					

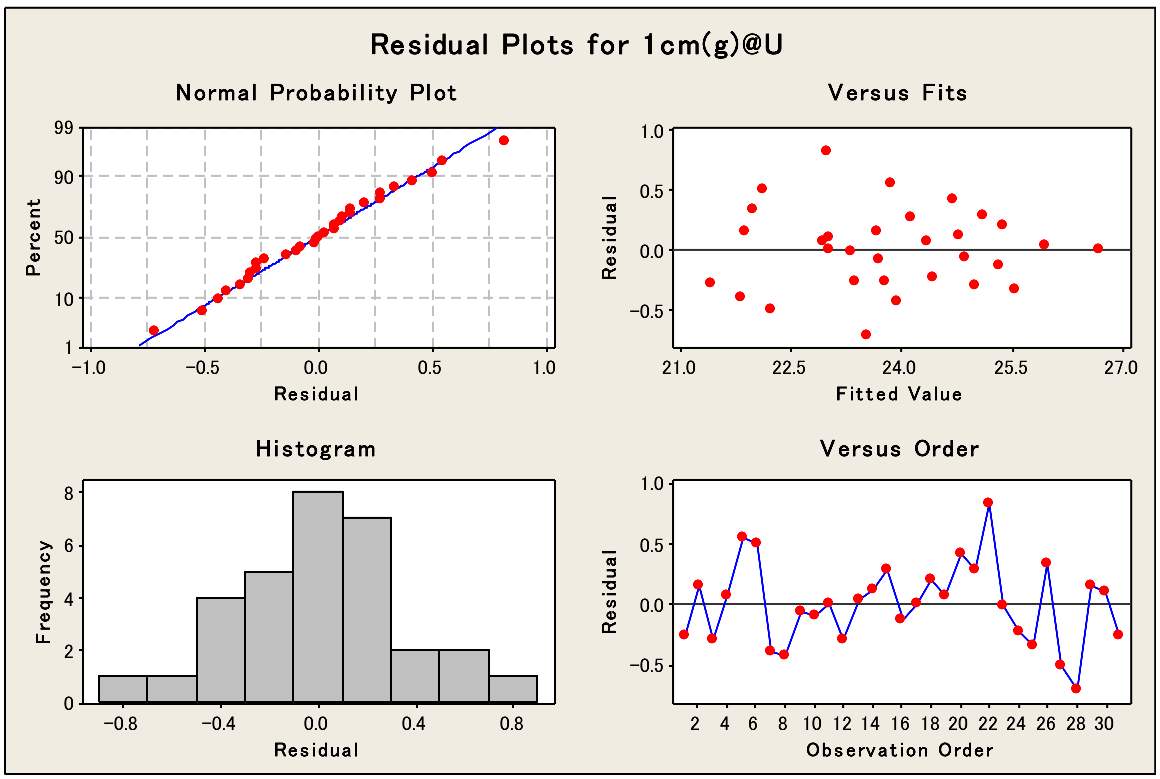


Figure 76: Residual Plots for 1cm Sound Area on Campus with All Data

Table 41: Regression Analysis Result of 1cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 141 + 0.667\ x^1 - 0.0726\ x^2 - 4.38\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.66685	0.08200	8.13	0.000
x^2	Temperature from Website in Orlando	-0.07261	0.04266	-1.70	0.100
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	-4.3794	0.7638	-5.73	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=0.384780					
R-Sq=93.0%					
P=0.000					

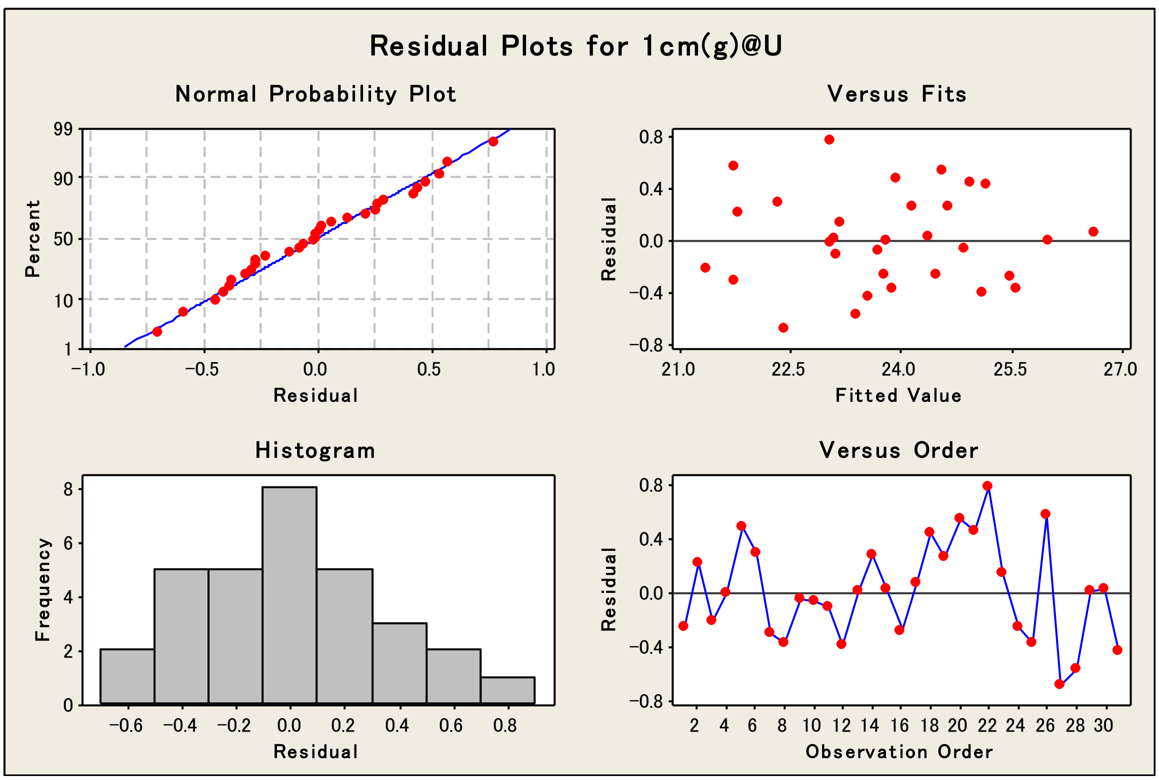


Figure 77: Residual Plots for 1cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

Next, the analysis for the bridge is conducted. Table 42 and Figure 78 show the results at the bridge. From the result, it is also found that the factor of pressure is significant, since the P value is less than α=0.05. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 43 and Figure 79 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 42: Regression Analysis Result of 1cm Sound Area at Bridge with All Data

The regression equation					
$y = 64.3 + 0.644 x^1 + 0.150 x^2 + 4.42 x^3 - 0.151 x^4 - 1.98 x^5 + 0.0021 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.64446	0.07742	8.32	0.000
x^2	Temperature from Website in Wildwood	0.1501	0.1356	1.11	0.279
x^3	Humidity from Website in Wildwood	4.420	3.081	1.43	0.164
x^4	Dew Point from Website in Wildwood	-0.1510	0.1660	-1.30	0.205
x^5	Pressure from Website in Wildwood	-1.9788	0.9191	-2.15	0.042
x^6	Wind Speed from Website in Wildwood	0.00205	0.03452	0.06	0.953
S=0.437412					
R-Sq=96.0%					
P=0.000					

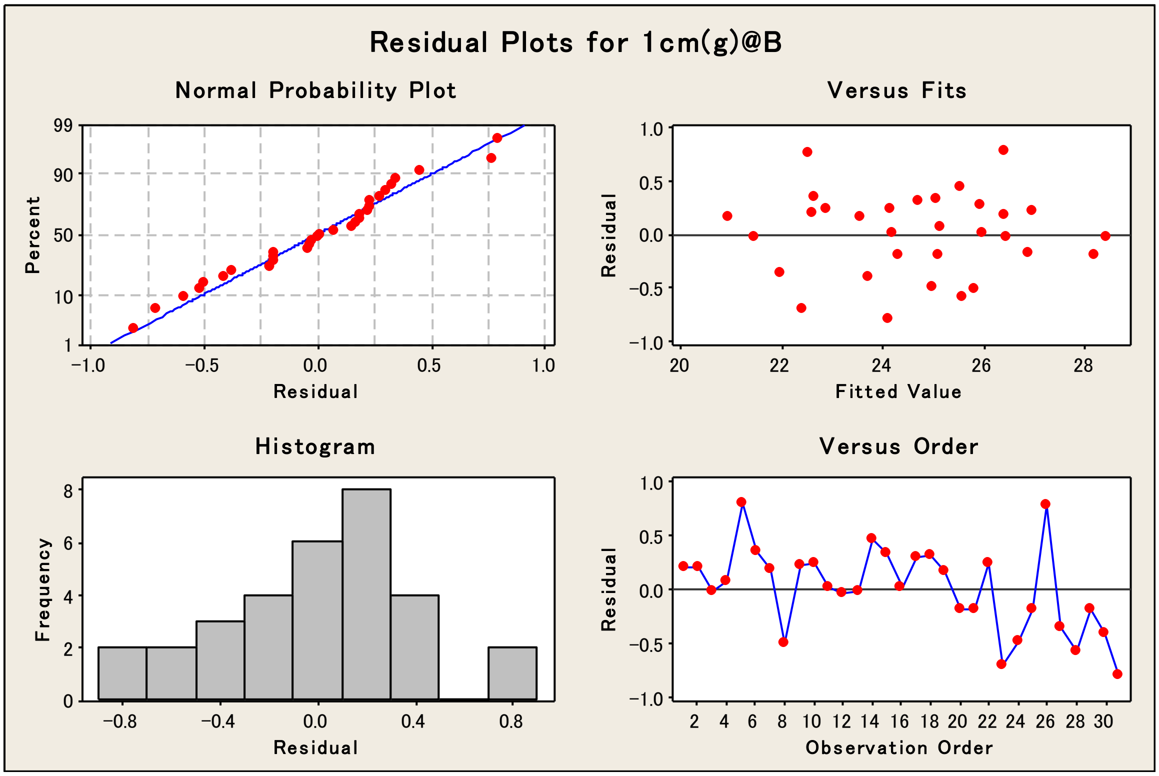


Figure 78: Residual Plots for 1cm Sound Area at Bridge with All Data

Table 43: Regression Analysis Result of 1cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 81.4 + 0.663\ x^1 - 0.0348\ x^2 - 2.40\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.66268	0.06659	9.95	0.000
x^2	Temperature from Website in Wildwood	-0.03482	0.04434	-0.79	0.439
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-2.3998	0.7984	-3.01	0.006
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.434426					
R-Sq=95.5%					
P=0.000					

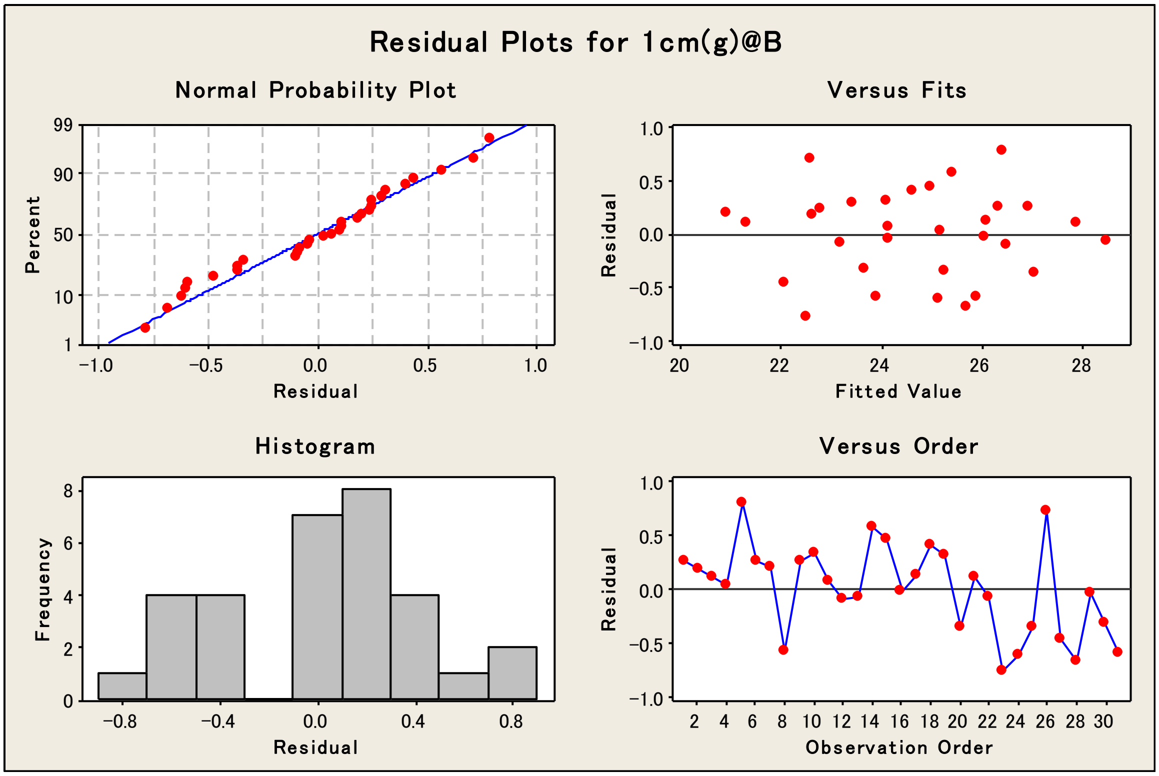


Figure 79: Residual Plots for 1cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

Finally, the equation to calculate the concrete surface temperature at the bridge was developed using significant factors from the results of campus and the bridge. Table 44 and Figure 80 show the results.

Table 44: Regression Analysis Result of 1cm Sound Area at Bridge (Final)

The regression equation					
$y = -44.2 + 0.719 x^1 + 0.094 x^2 - 0.149 x^3 + 0.47 x^4 + 0.339 x^5 + 1.03 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 1cm Sound Area at UCF	0.7186	0.4066	1.77	0.090
x^2	Ambient Air Temperature at UCF	0.0940	0.3174	0.30	0.770
x^3	Temperature from Website in Orlando	-0.1487	0.1784	-0.83	0.413
x^4	Pressure from Website in Orlando	0.468	5.826	0.08	0.937
x^5	Temperature from Website in Wildwood	0.3388	0.1225	2.77	0.011
x^6	Pressure from Website in Wildwood	1.034	5.591	0.18	0.855
S=0.782578					
R-Sq=87.1%					
P=0.000					

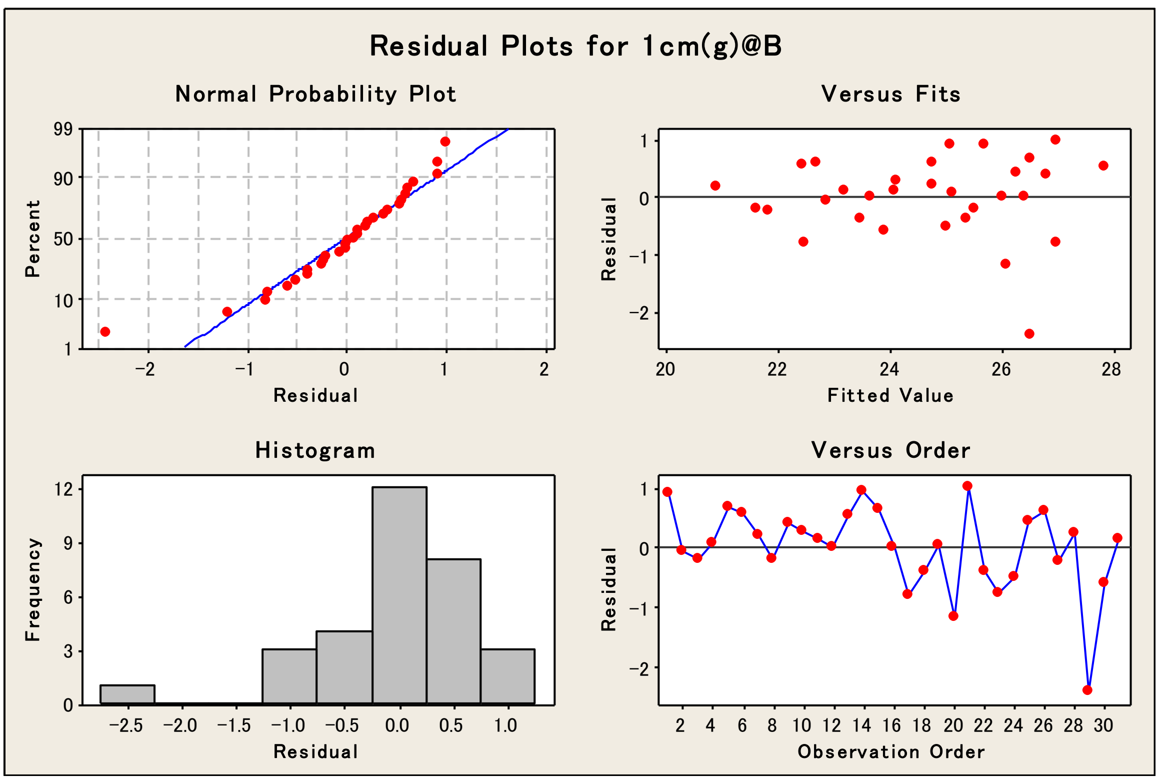


Figure 80: Residual Plots for 1cm Sound Area at Bridge (Final)

2cm Thickness

The first is about the results of damaged area. Table 45 and Figure 81 show the result on campus with all factors. As the past results, it shows that the factor of pressure is significant, since the P value of the pressure is 0. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 46 and Figure 82 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 45: Regression Analysis Result of 2cm Damaged Area on Campus with All Data

The regression equation					
$y = 152 + 0.687 x^1 - 0.039 x^2 + 0.29 x^3 - 0.059 x^4 - 4.74 x^5 - 0.0270 x^6$					
Predictor		Coef	SE Coef	T	P
X^1	Ambient Air Temperature at UCF	0.68686	0.09351	7.35	0.000
x^2	Temperature from Website in Orlando	-0.0387	0.2391	-0.16	0.873
x^3	Humidity from Website in Orlando	0.291	5.103	0.06	0.955
x^4	Dew Point from Website in Orlando	-0.0588	0.2198	-0.27	0.791
x^5	Pressure from Website in Orlando	-4.744	1.076	-4.41	0.000
x^6	Wind Speed from Website in Orlando	-0.02702	0.02105	-1.28	0.212
S=0.399842					
R-Sq=93.5%					
P=0.000					

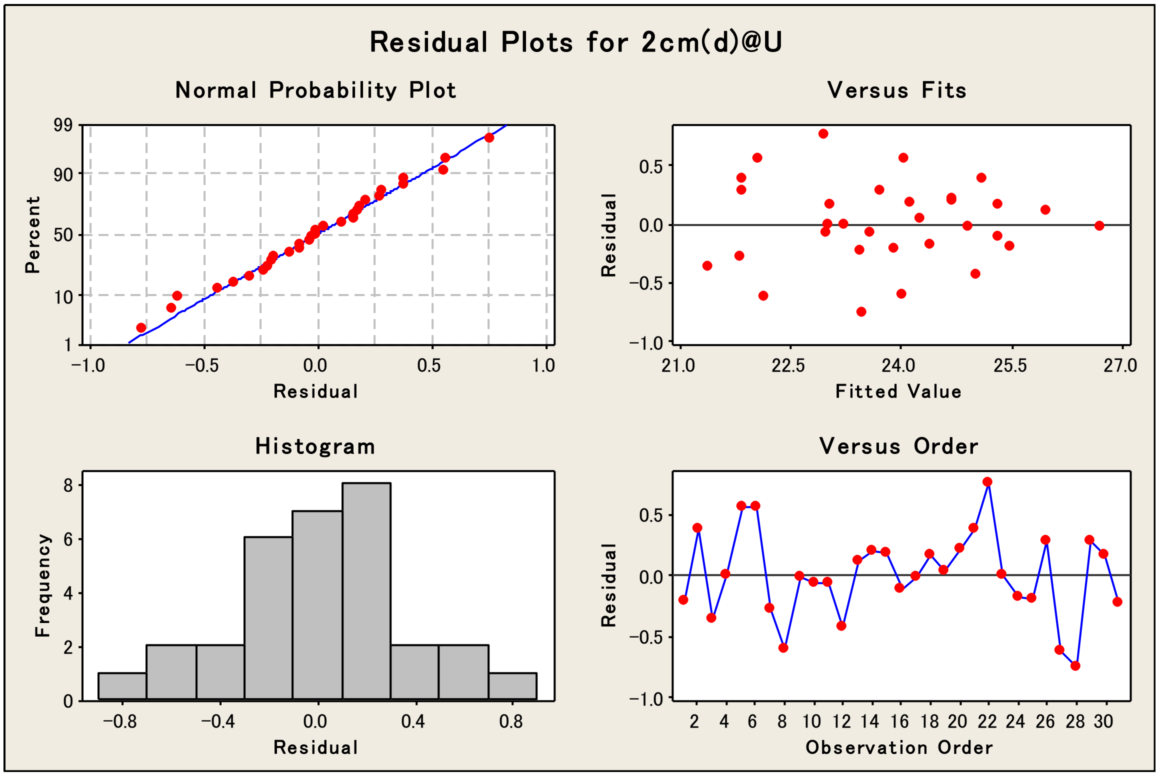


Figure 81: Residual Plots for 2cm Damaged Area on Campus with All Data

Table 46: Regression Analysis Result of 2cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 125 + 0.703\,x^1 - 0.0775\,x^2 - 3.86\,x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.70261	0.08453	8.31	0.000
x^2	Temperature from Website in Orlando	-0.07755	0.04397	-1.76	0.089
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	-3.8620	0.7873	-4.91	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=0.396642					
R-Sq=92.8%					
P=0.000					

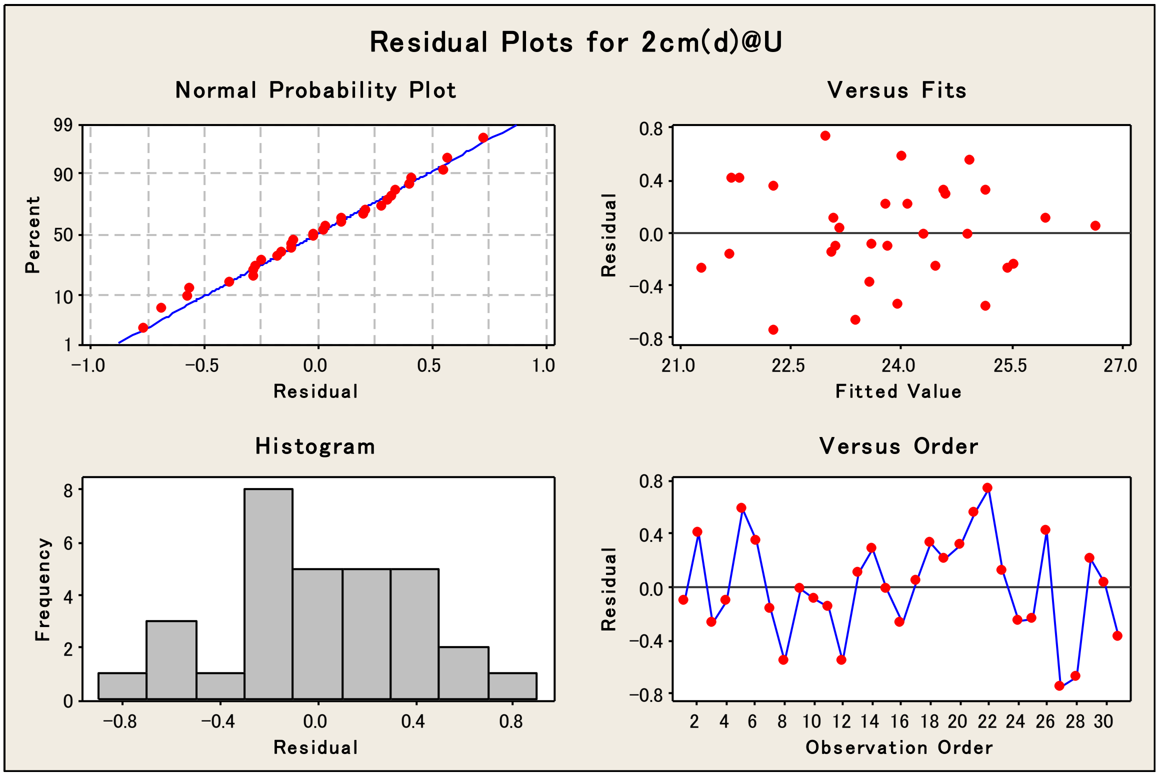


Figure 82: Residual Plots for 2cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

Next, the analysis for the bridge is conducted. Table 47 and Figure 83 show the results at the bridge. Although, the factor of pressure is always significant in the past results, this result presented the pressure factor is not significant. There is no factors whose P values are less than α=0.05. Suffice it to say that the factor of humidity is the most significant, even its P value is larger than α=0.05. Then, analyses using the pressure factor same as the past analyses and using humidity factor were conducted and compared. Table 48 and Figure 84 show the result without humidity, dew point and wind speed, or with pressure. Table 49 and Figure 85 show the result without dew point, pressure and wind speed, or with humidity. When comparing the R-square, there is little difference between the result with pressure and that with humidity.

Table 47: Regression Analysis Result of 2cm Damaged Area at Bridge with All Data

The regression equation					
$y = 36.0 + 0.670 x^1 + 0.191 x^2 + 5.09 x^3 - 0.170 x^4 - 1.10 x^5 + 0.0059 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.66978	0.06571	10.19	0.000
x^2	Temperature from Website in Wildwood	0.1909	0.1151	1.66	0.110
x^3	Humidity from Website in Wildwood	5.094	2.615	1.95	0.063
x^4	Dew Point from Website in Wildwood	-0.17018	0.09846	-1.73	0.097
x^5	Pressure from Website in Wildwood	-1.1019	0.7801	-1.41	0.171
x^6	Wind Speed from Website in Wildwood	0.00586	0.02930	0.20	0.843
S=0.371275					
R-Sq=97.3%					
P=0.000					

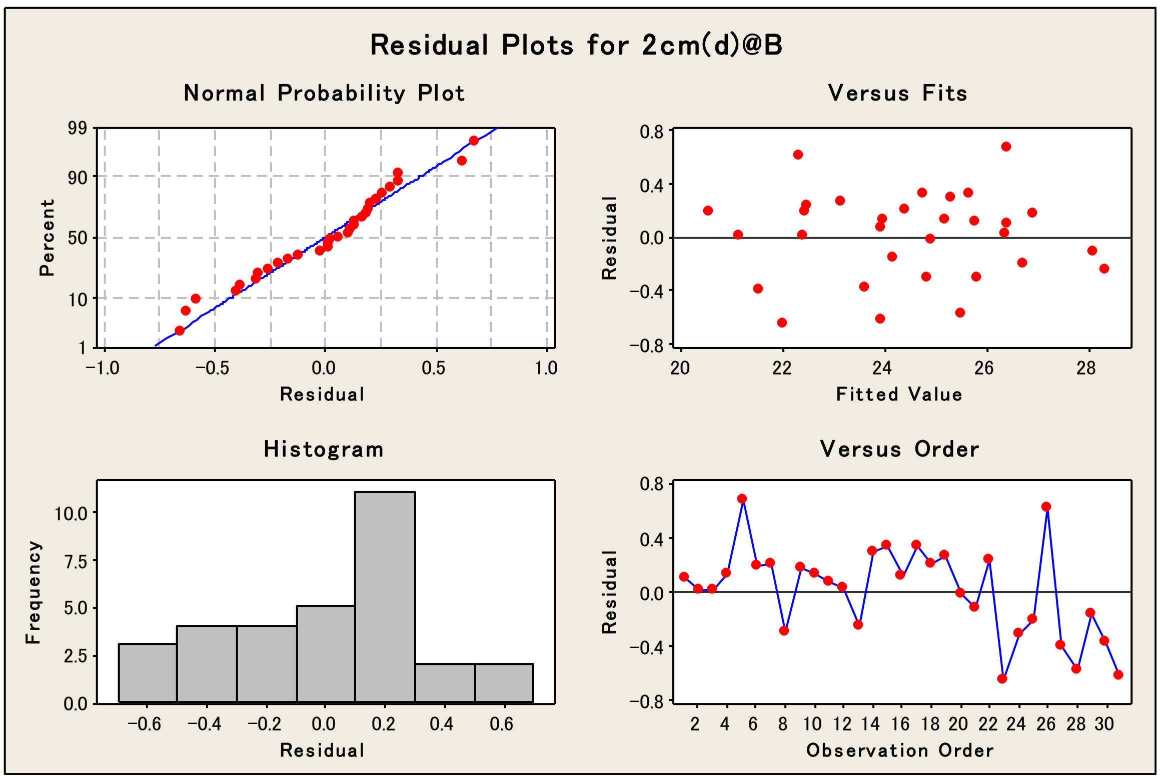


Figure 83: Residual Plots for 2cm Damaged Area at Bridge with All Data

Table 48: Regression Analysis Result of 2cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 57.4 + 0.693\ x^1 - 0.0222\ x^2 - 1.64\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.69310	0.05859	11.83	0.000
x^2	Temperature from Website in Wildwood	-0.02217	0.03901	-0.57	0.574
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-1.6401	0.7025	-2.33	0.027
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.382273					
R-Sq=96.8%					
P=0.000					

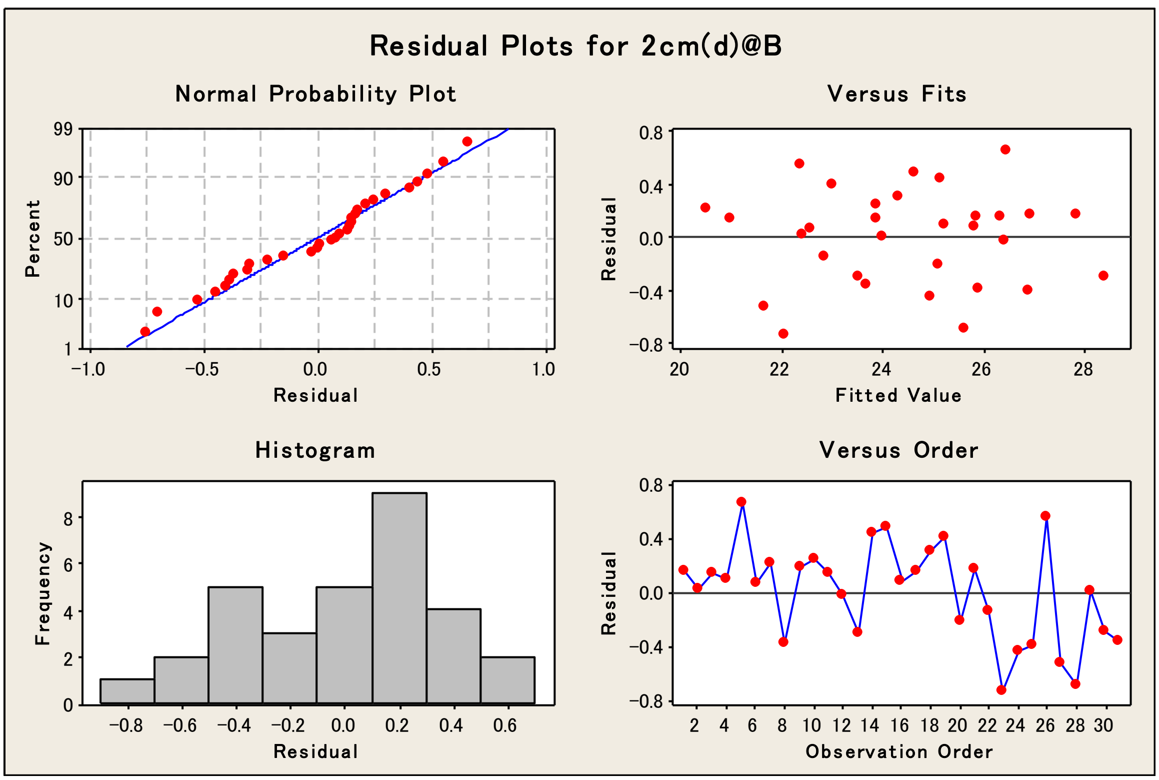


Figure 84: Residual Plots for 2cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

Table 49: Regression Analysis Result of 2cm Damaged Area at Bridge without Dew Point, Pressure and Wind Speed

The regression equation					
$y = 5.99 + 0.711 x^1 + 0.0194 x^2 + 1.03 x^3$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.71098	0.06026	11.80	0.000
x^2	Temperature from Website in Wildwood	0.01939	0.04890	0.40	0.695
x^3	Humidity from Website in Wildwood	1.0323	0.6145	1.68	0.105
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-	-	-	-
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.398758					
R-Sq=96.6%					
P=0.000					

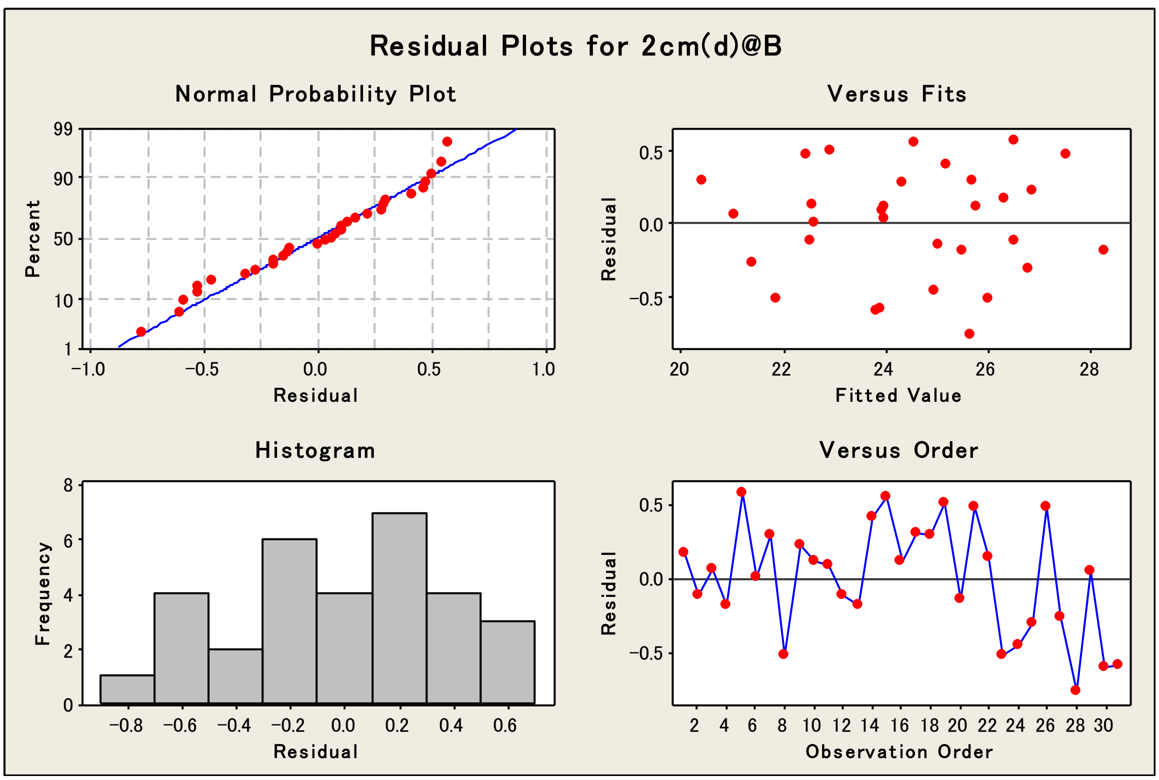


Figure 85: Residual Plots for 2cm Damaged Area at Bridge without Dew Point, Pressure and Wind Speed

Finally, from the results above, the equation to calculate the concrete surface temperature at the bridge was developed using significant factors from the results above. Since there is little difference between the results at the bridge using pressure and humidity, two equations were developed and compared. Table 50, 51, Figure 86 and 87 show the results. When comparing the R-square, there is no difference between them.

Table 50: Regression Analysis Result of 2cm Damaged Area at Bridge (Final-1)

The regression equation					
$y = - 52.2 + 0.582 x^1 + 0.219 x^2 - 0.130 x^3 + 0.59 x^4 + 0.328 x^5 + 1.17 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 2cm Damaged Area at UCF	0.5824	0.3759	1.55	0.134
x^2	Ambient Air Temperature at UCF	0.2195	0.3124	0.70	0.489
x^3	Temperature from Website in Orlando	-0.1303	0.1737	-0.75	0.460
x^4	Pressure from Website in Orlando	0.593	5.688	0.10	0.918
x^5	Temperature from Website in Wildwood	0.3283	0.1167	2.81	0.010
x^6	Pressure from Website in Wildwood	1.171	5.433	0.22	0.831
S=0.763907					
R-Sq=88.8%					
P=0.000					

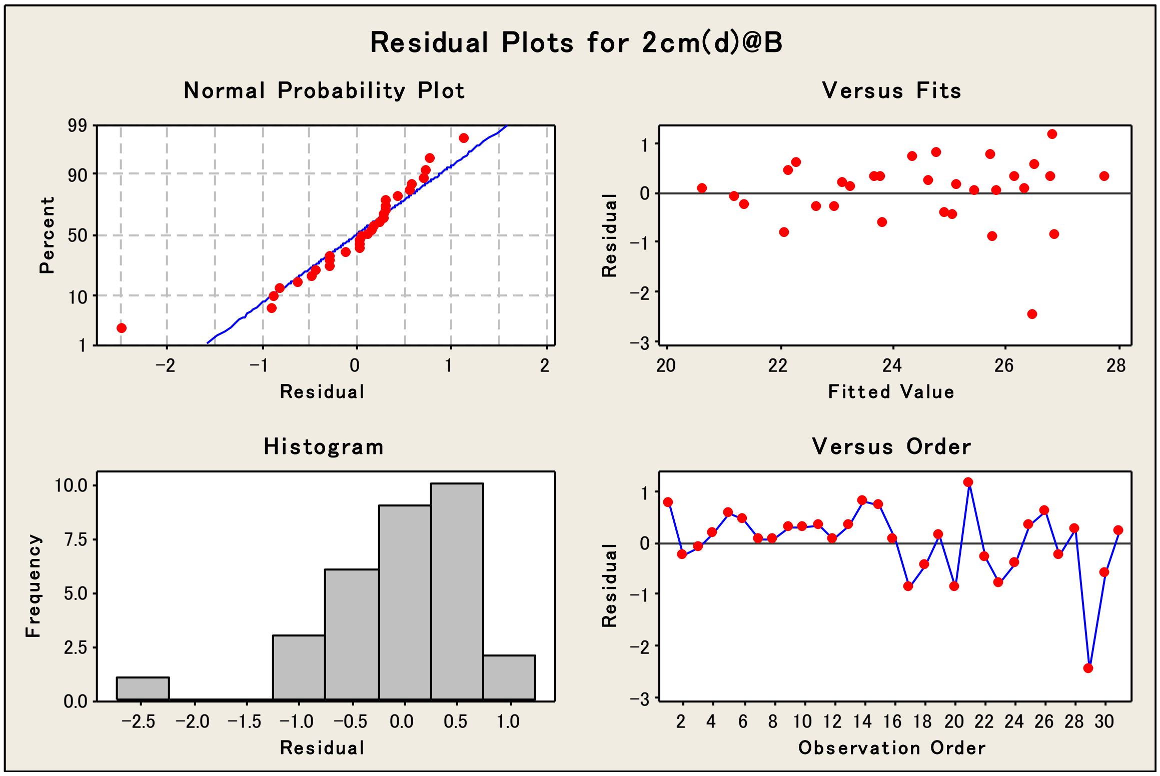


Figure 86: Residual Plots for 2cm Damaged Area at Bridge (Final-1)

Table 51: Regression Analysis Result of 2cm Damaged Area at Bridge (Final-2)

The regression equation					
$y = - 40.5 + 0.538 x^1 + 0.253 x^2 - 0.122 x^3 + 1.41 x^4 + 0.297 x^5 - 0.43 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 2cm Damaged Area at UCF	0.5377	0.3953	1.36	0.186
x^2	Ambient Air Temperature at UCF	0.2527	0.3420	0.74	0.467
x^3	Temperature from Website in Orlando	-0.1218	0.1516	-0.80	0.430
x^4	Pressure from Website in Orlando	1.409	2.388	0.59	0.561
x^5	Temperature from Website in Wildwood	0.2972	0.1153	2.58	0.017
x^6	Humidity from Website in Wildwood	-0.428	1.45	-0.30	0.770
S=0.763260					
R-Sq=88.8%					
P=0.000					

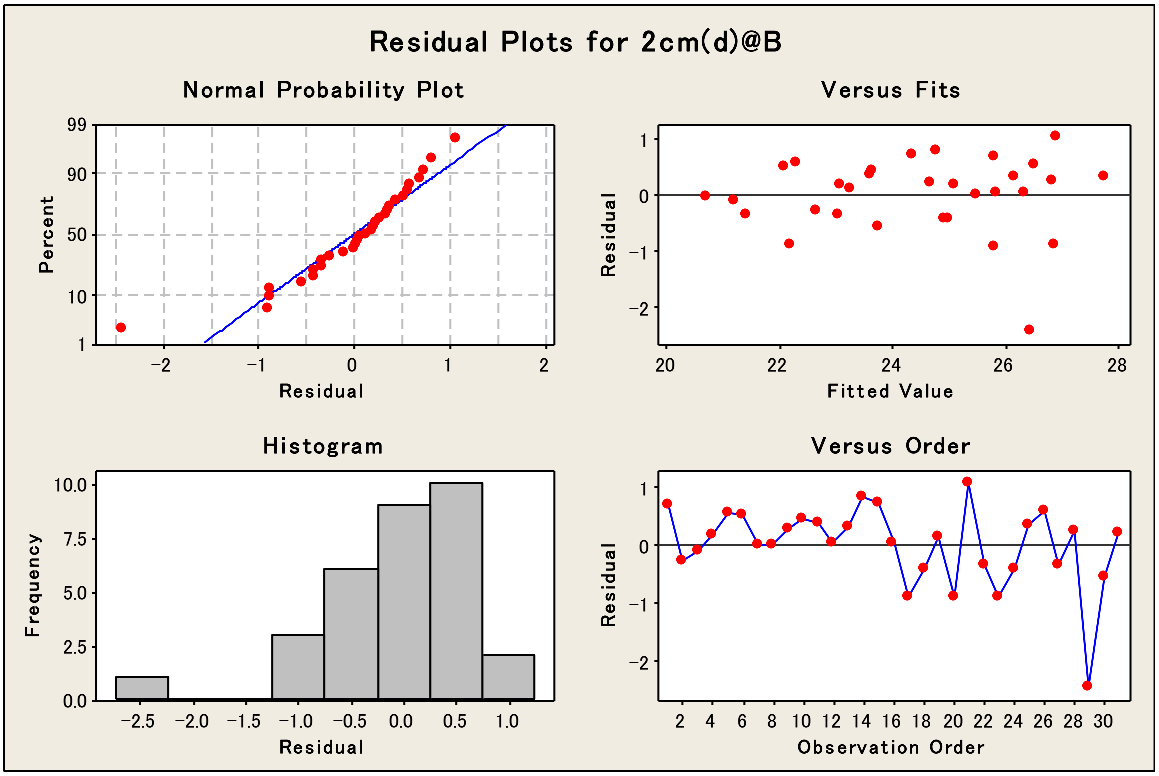


Figure 87: Residual Plots for 2cm Damaged Area at Bridge (Final-2)

Next is about the results of sound area. Table 52and Figure 88 show the result on campus with all factors. It shows that the factor of pressure is significant, since the P value of the pressure is 0. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 53 and Figure 89 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 52: Regression Analysis Result of 2cm Sound Area on Campus with All Data

The regression equation					
$y = 139 + 0.751 x^1 - 0.038 x^2 + 0.61 x^3 - 0.079 x^4 - 4.36 x^5 - 0.0181 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.75098	0.08107	9.26	0.000
x^2	Temperature from Website in Orlando	-0.0379	0.2073	-0.18	0.856
x^3	Humidity from Website in Orlando	0.615	4.424	0.14	0.891
x^4	Dew Point from Website in Orlando	-0.0787	0.1906	-0.41	0.683
x^5	Pressure from Website in Orlando	-4.3584	0.9331	-4.67	0.000
x^6	Wind Speed from Website in Orlando	-0.01806	0.01825	-0.99	0.332
S=0.34665					
R-Sq=95.4%					
P=0.000					

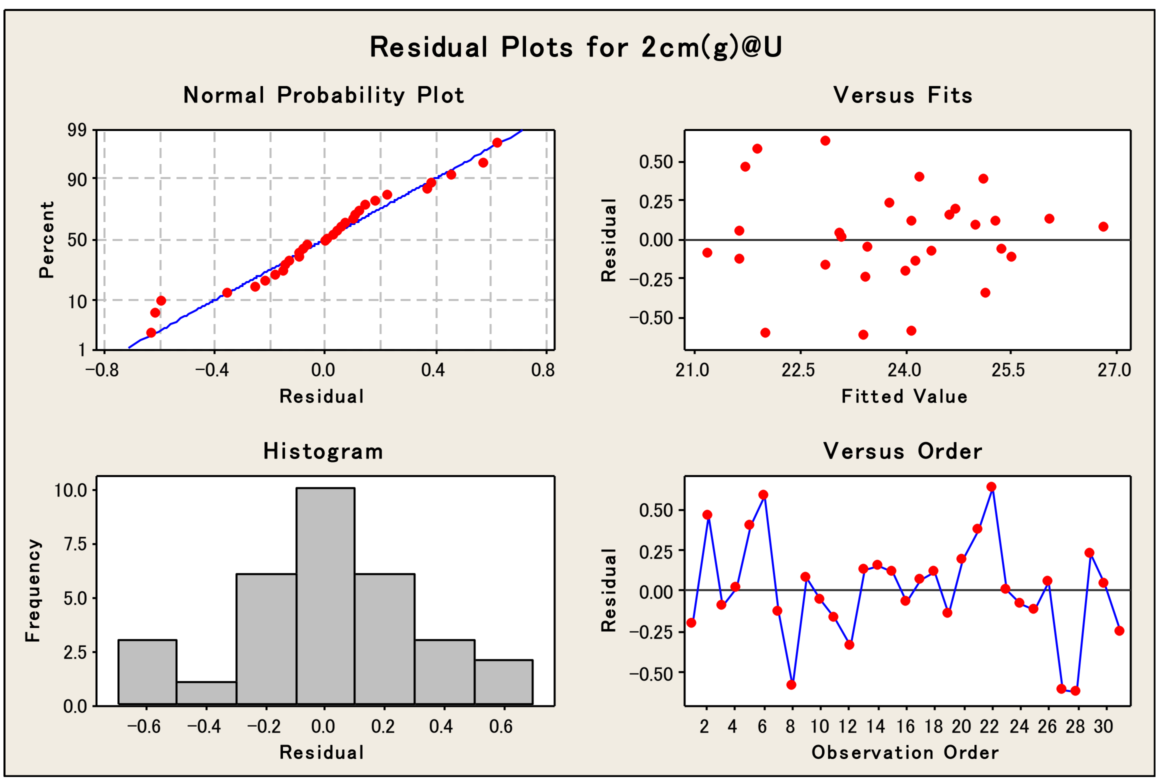


Figure 88: Residual Plots for 2cm Sound Area on Campus with All Data

Table 53: Regression Analysis Result of 2cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 111 + 0.752\, x^1 - 0.0773\, x^2 - 3.44\, x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.78232	0.07327	10.27	0.000
x^2	Temperature from Website in Orlando	-0.07734	0.03811	-2.03	0.052
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	-3.4427	0.6824	-5.05	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=0.343785					
R-Sq=94.9%					
P=0.000					

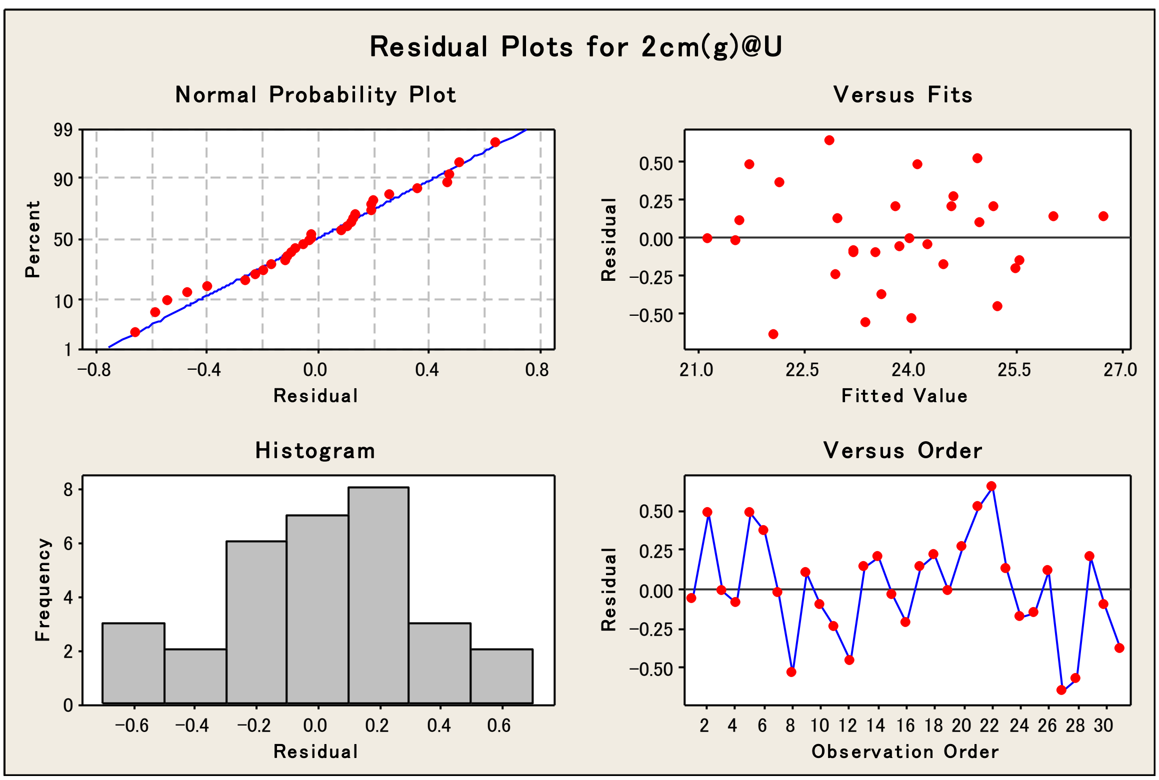


Figure 89: Residual Plots for 2cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

Next, the analysis for the bridge is conducted. Table 54 and Figure 90 show the results at the bridge. Same as the result of damaged area, it is found the pressure factor is not significant. Instead of it, the factor of humidity is the most significant, since its P value is smaller than α=0.05. Then, analyses using the pressure factor same as the past analyses and using humidity factor were conducted and compared. Table 55 and Figure 91 show the result without humidity, dew point and wind speed, or with pressure. Table 56 and Figure 92 show the result without dew point, pressure and wind speed, or with humidity. When comparing the R-square, there is little difference between the result with pressure and that with humidity.

Table 54: Regression Analysis Result of 2cm Sound Area at Bridge with All Data

The regression equation					
$y = 33.0 + 0.636 x^1 + 0.255 x^2 + 6.49 x^3 - 0.230 x^4 - 1.02 x^5 + 0.0063 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.63647	0.07632	8.34	0.000
x^2	Temperature from Website in Wildwood	0.2549	0.1337	1.91	0.069
x^3	Humidity from Website in Wildwood	6.488	3.037	2.14	0.043
x^4	Dew Point from Website in Wildwood	-0.2303	0.1144	-2.01	0.055
x^5	Pressure from Website in Wildwood	-1.0210	0.9061	-1.13	0.271
x^6	Wind Speed from Website in Wildwood	0.00630	0.03403	0.19	0.855
S=0.431219					
R-Sq=96.3%					
P=0.000					

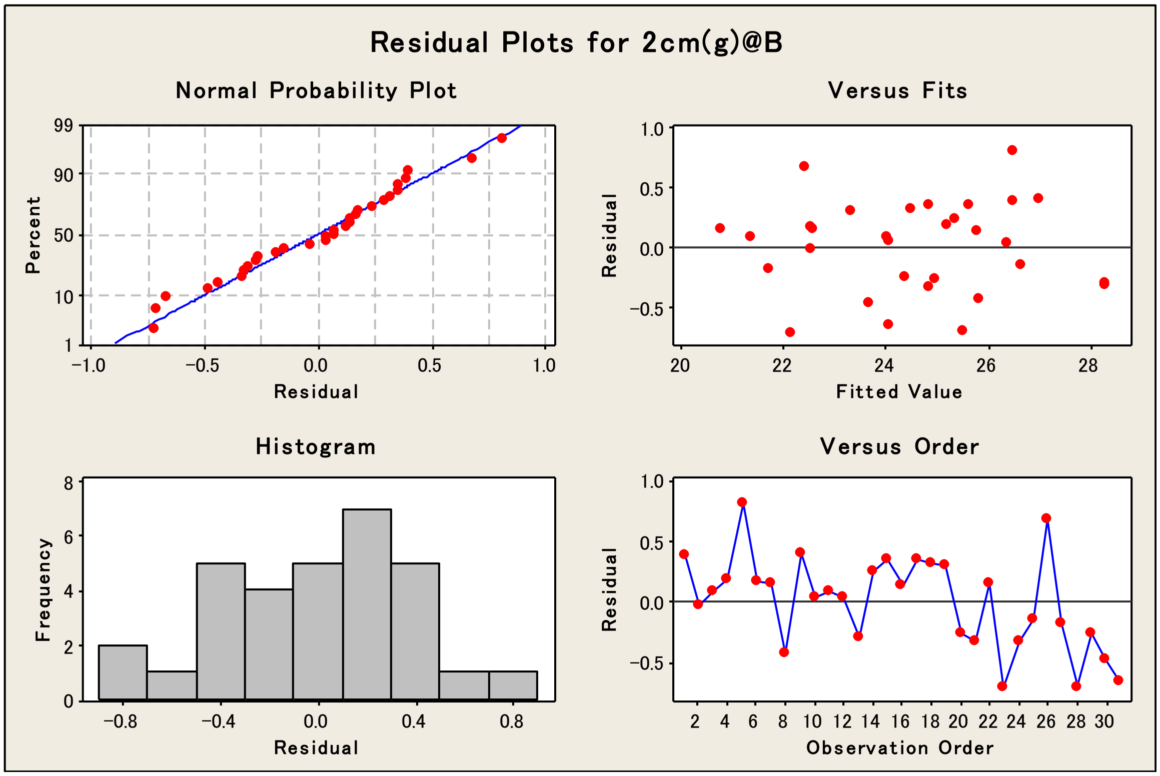


Figure 90: Residual Plots for 2cm Sound Area at Bridge with All Data

Table 55: Regression Analysis Result of 2cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 54.5 + 0.667 x^1 - 0.0162 x^2 - 1.53 x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.66736	0.06932	9.63	0.000
x^2	Temperature from Website in Wildwood	-0.01620	0.04616	-0.35	0.728
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-1.5265	0.8312	-1.84	0.077
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.452667					
R-Sq=95.4%					
P=0.000					

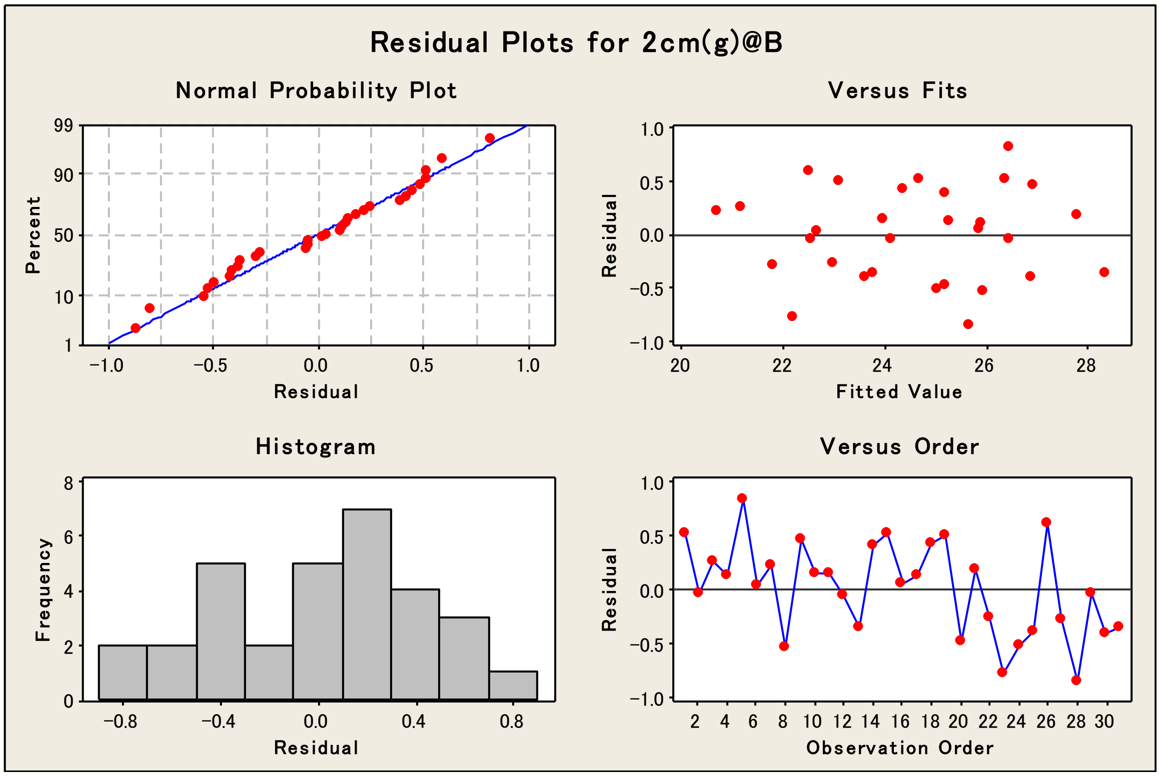


Figure 91: Residual Plots for 2cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

Table 56: Regression Analysis Result of 2cm Sound Area at Bridge without Dew Point, Pressure and Wind Speed

The regression equation					
$y = 6.97 + 0.685 x^1 + 0.0153 x^2 + 0.799 x^3$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.68505	0.07090	9.66	0.000
x^2	Temperature from Website in Wildwood	0.01533	0.05754	0.27	0.792
x^3	Humidity from Website in Wildwood	0.7991	0.7231	1.11	0.279
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-	-	-	-
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.469191					
R-Sq=95.0%					
P=0.000					

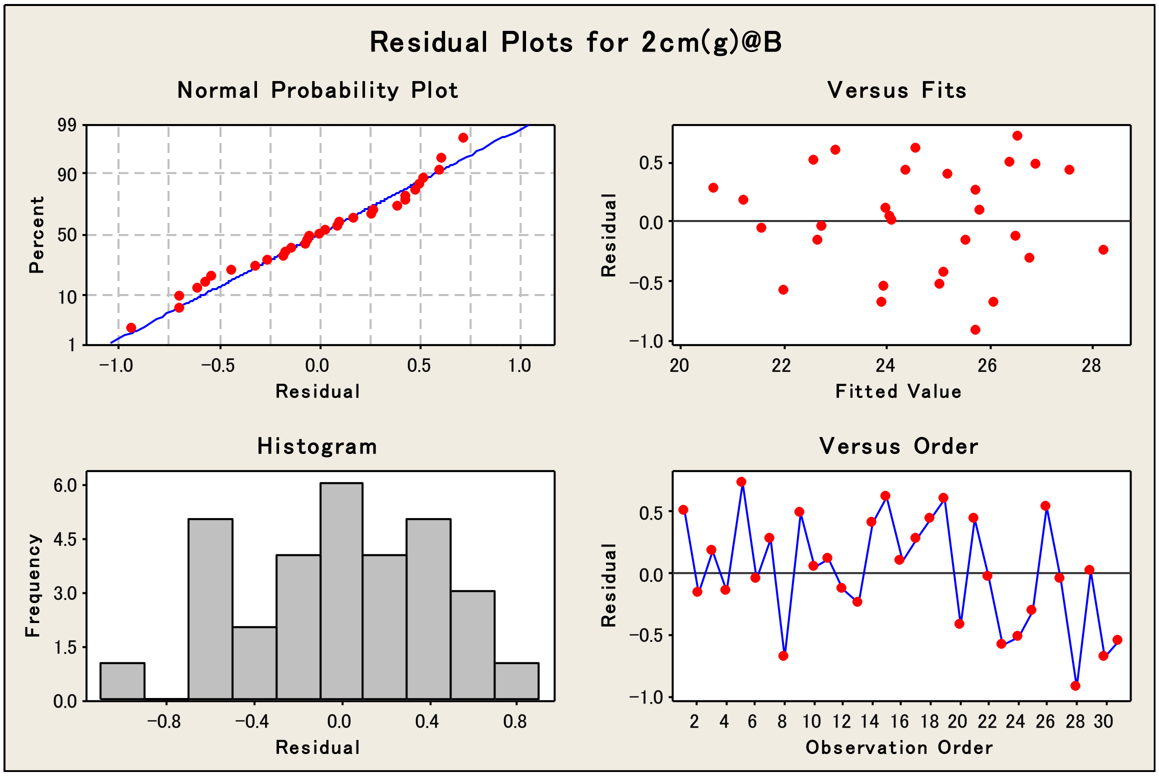


Figure 92: Residual Plots for 2cm Sound Area at Bridge without Dew Point, Pressure and Wind Speed

Finally, from the results above, the equation to calculate the concrete surface temperature at the bridge was developed using significant factors from the results above. Since there is little difference between the results at the bridge using pressure and humidity, two equations were developed and compared. Table 57, 58, Figure 93 and 94 show the results. When comparing the R-square, there is no difference between them.

Table 57: Regression Analysis Result of 2cm Sound Area at Bridge (Final-1)

The regression equation					
$y = -41.2 + 0.547x^1 + 0.179x^2 - 0.119x^3 + 1.41x^4 + 0.317x^5 + 0.05x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 2cm Sound Area at UCF	0.5474	0.4529	1.21	0.239
x^2	Ambient Air Temperature at UCF	0.1793	0.3863	0.46	0.647
x^3	Temperature from Website in Orlando	-0.0664	0.1025	-0.65	0.524
x^4	Pressure from Website in Orlando	1.413	6.075	0.23	0.818
x^5	Temperature from Website in Wildwood	0.3167	0.1219	2.6	0.016
x^6	Pressure from Website in Wildwood	0.047	5.715	0.01	0.994
S=0.806231					
R-Sq=87.0%					
P=0.000					

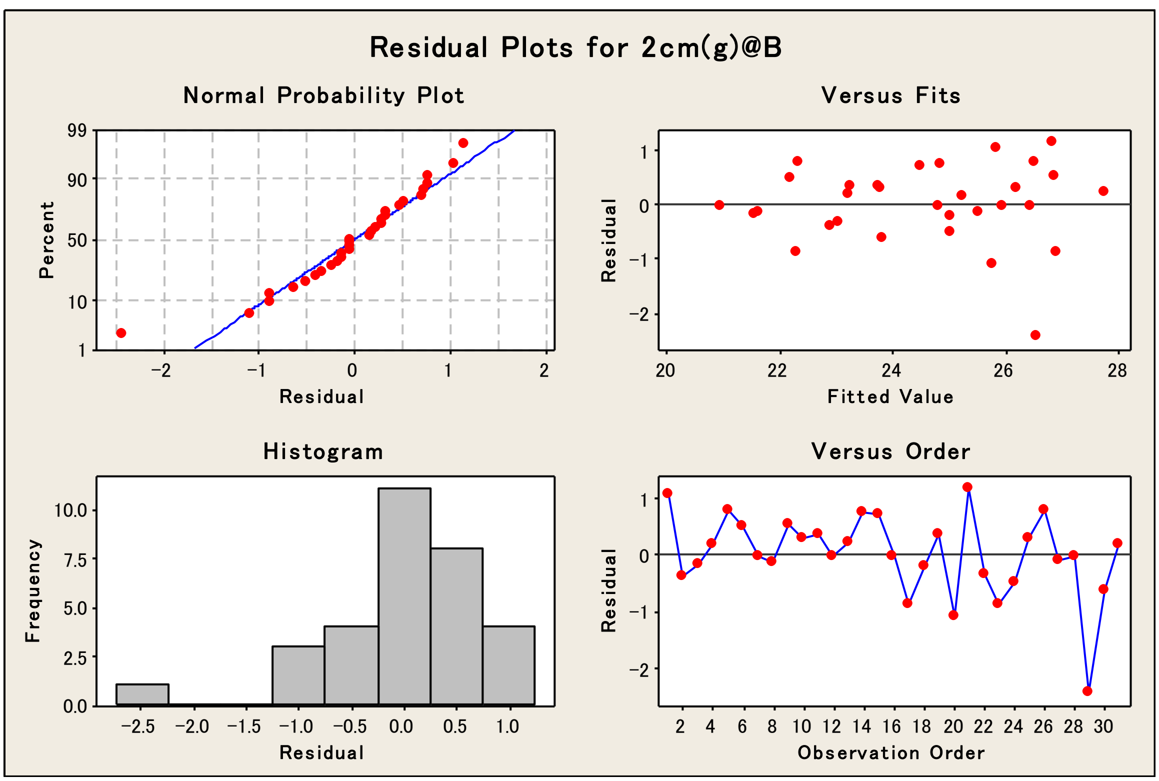


Figure 93: Residual Plots for 2cm Sound Area at Bridge (Final-1)

Table 58: Regression Analysis Result of 2cm Sound Area at Bridge (Final-2)

The regression equation					
$y = -21.4 + 0.467 x^1 + 0.264 x^2 - 0.0766 x^3 + 0.93 x^4 + 0.292 x^5 - 0.61 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 2cm Sound Area at UCF	0.4669	0.4976	0.94	0.357
x^2	Ambient Air Temperature at UCF	0.2638	0.4399	0.60	0.554
x^3	Temperature from Website in Orlando	-0.07662	0.09095	-0.84	0.408
x^4	Pressure from Website in Orlando	0.929	2.675	0.35	0.731
x^5	Temperature from Website in Wildwood	0.2915	0.1214	2.40	0.024
x^6	Humidity from Website in Wildwood	-0.611	1.594	-0.38	0.705
S=0.803772					
R-Sq=87.0%					
P=0.000					

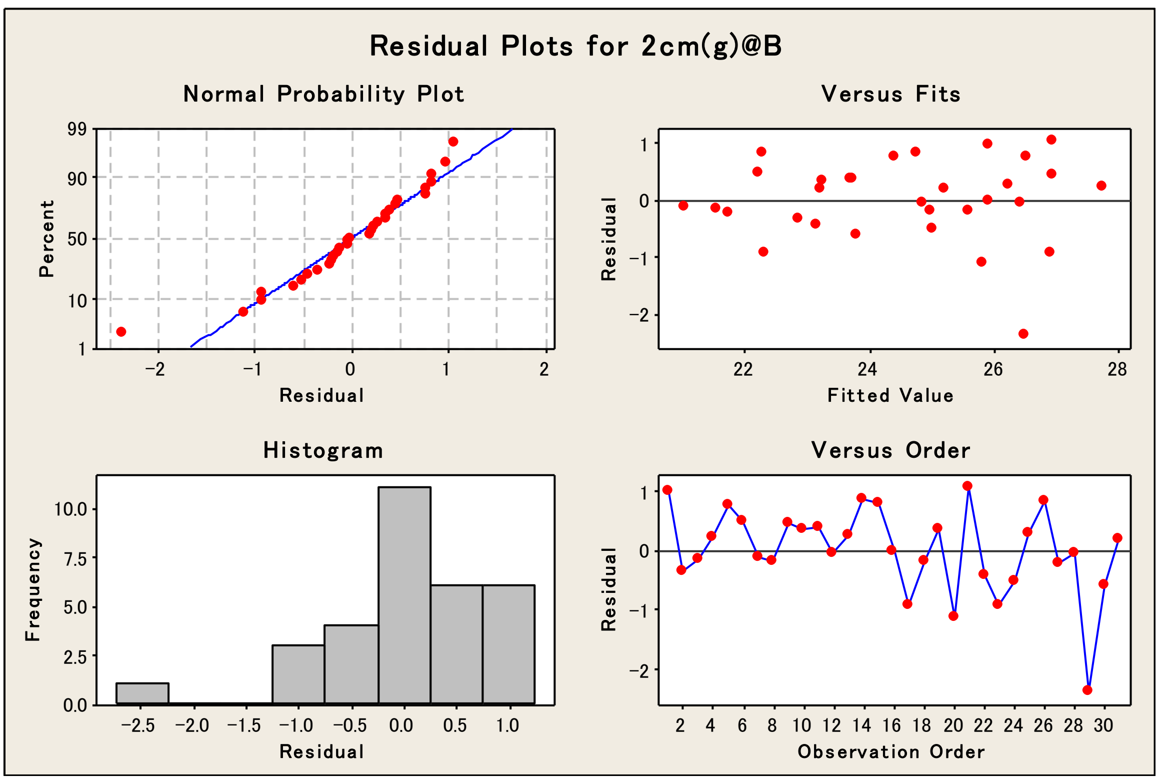


Figure 94: Residual Plots for 2cm Sound Area at Bridge (Final-2)

3cm Thickness

The first is about the results of damaged area. Table 59 and Figure 95 show the result on campus with all factors. As the past results, it shows that the factor of pressure is significant, since the P value of the pressure is 0. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 60 and Figure 96 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 59: Regression Analysis Result of 3cm Damaged Area on Campus with All Data

The regression equation					
$y = 150 + 0.615 x^1 + 0.056 x^2 + 1.61 x^3 - 0.088 x^4 - 4.72 x^5 - 0.0353 x^6$					
Predictor		Coef	SE Coef	T	P
X^1	Ambient Air Temperature at UCF	0.6153	0.1049	5.86	0.000
x^2	Temperature from Website in Orlando	0.0556	0.2683	0.21	0.838
x^3	Humidity from Website in Orlando	1.613	5.727	0.28	0.781
x^4	Dew Point from Website in Orlando	-0.0879	0.2467	-0.36	0.725
x^5	Pressure from Website in Orlando	-4.724	1.208	-3.91	0.001
x^6	Wind Speed from Website in Orlando	-0.03530	0.02363	-1.49	0.148
S=0.448764					
R-Sq=91.7%					
P=0.000					

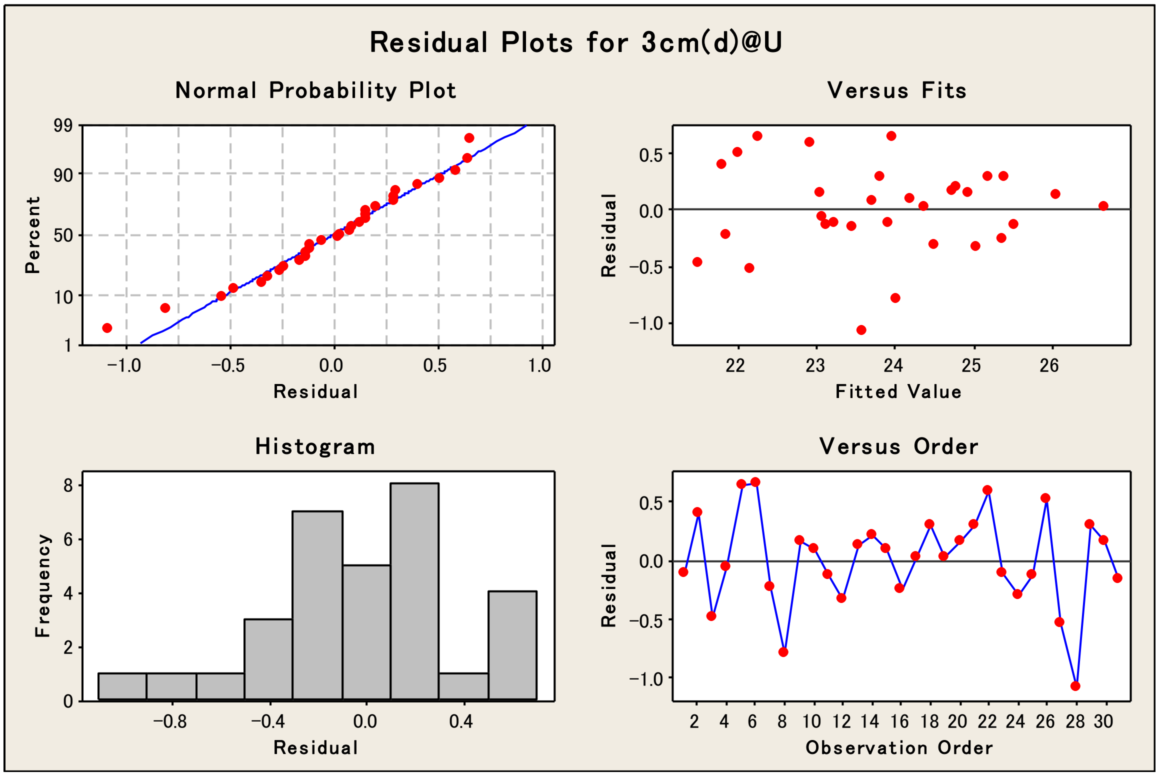


Figure 95: Residual Plots for 3cm Damaged Area on Campus with All Data

Table 60: Regression Analysis Result of 3cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 133 + 0.657 x^1 - 0.0593 x^2 - 4.12 x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.65743	0.09444	6.96	0.000
x^2	Temperature from Website in Orlando	-0.05930	0.04912	-1.21	0.238
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	-4.1155	0.8796	-4.68	0.000
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=0.443123					
R-Sq=90.9%					
P=0.000					

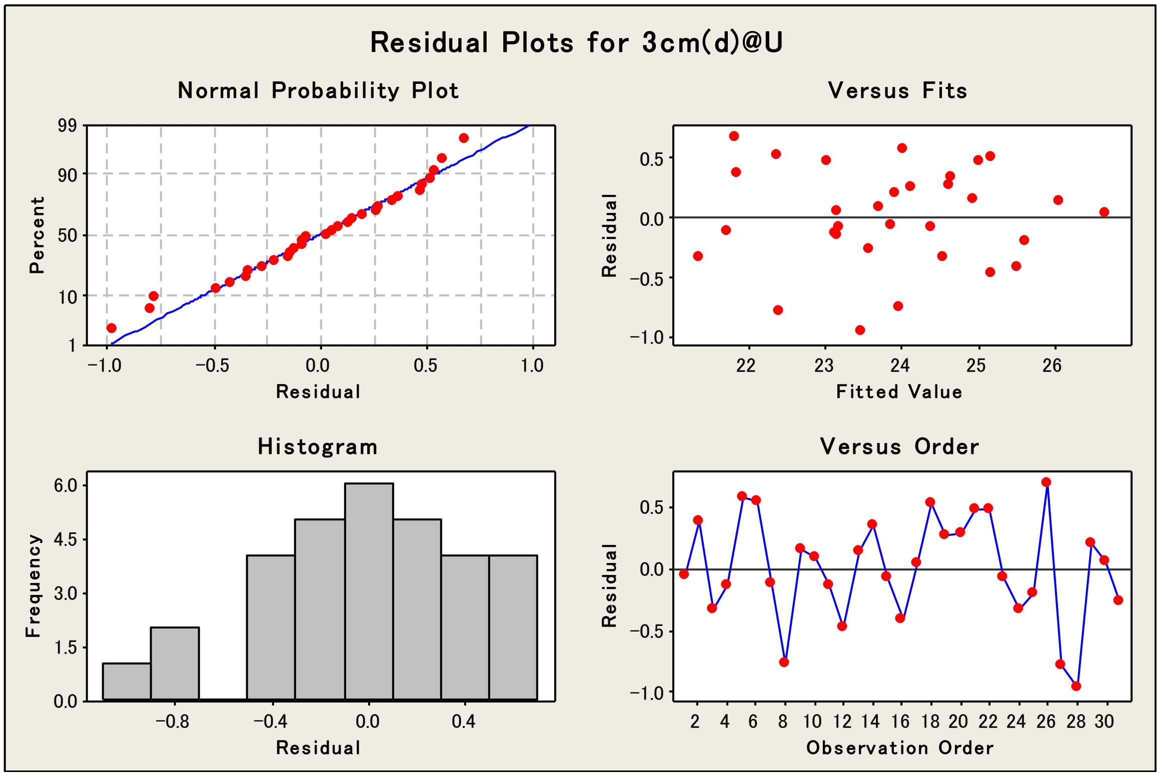


Figure 96: Residual Plots for 3cm Damaged Area on Campus without Humidity, Dew Point and Wind Speed

Next, the analysis for the bridge is conducted. Table 61 and Figure 97 show the results at the bridge. This result also presents the pressure factor is not significant. There is no factors whose P values are less than α=0.05. Suffice it to say that the factor of humidity is the most significant, even its P value is larger than α=0.05. Then, analyses using the pressure factor same as the past analyses and using humidity factor were conducted and compared. Table 62 and Figure 98 show the result without humidity, dew point and wind speed, or with pressure. When comparing the R-square, there is little difference between the result with pressure and that with humidity.

Table 61: Regression Analysis Result of 3cm Damaged Area at Bridge with All Data

The regression equation					
$y = 45.9 + 0.654\ x^1 + 0.177\ x^2 + 5.41\ x^3 - 0.182\ x^4 - 1.41\ x^5 - 0.0021\ x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.65363	0.07485	8.73	0.000
x^2	Temperature from Website in Wildwood	0.1775	0.1311	1.35	0.188
x^3	Humidity from Website in Wildwood	5.405	2.979	1.81	0.082
x^4	Dew Point from Website in Wildwood	-0.1816	0.1122	-1.62	0.118
x^5	Pressure from Website in Wildwood	-1.4064	0.8886	-1.58	0.127
x^6	Wind Speed from Website in Wildwood	-0.00210	0.03338	-0.06	0.950
S=0.422903					
R-Sq=96.0%					
P=0.000					

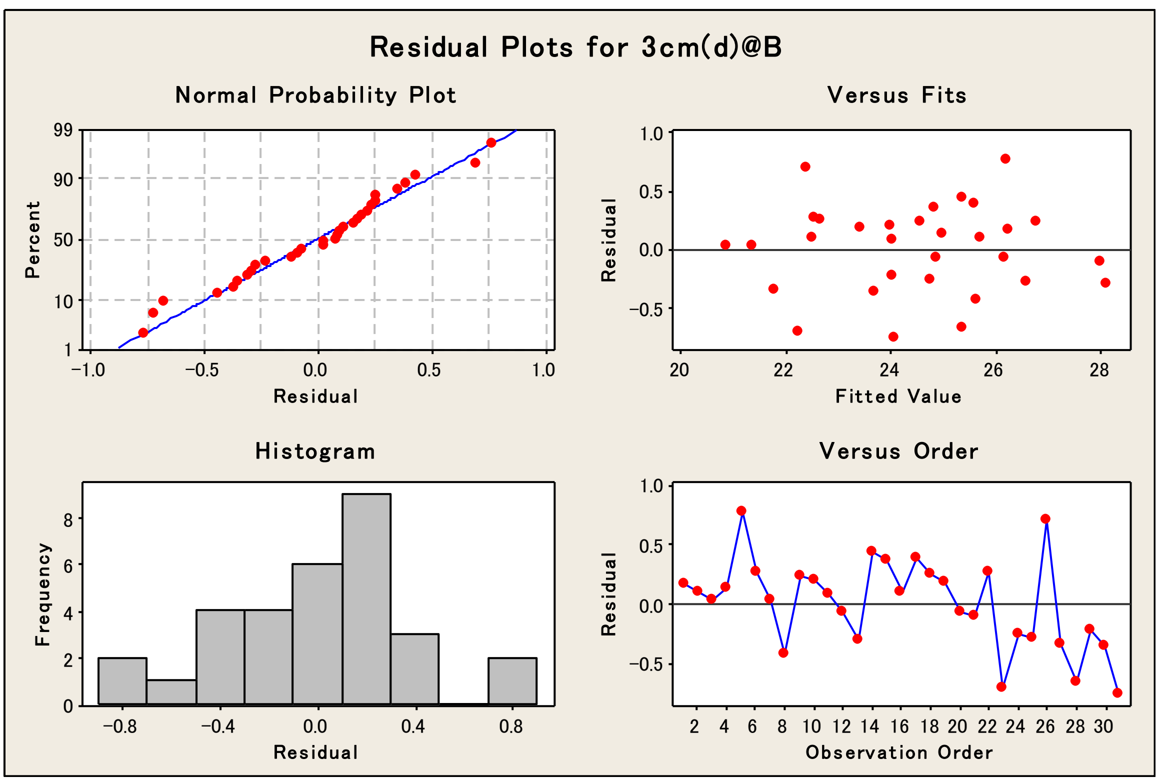


Figure 97: Residual Plots for 3cm Damaged Area at Bridge with All Data

Table 62: Regression Analysis Result of 3cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 68.0 + 0.672\ x^1 - 0.0490\ x^2 - 1.96\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.67156	0.06665	10.08	0.000
x^2	Temperature from Website in Wildwood	-0.04900	0.04437	-1.10	0.279
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-1.9570	0.7991	-2.45	0.021
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.434799					
R-Sq=95.3%					
P=0.000					

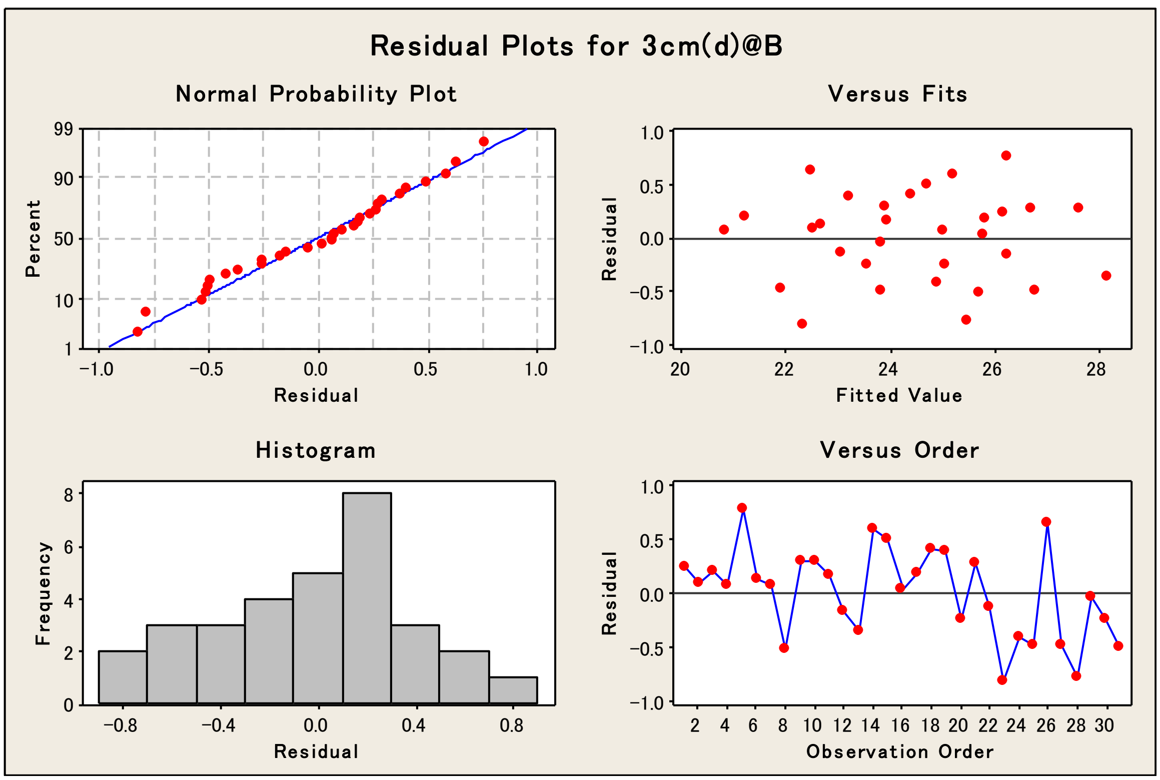


Figure 98: Residual Plots for 3cm Damaged Area at Bridge without Humidity, Dew Point and Wind Speed

Finally, from the results above, the equation to calculate the concrete surface temperature at the bridge was developed using significant factors from the results above. Since there is little difference between the results at the bridge using pressure and humidity, two equations were developed and compared. Table 63, 64, Figure 99 and 100 show the results. When comparing the R-square, there is no difference between them.

Table 63: Regression Analysis Result of 3cm Damaged Area at Bridge (Final-1)

The regression equation					
$y = -57.1 + 0.724 x^1 + 0.113 x^2 - 0.141 x^3 + 1.93 x^4 + 0.308 x^5 - 0.01 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 3cm Damaged Area at UCF	0.7242	0.3332	2.17	0.040
x^2	Ambient Air Temperature at UCF	0.1128	0.2797	0.40	0.690
x^3	Temperature from Website in Orlando	-0.1407	0.1709	-0.82	0.418
x^4	Pressure from Website in Orlando	1.933	5.677	0.34	0.736
x^5	Temperature from Website in Wildwood	0.3078	0.1149	2.68	0.013
x^6	Pressure from Website in Wildwood	-0.010	5.327	0.00	0.998
S=0.751857					
R-Sq=87.5%					
P=0.000					

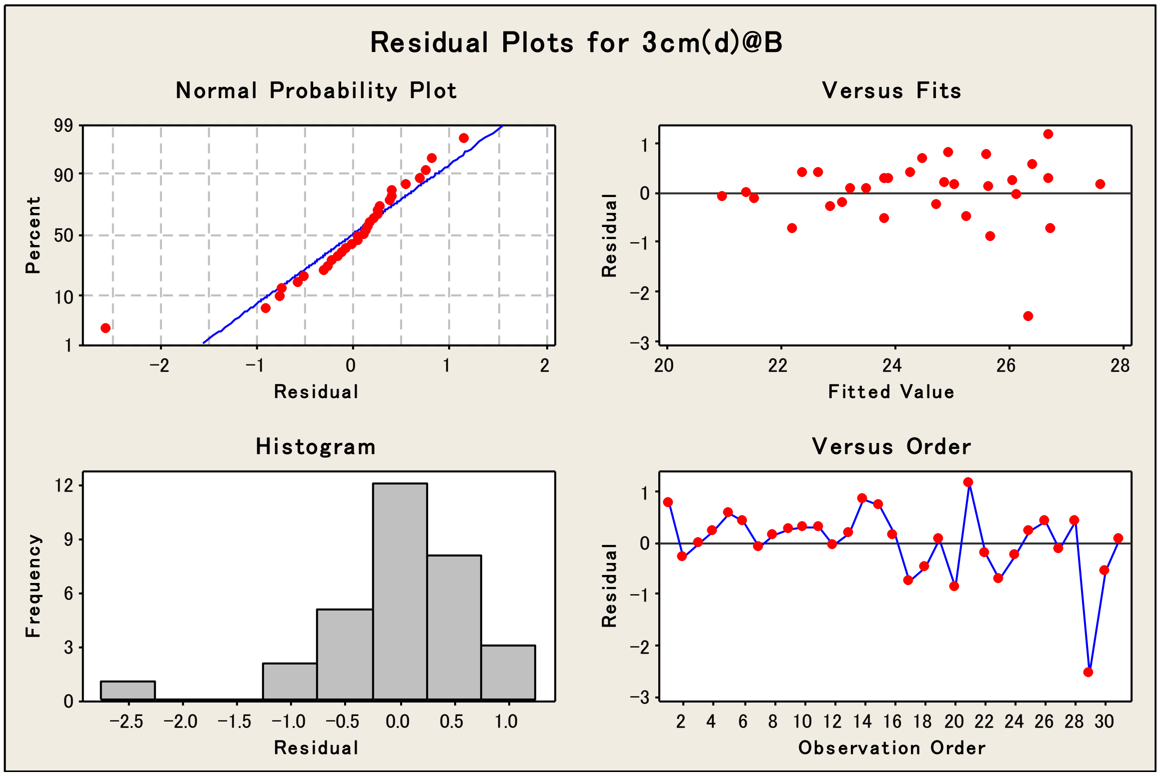


Figure 99: Residual Plots for 3cm Damaged Area at Bridge (Final-1)

Table 64: Regression Analysis Result of 3cm Damaged Area at Bridge (Final-2)

The regression equation					
$y = -47.4 + 0.700\ x^1 + 0.148\ x^2 - 0.152\ x^3 + 1.63\ x^4 + 0.288\ x^5 - 0.48\ x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 3cm Damaged Area at UCF	0.7001	0.3396	2.06	0.050
x^2	Ambient Air Temperature at UCF	0.1480	0.2881	0.51	0.612
x^3	Temperature from Website in Orlando	-0.1521	0.1472	-1.03	0.312
x^4	Pressure from Website in Orlando	1.628	2.207	0.74	0.468
x^5	Temperature from Website in Wildwood	0.2884	0.1129	2.55	0.017
x^6	Humidity from Website in Wildwood	-0.477	1.378	-0.35	0.732
S=0.749986					
R-Sq=87.5%					
P=0.000					

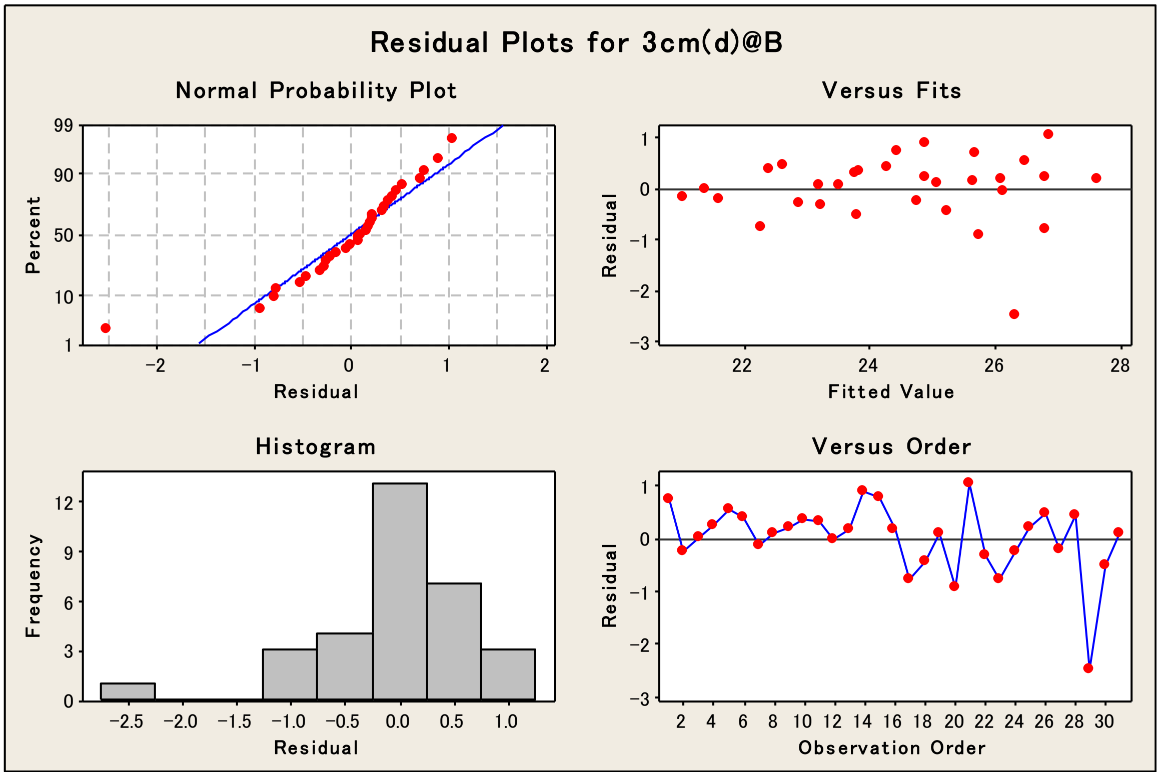


Figure 100: Residual Plots for 3cm Damaged Area at Bridge (Final-2)

Next is about the results of sound area. Table 65 and Figure 101 show the result on campus with all factors. It shows that the factor of pressure is significant, since its P value of the pressure is smaller than α=0.05. Then, the equation to calculate the concrete surface temperature was developed using pressure factor. Table 66 and Figure 102 show the result of it. When looking at the R-square, it still gives a large percentage, it can be said that the equation is fine.

Table 65: Regression Analysis Result of 3cm Sound Area on Campus with All Data

The regression equation					
$y = 126 + 0.615\,x^1 + 0.136\,x^2 + 3.31\,x^3 - 0.159\,x^4 - 3.98\,x^5 - 0.0370\,x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.6148	0.1044	5.89	0.000
x^2	Temperature from Website in Orlando	0.1364	0.2668	0.51	0.614
x^3	Humidity from Website in Orlando	3.312	5.695	0.58	0.566
x^4	Dew Point from Website in Orlando	-0.1587	0.2453	-0.65	0.524
x^5	Pressure from Website in Orlando	-3.985	1.201	-3.32	0.003
x^6	Wind Speed from Website in Orlando	-0.03702	0.02349	-1.58	0.128
S=0.446208					
R-Sq=91.4%					
P=0.000					

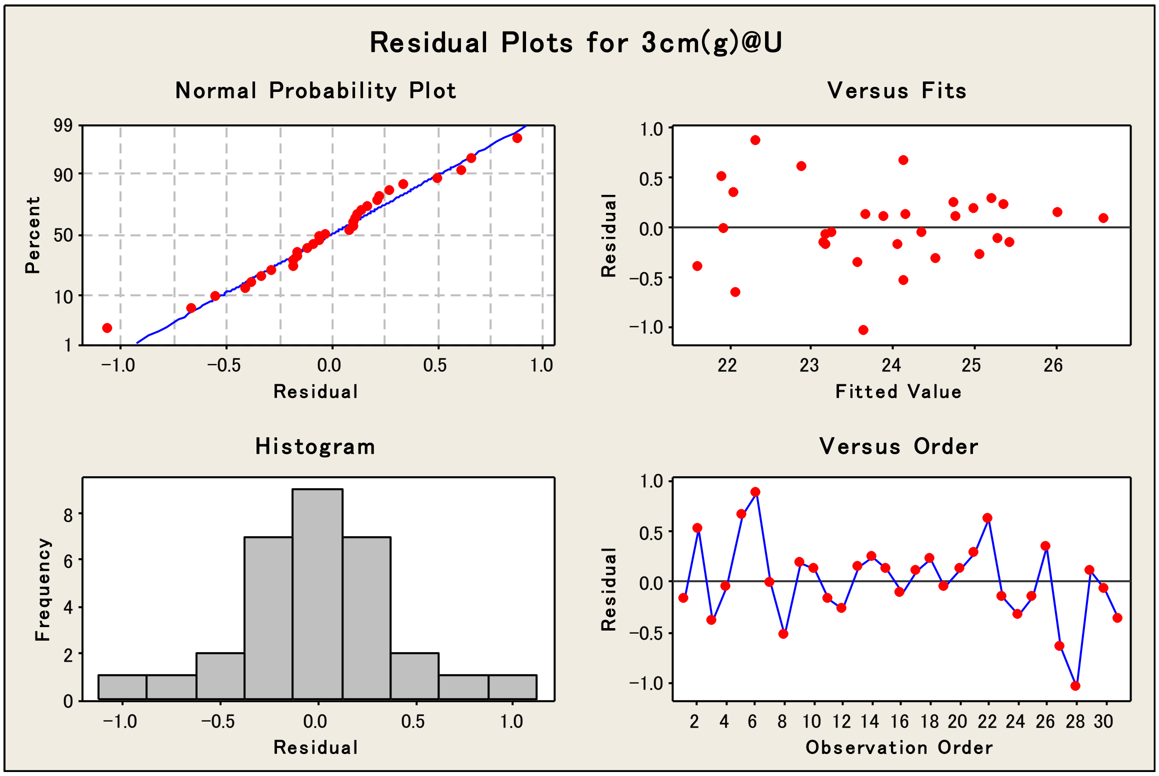


Figure 101: Residual Plots for 3cm Sound Area on Campus with All Data

Table 66: Regression Analysis Result of 3cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 109 + 0.663\ x^1 - 0.0561\ x^2 - 3.32\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at UCF	0.66329	0.09436	7.03	0.000
x^2	Temperature from Website in Orlando	-0.05614	0.04908	-1.14	0.263
x^3	Humidity from Website in Orlando	-	-	-	-
x^4	Dew Point from Website in Orlando	-	-	-	-
x^5	Pressure from Website in Orlando	-3.3169	0.8789	-3.77	0.001
x^6	Wind Speed from Website in Orlando	-	-	-	-
S=0.442768					
R-Sq=90.5%					
P=0.000					

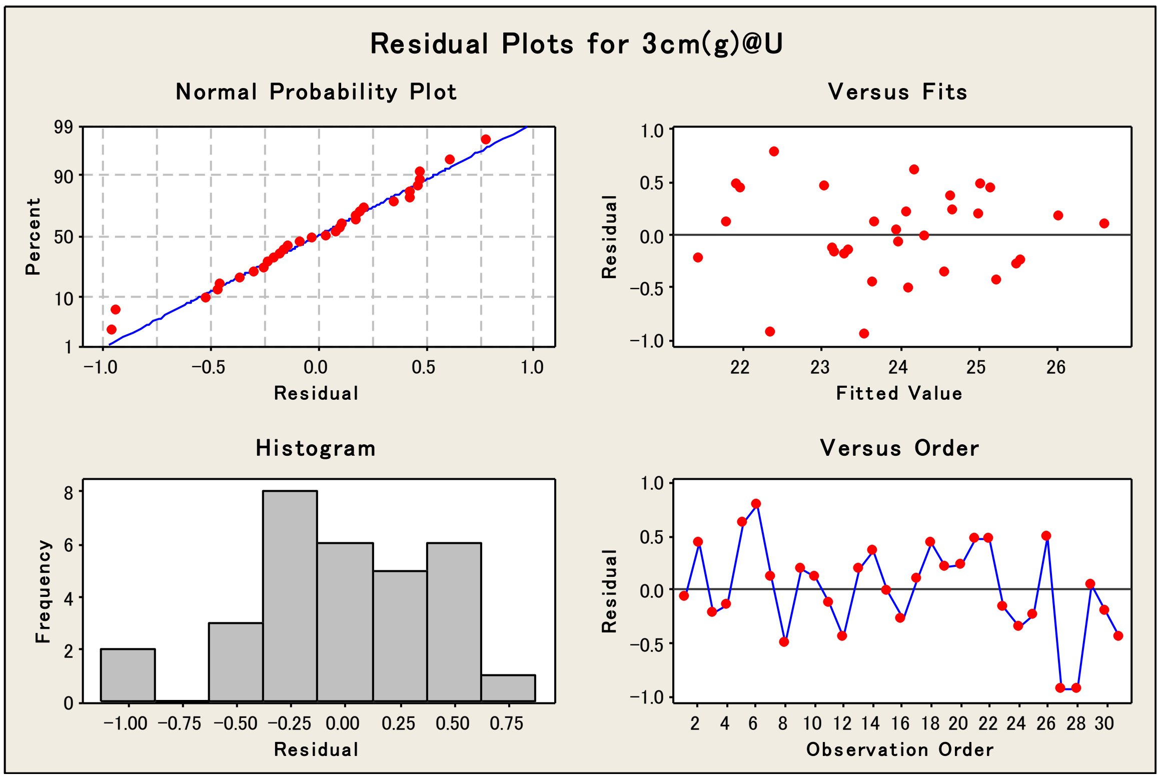


Figure 102: Residual Plots for 3cm Sound Area on Campus without Humidity, Dew Point and Wind Speed

Next, the analysis for the bridge is conducted. Table 67 and Figure 103 show the results at the bridge. Same as the result of damaged area, it is found the pressure factor is not significant. Instead of it, the factor of humidity is significant, since its P value is smaller than $\alpha=0.05$. Then, analyses using the pressure factor same as the past analyses and using humidity factor were conducted and compared. Table 68 and Figure 104 show the result without humidity, dew point and wind speed, or with pressure. Table 69 and Figure 105 show the result without dew point, pressure and wind speed, or with humidity. When comparing the R-square, there is little difference between the result with pressure and that with humidity.

Table 67: Regression Analysis Result of 3cm Sound Area at Bridge with All Data

The regression equation					
$y = 16.6 + 0.716 x^1 + 0.263 x^2 + 6.86 x^3 - 0.227 x^4 - 0.554 x^5 - 0.0107 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.71626	0.06981	10.26	0.000
x^2	Temperature from Website in Wildwood	0.2635	0.1223	2.15	0.041
x^3	Humidity from Website in Wildwood	6.857	2.778	2.47	0.021
x^4	Dew Point from Website in Wildwood	-0.2265	0.1046	-2.17	0.041
x^5	Pressure from Website in Wildwood	-0.5543	0.8288	-0.67	0.510
x^6	Wind Speed from Website in Wildwood	-0.01071	0.03113	-0.34	0.734
S=0.394442					
R-Sq=97.3%					
P=0.000					

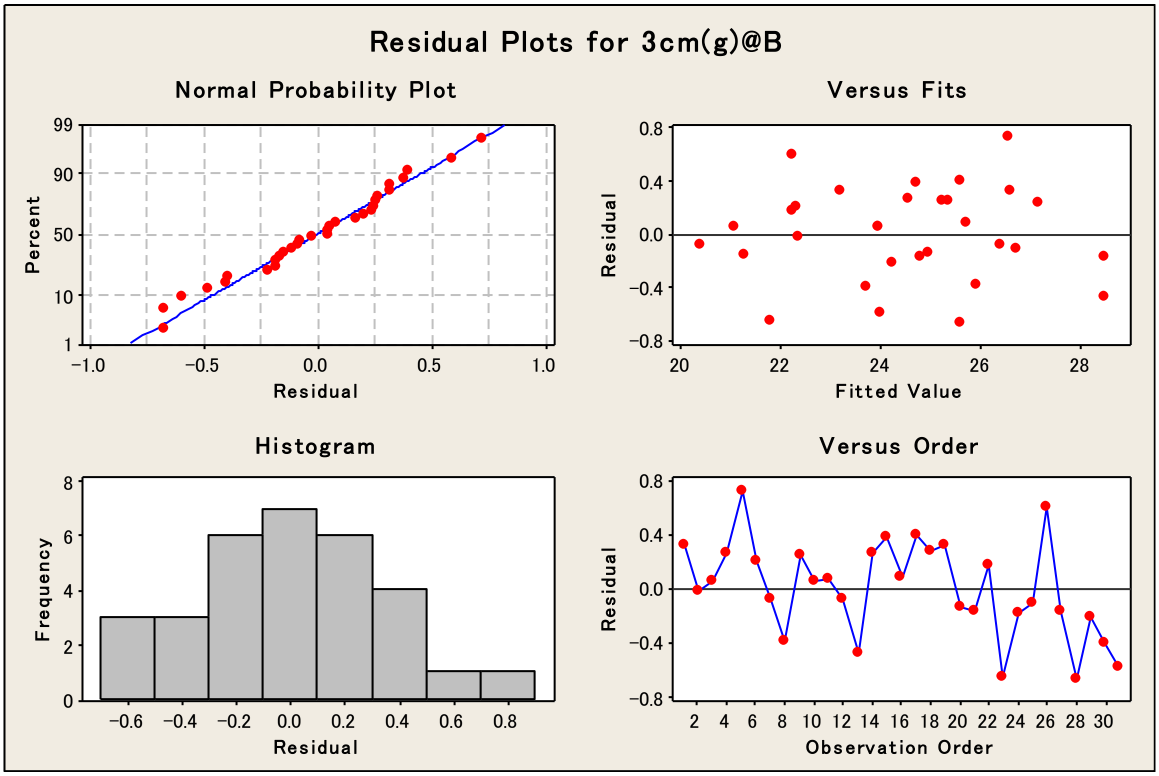


Figure 103: Residual Plots for 3cm Sound Area at Bridge with All Data

Table 68: Regression Analysis Result of 3cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

The regression equation					
$y = 46.2 + 0.732\ x^1 - 0.0243\ x^2 - 1.30\ x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.73163	0.06724	10.88	0.000
x^2	Temperature from Website in Wildwood	-0.02427	0.04477	-0.54	0.592
x^3	Humidity from Website in Wildwood	-	-	-	-
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-1.2982	0.8062	-1.61	0.119
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.438655					
R-Sq=96.2%					
P=0.000					

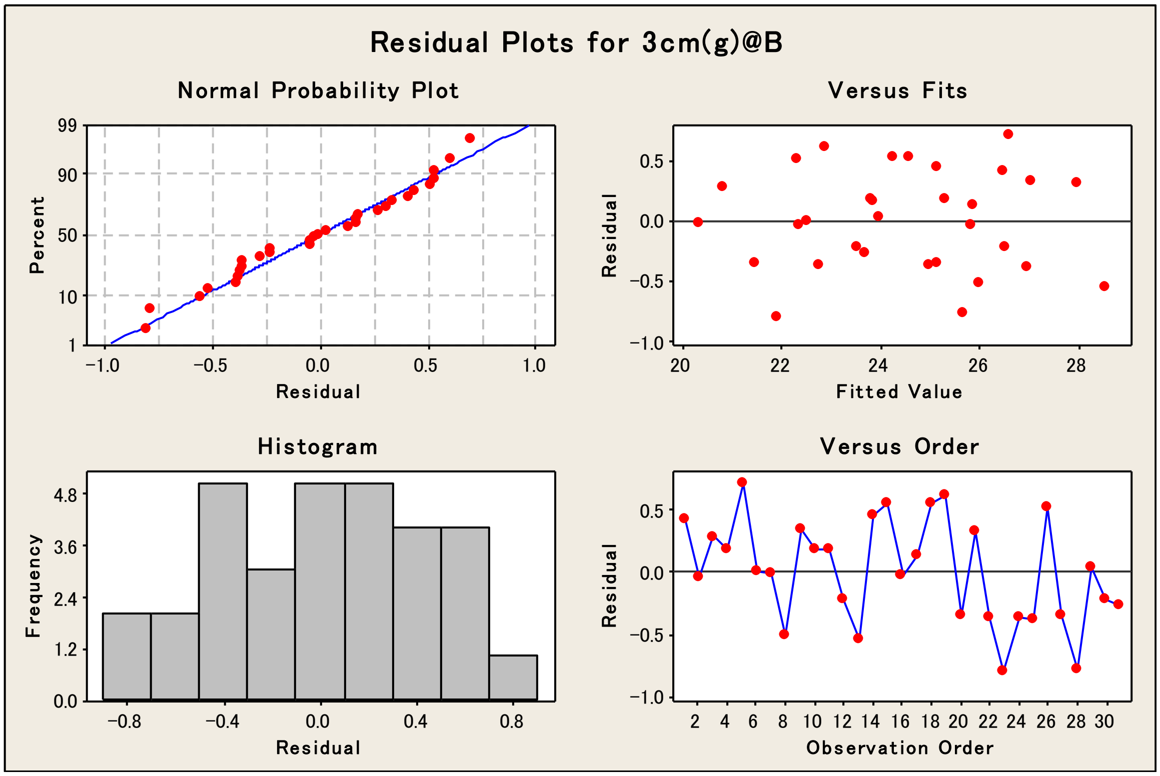


Figure 104: Residual Plots for 3cm Sound Area at Bridge without Humidity, Dew Point and Wind Speed

Table 69: Regression Analysis Result of 3cm Sound Area at Bridge without Dew Point, Pressure and Wind Speed

The regression equation					
$y = 5.34 + 0.745 x^1 + 0.0149 x^2 + 0.958 x^5$					
Predictor		Coef	SE Coef	T	P
x^1	Ambient Air Temperature at Bridge	0.74488	0.06700	11.12	0.000
x^2	Temperature from Website in Wildwood	0.01486	0.05437	0.27	0.787
x^3	Humidity from Website in Wildwood	0.9581	0.6833	1.40	0.172
x^4	Dew Point from Website in Wildwood	-	-	-	-
x^5	Pressure from Website in Wildwood	-	-	-	-
x^6	Wind Speed from Website in Wildwood	-	-	-	-
S=0.443375					
R-Sq=96.1%					
P=0.000					

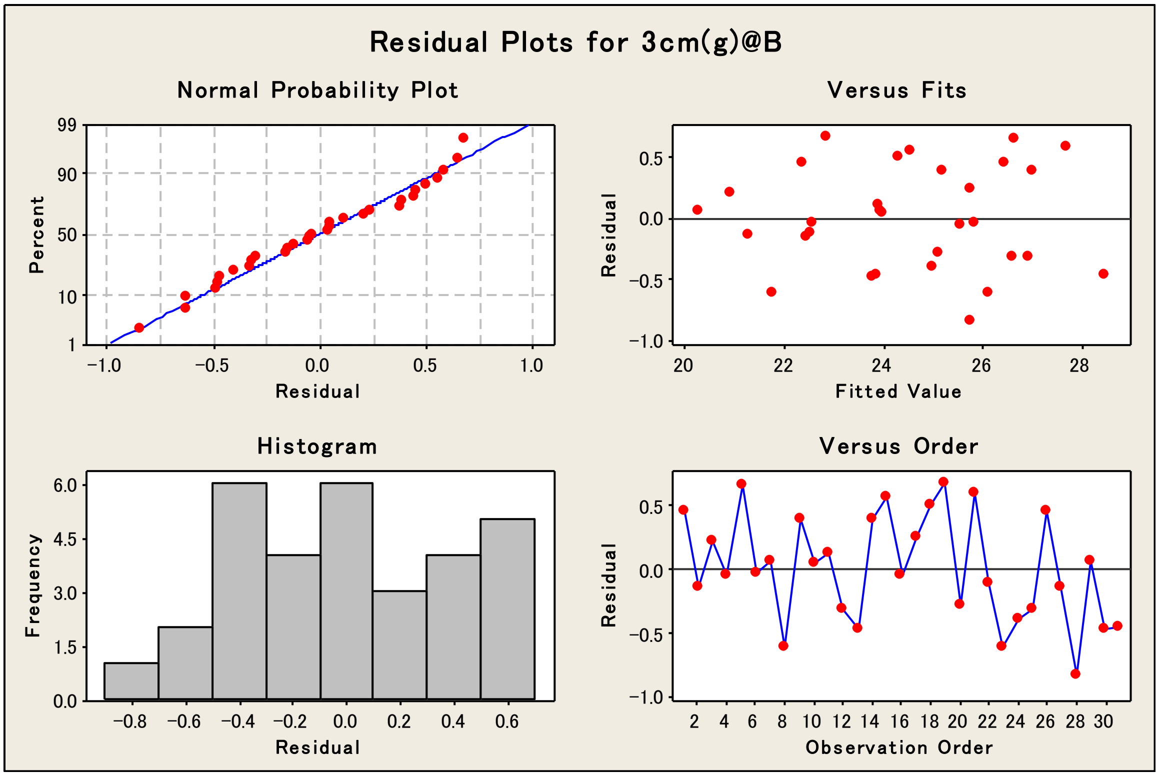


Figure 105: Residual Plots for 3cm Sound Area at Bridge without Dew Point, Pressure and Wind Speed

Finally, from the results above, the equation to calculate the concrete surface temperature at the bridge was developed using significant factors from the results above. Since there is little difference between the results at the bridge using pressure and humidity, two equations were developed and compared. Table 70, 71, Figure 106 and 107 show the results. When comparing the R-square, there is no difference between them.

Table 70: Regression Analysis Result of 3cm Sound Area at Bridge (Final-1)

The regression equation					
$y = -68.7 + 0.742 x^1 + 0.163 x^2 - 0.156 x^3 + 2.26 x^4 + 0.355 x^5 - 0.03 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 3cm Sound Area at UCF	0.7416	0.3518	2.11	0.046
x^2	Ambient Air Temperature at UCF	0.1625	0.3006	0.54	0.594
x^3	Temperature from Website in Orlando	-0.1555	0.1802	-0.86	0.397
x^4	Pressure from Website in Orlando	2.258	6.006	0.38	0.710
x^5	Temperature from Website in Wildwood	0.3552	0.1204	2.95	0.007
x^6	Pressure from Website in Wildwood	-0.028	5.631	0.00	0.996
S=0.792692					
R-Sq=89.0%					
P=0.000					

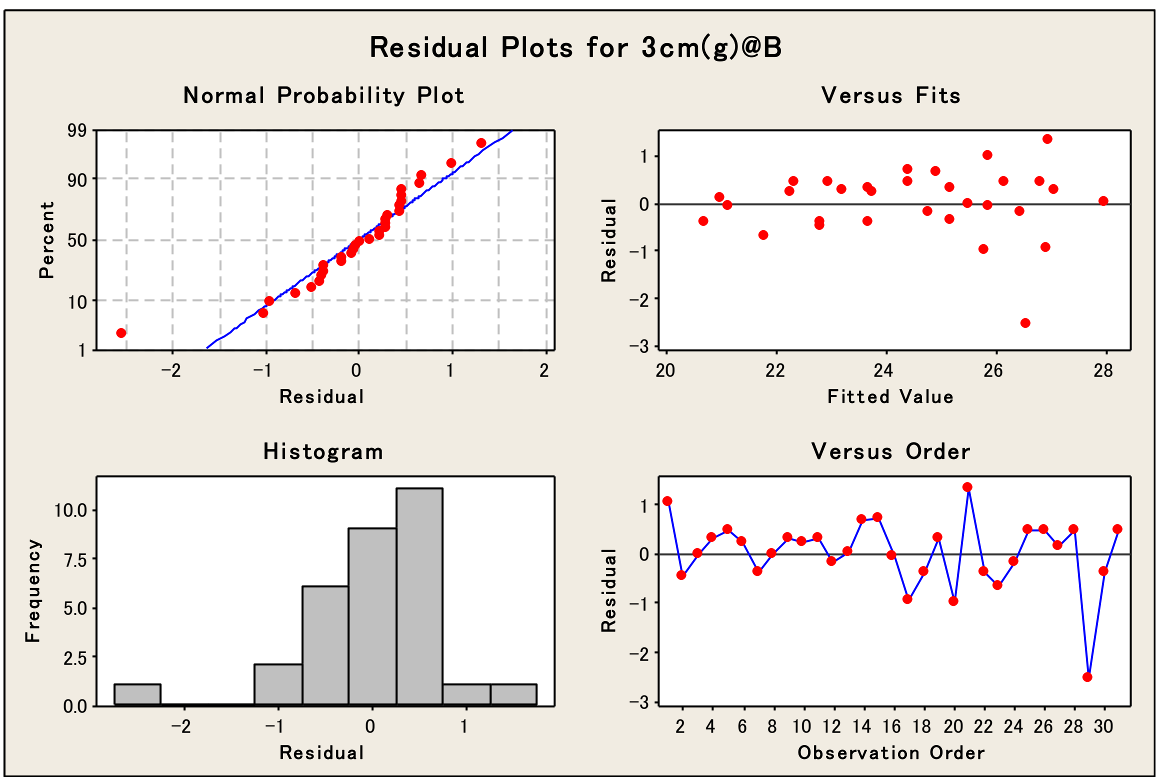


Figure 106: Residual Plots for 3cm Sound Area at Bridge (Final-1)

Table 71: Regression Analysis Result of 3cm Sound Area at Bridge (Final-2)

The regression equation					
$y = -61.3 + 0.719 x^1 + 0.193 x^2 - 0.165 x^3 + 2.01 x^4 + 0.340 x^5 - 0.37 x^6$					
Predictor		Coef	SE Coef	T	P
x^1	Concrete Temperature of 3cm Sound Area at UCF	0.7185	0.3623	1.98	0.059
x^2	Ambient Air Temperature at UCF	0.1929	0.3104	0.62	0.540
x^3	Temperature from Website in Orlando	-0.1646	0.1554	-1.06	0.300
x^4	Pressure from Website in Orlando	2.005	2.189	0.92	0.369
x^5	Temperature from Website in Wildwood	0.3403	0.1197	2.84	0.009
x^6	Humidity from Website in Wildwood	-0.366	1.472	-0.25	0.806
S=0.791672					
R-Sq=89.0%					
P=0.000					

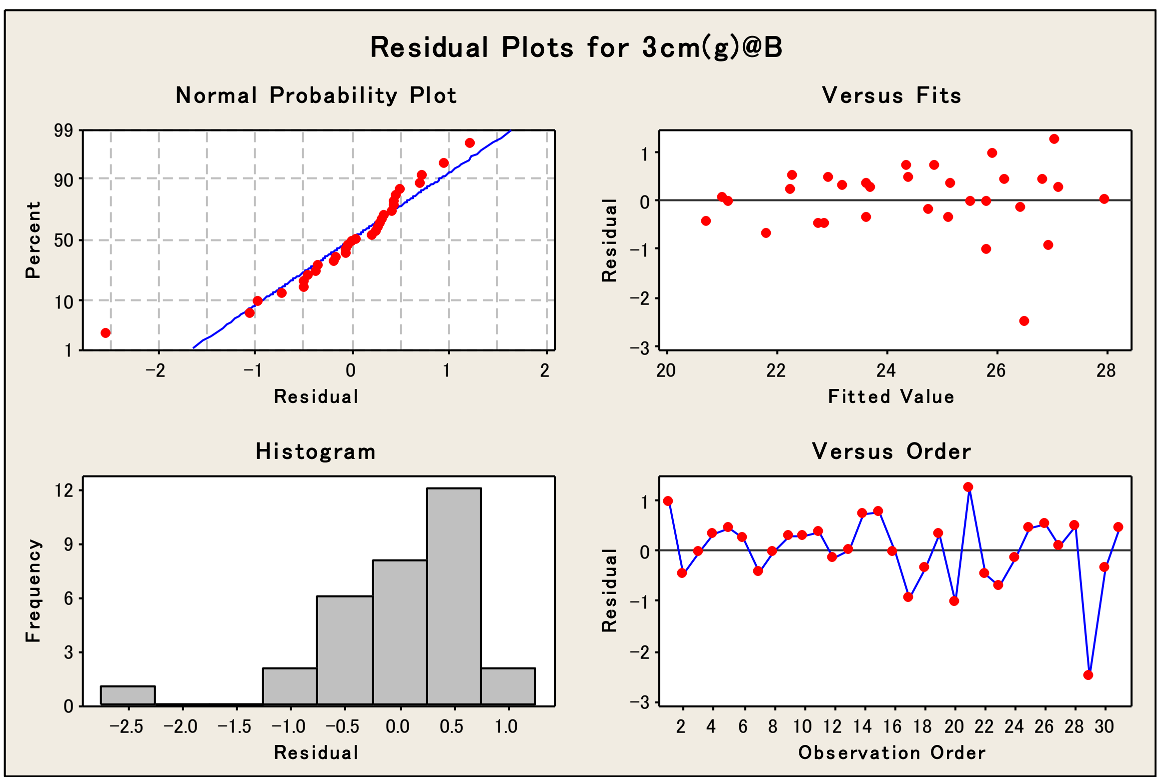


Figure 107: Residual Plots for 3cm Sound Area at Bridge (Final-2)

Prediction for IR Test Duration

Applicable duration for infrared thermography technology inspection at the bridge is determined by using prediction formulae for concrete surface temperature obtained in the previous section. Applicable duration for infrared thermography technology inspection is the period when there is a temperature differential of 0.2 ºC between damaged concrete surface and sound concrete surface as mentioned before. It is judged whether the duration obtained from prediction formulae is suitable by comparing the duration in the actually acquired data with the duration obtained from prediction formulae.

Bridge Deck Top Inspection

It starts with the results of 1cm thick concrete test piece. Figure 108 shows the result of the actual acquired data at the fields. X axis represents time and Y axis represents temperature in Celsius. The blue line shows the concrete surface temperature of sound area and the red line show that of damaged area. As shown in the graph, although the temperature differs from day to day, it is found that the periods from 12:00pm to 6:00pm and from 12:00am to 6:00am are suitable duration for infrared thermography technology inspection. Figure 109 shows the result obtained from the prediction formulae. As shown in the graph, it is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are suitable duration same as the result of actual collected data.

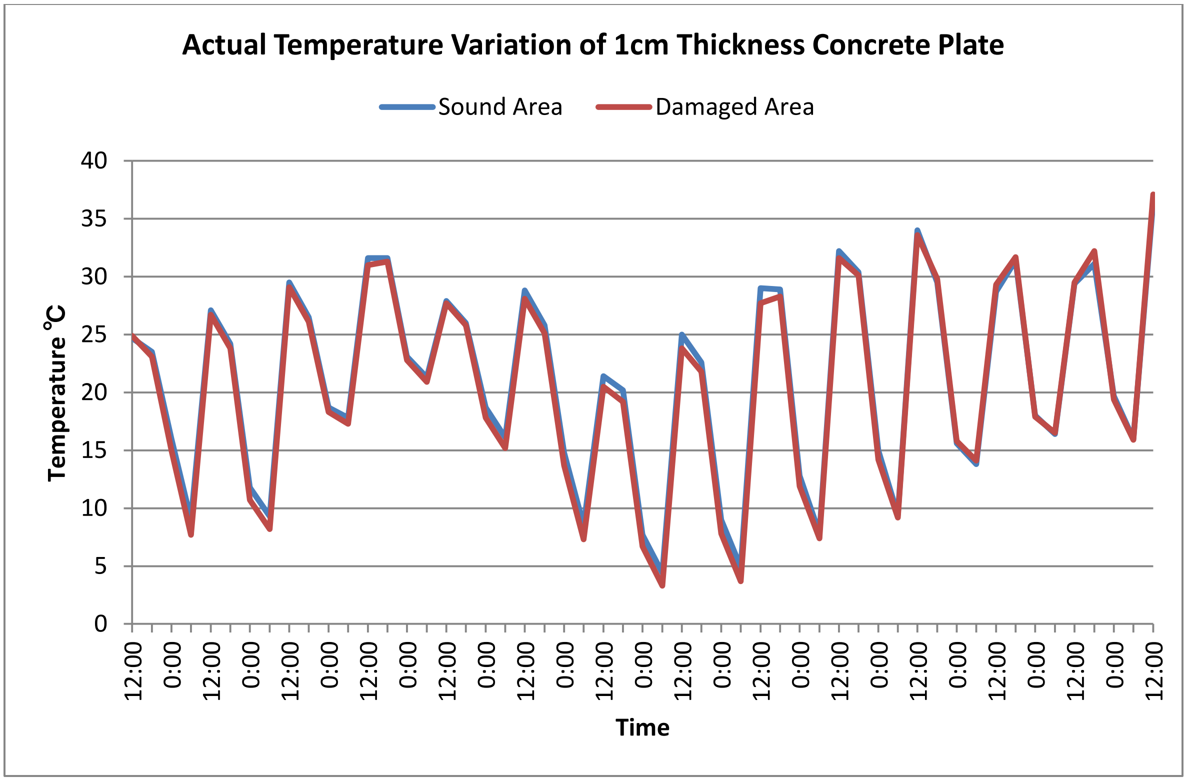


Figure 108: Actual Temperature Variation of 1cm Thick Concrete Plate

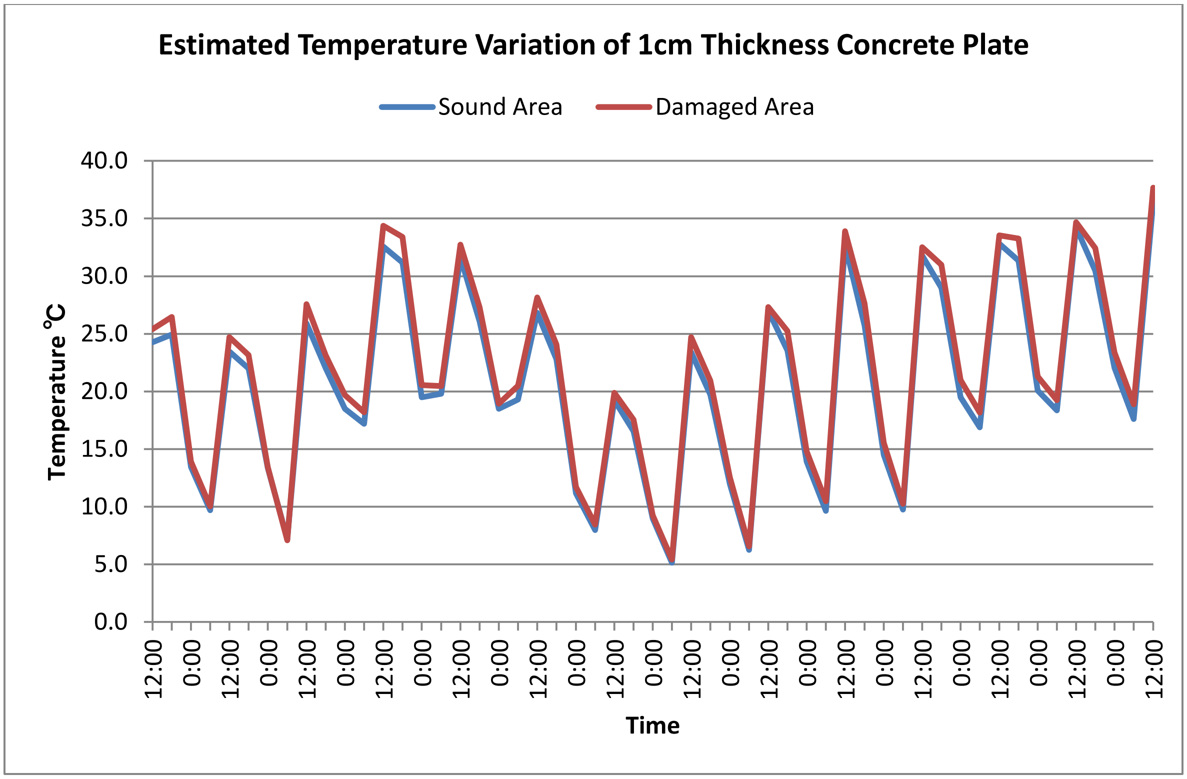


Figure 109: Estimated Temperature Variation of 1cm Thick Concrete Plate

Secondly, the results of 2cm thick concrete test piece are presented. Figure 110 shows the result of the actual acquired data at the fields. As shown in the graph, it is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are suitable duration. Figure 111 shows the result obtained from the prediction formulae. As shown in the graph, it is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are suitable duration same as the result of actual collected data.

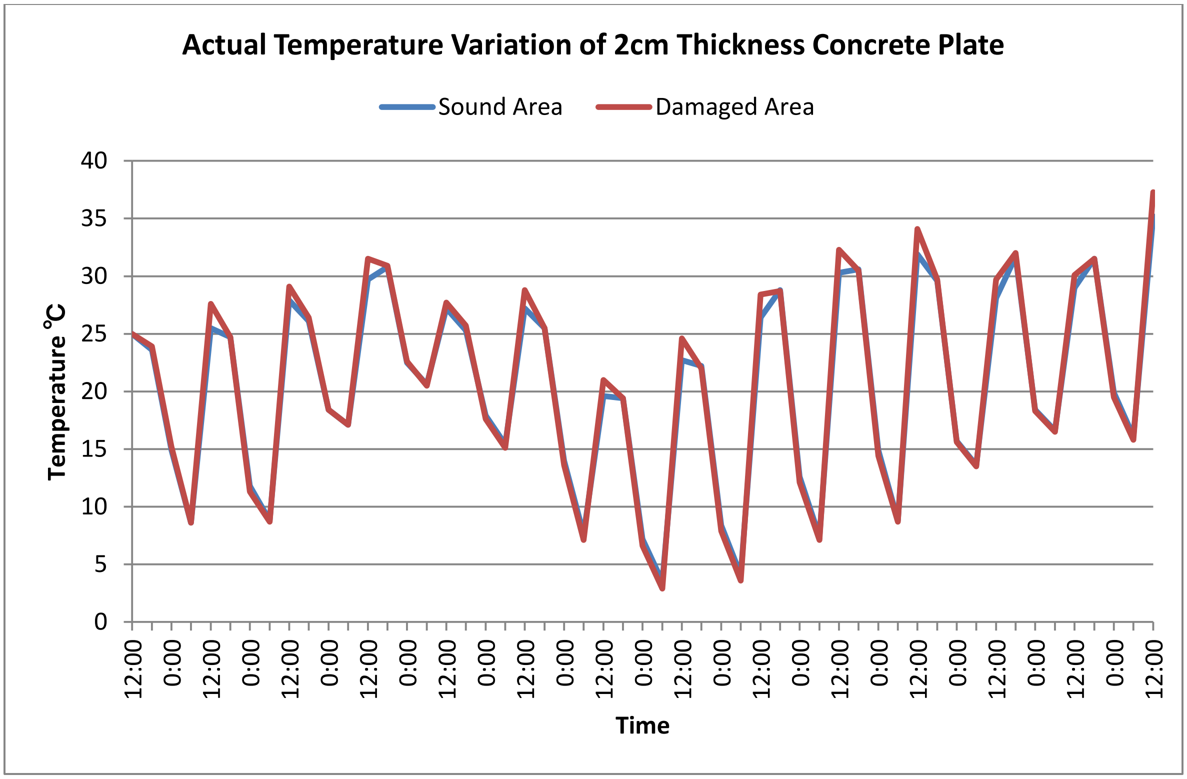


Figure 110: Actual Temperature Variation of 2cm Thick Concrete Plate

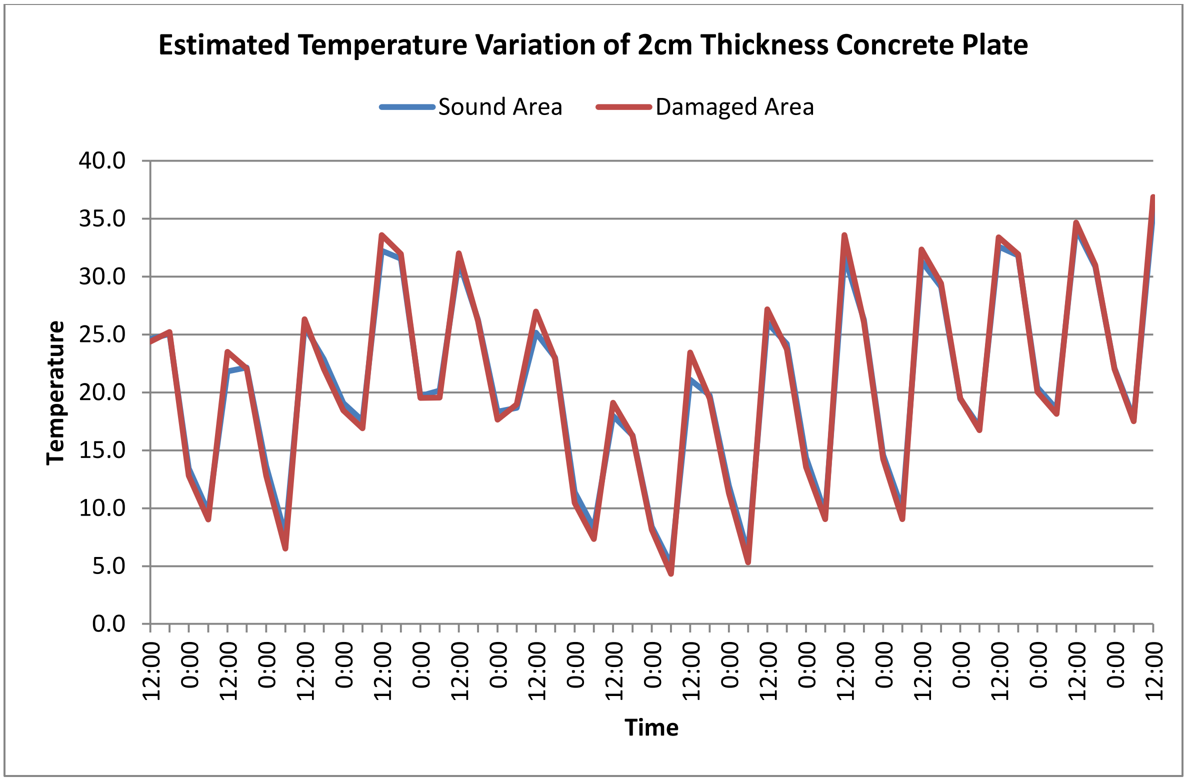


Figure 111: Estimated Temperature Variation of 2cm Thick Concrete Plate

Finally, the results of 3cm thick concrete test piece are presented. Figure 112 shows the result of the actual acquired data at the fields. As shown in the graph, the temperature variation seems to be inconsistent and anytime seems to be applicable for infrared inspection. However, it is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are always suitable duration. Figure 113 shows the result obtained from the prediction formulae. Although this graph also seems to be inconsistent, it is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are most suitable duration than other time zones.

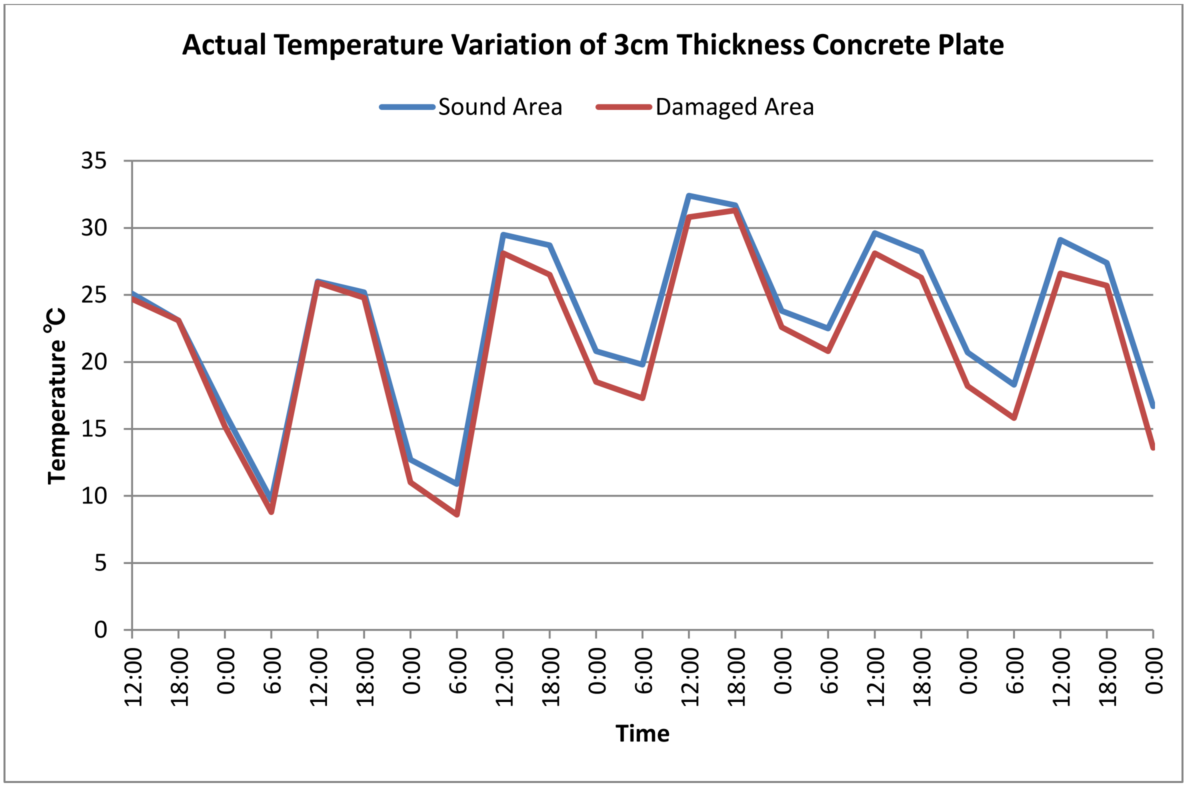


Figure 112: Actual Temperature Variation of 3cm Thick Concrete Plate

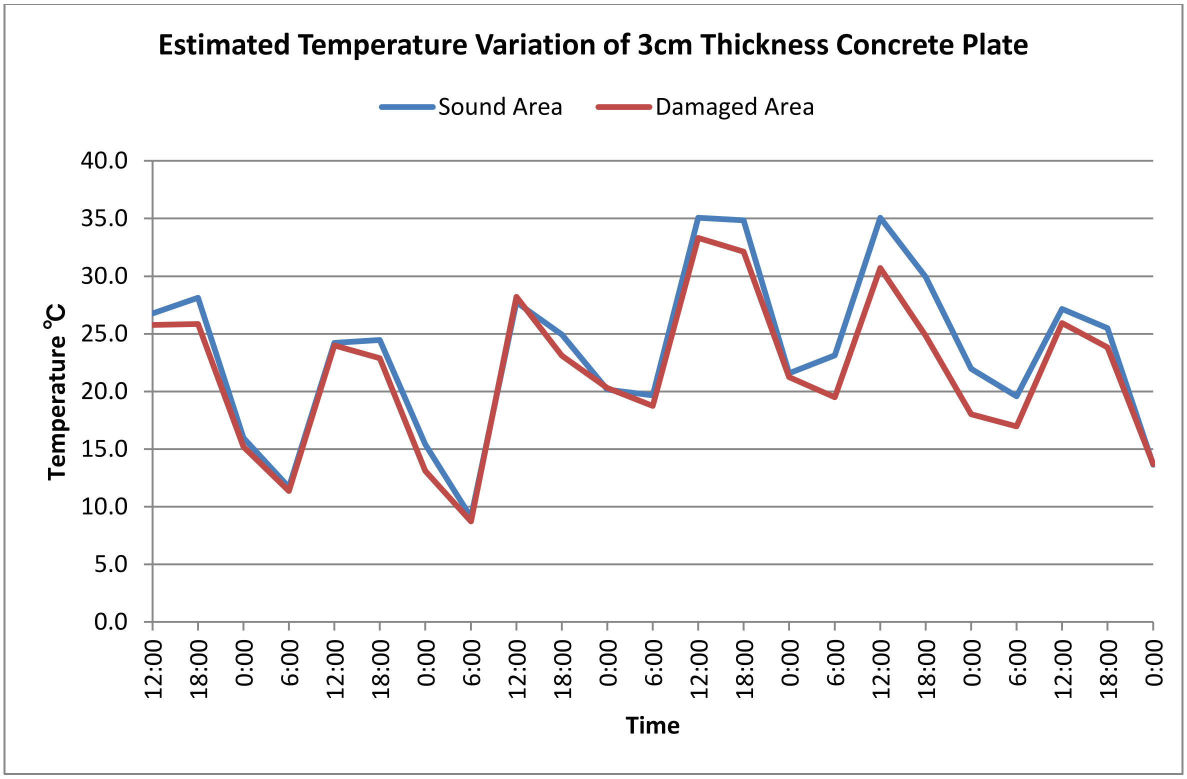


Figure 113: Estimated Temperature Variation of 3cm Thick Concrete Plate

Underside of Bridge Deck Inspection

It starts with the results of 1cm thick concrete test piece. Figure 114 shows the result of the actual acquired data at the fields. X axis represents time and Y axis represents temperature in Celsius. The blue line shows the concrete surface temperature of sound area and the red line show that of damaged area. As shown in the graph, although the temperature differs from day to day, it is found that the periods from 12:00am to 6:00am are suitable duration for infrared thermography technology inspection. Figure 115 shows the result obtained from the prediction formulae. As shown in the graph, it is found that the periods when from 12:00am to 6:00am are suitable duration same as the result of actual collected data.

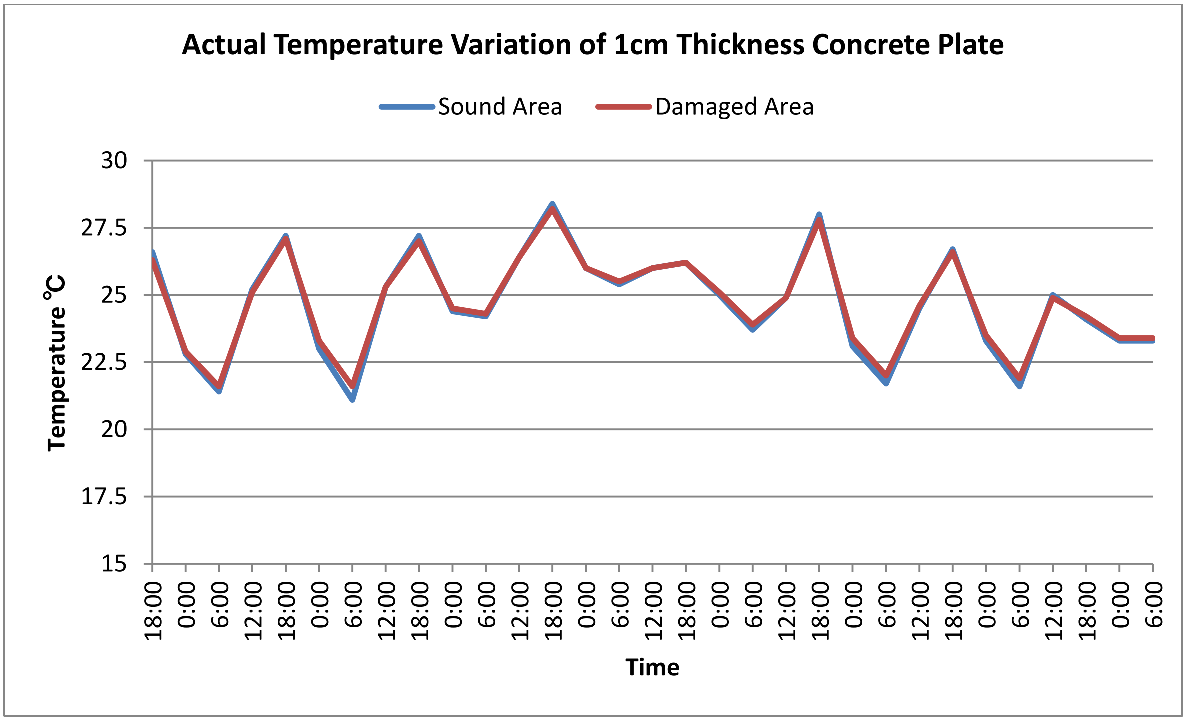


Figure 114: Actual Temperature Variation of 1cm Thick Concrete Plate

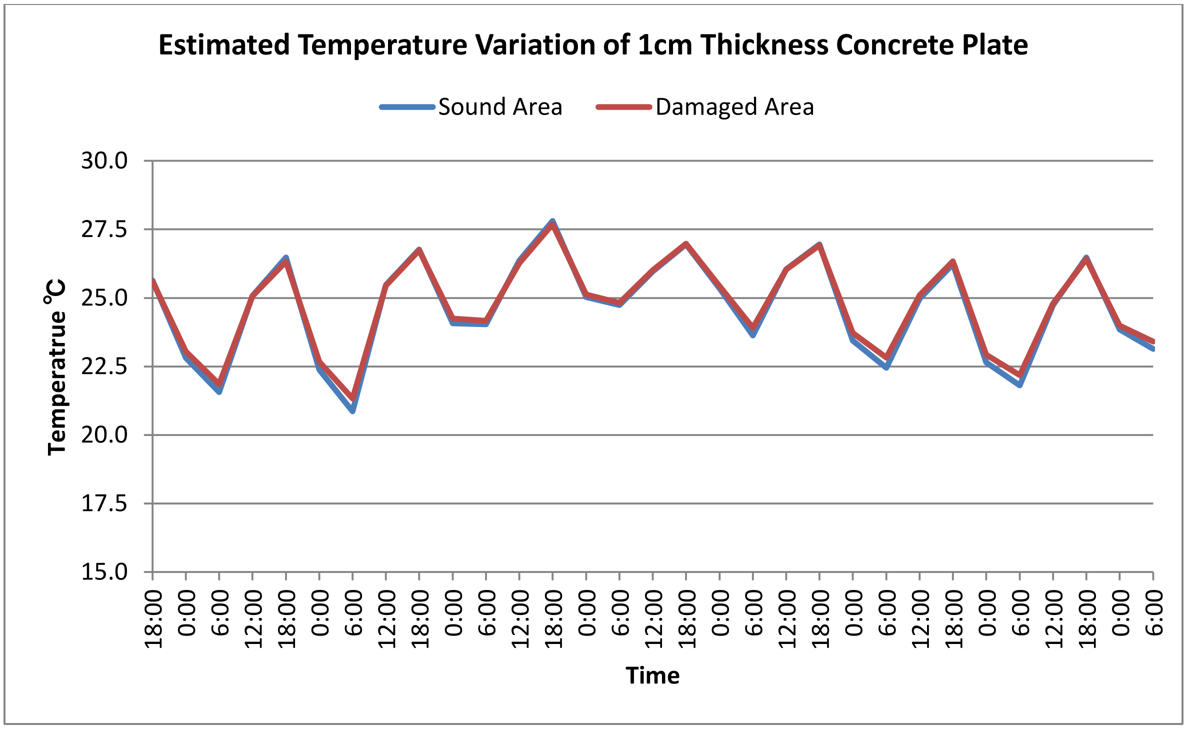


Figure 115: Estimated Temperature Variation of 1cm Thick Concrete Plate

Secondly, the results of 2cm thick concrete test piece are presented. Figure 116 shows the result of the actual acquired data at the fields. As shown in the graph, it is found that the periods when from 12:00am to 6:00am are suitable duration. Figure 117 shows the result obtained from the prediction formulae. As shown in the graph, it is found that the periods when from 12:00am to 6:00am are suitable duration same as the result of actual collected data.

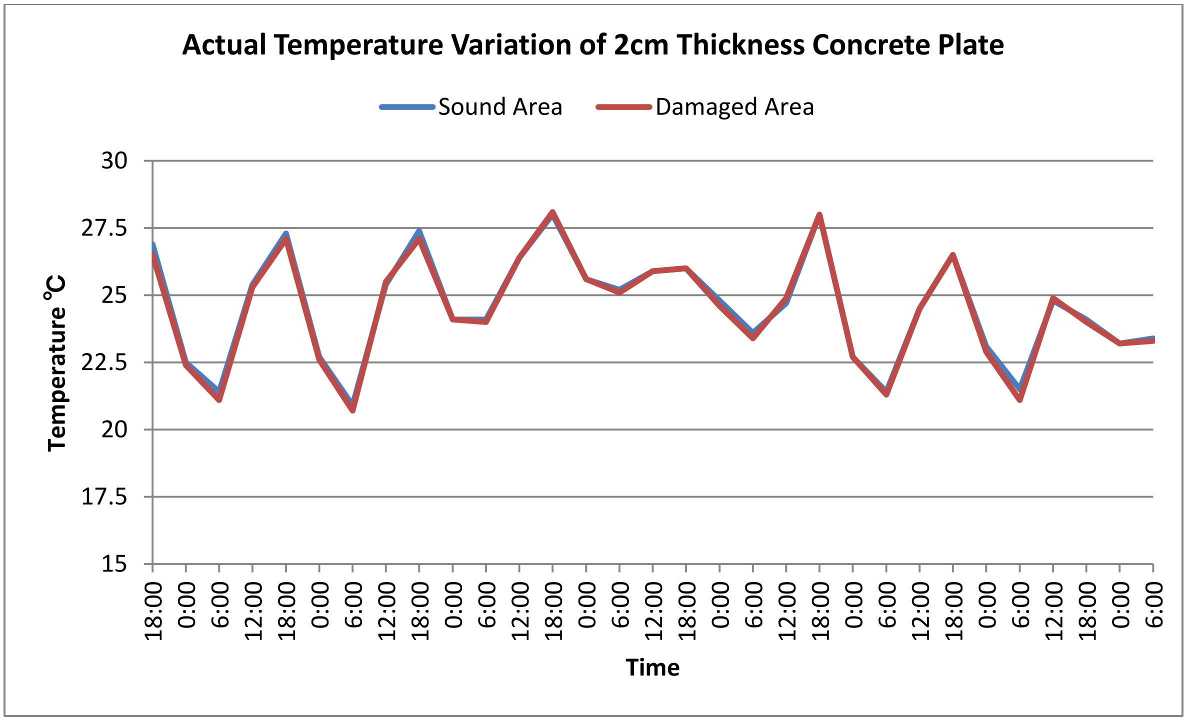


Figure 116: Actual Temperature Variation of 2cm Thick Concrete Plate

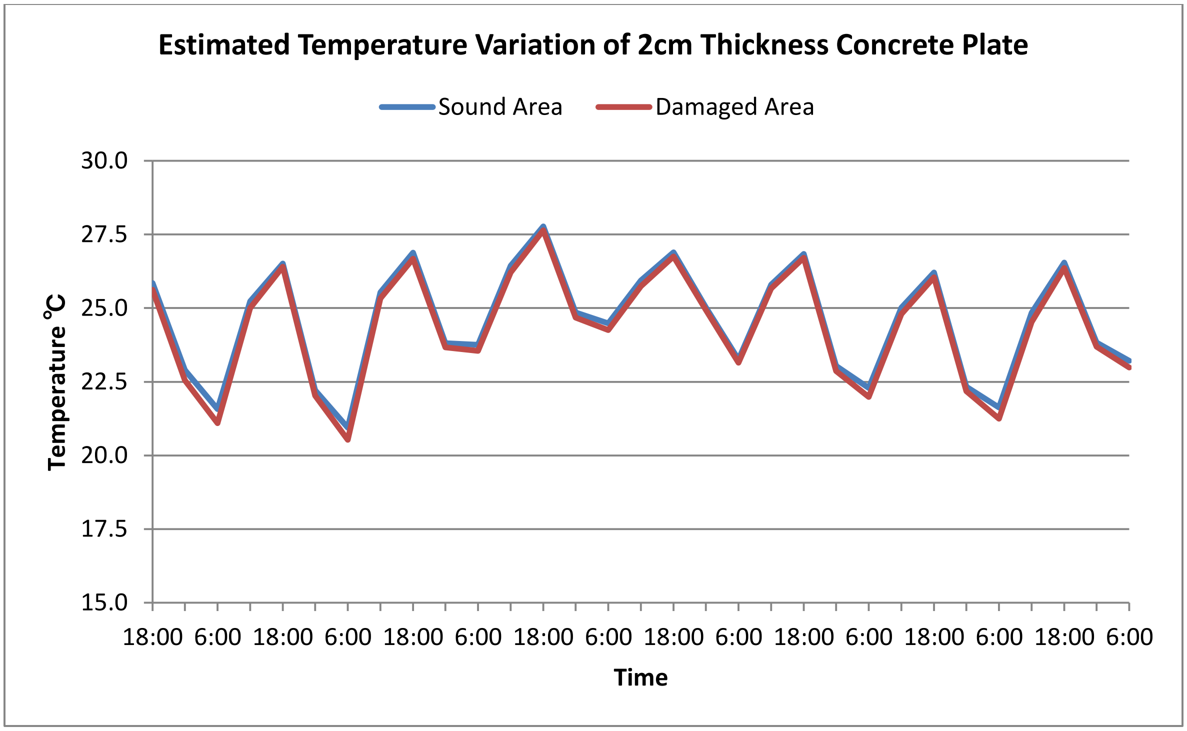


Figure 117: Estimated Temperature Variation of 2cm Thick Concrete Plate

Finally, the results of 3cm thick concrete test piece are presented. Figure 118 shows the result of the actual acquired data at the fields. As shown in the graph, it is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are always suitable duration. Figure 119 shows the result obtained from the prediction formulae. It is found that the periods when from 12:00pm to 6:00pm and from 12:00am to 6:00am are most suitable duration. In other two cases, which are 1cm and 2cm thick concrete, only the period when from 12:00am to 6:00am is the applicable. On the other hand, in this 3cm thick case, there are two applicable periods.

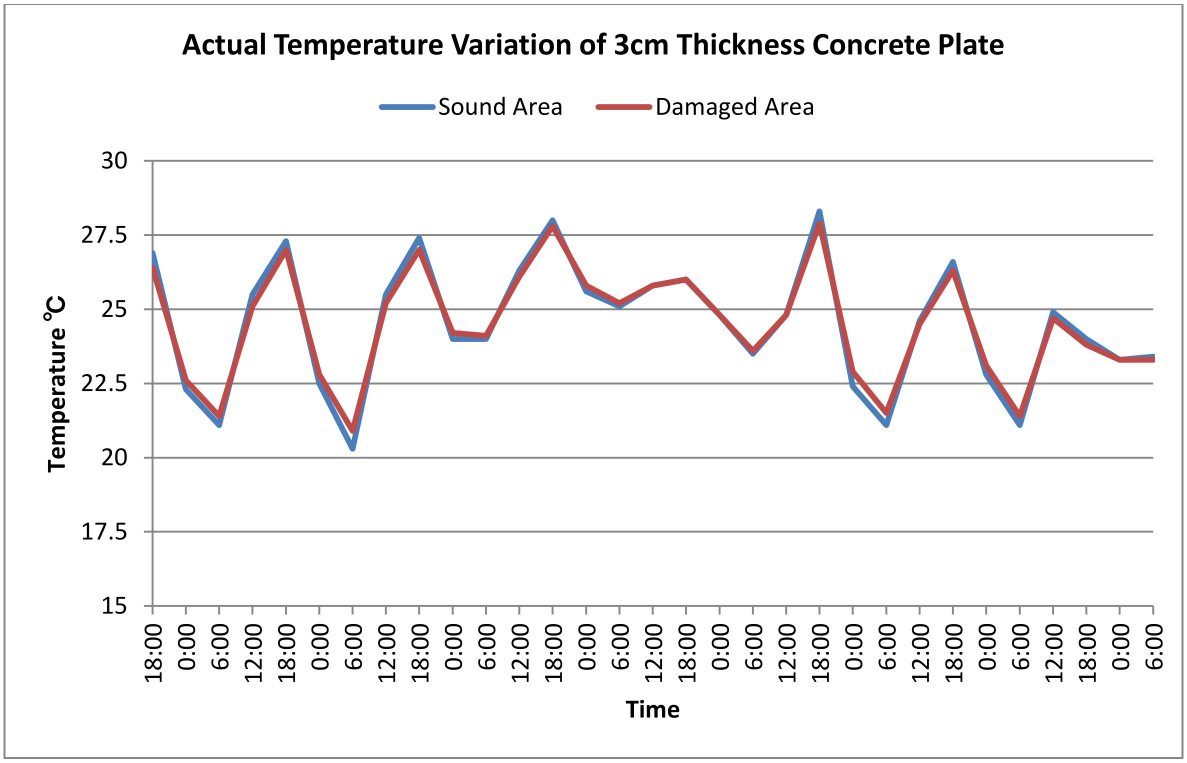


Figure 118: Actual Temperature Variation of 3cm Thick Concrete Plate

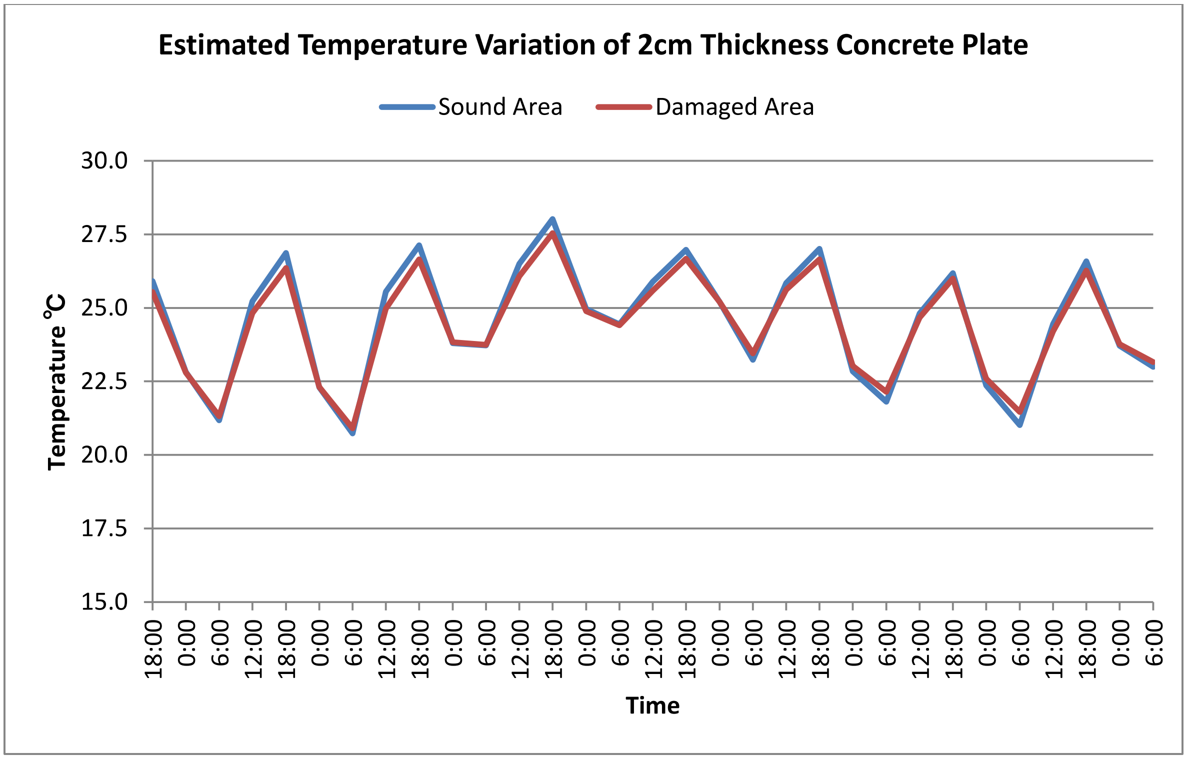


Figure 119: Estimated Temperature Variation of 3cm Thick Concrete Plate

<u>Sensitivity of IRTI to Delamination Volume</u>

Experiments and results mentioned above are about same volume of delamination but different depths from the concrete surface, which are 1cm, 2cm and 3cm (Figure 38). Meanwhile, in this section, experiments and results about the same depth from the concrete surface, but different volumes of delamination are investigated (Figure 39). Figure 120 shows concrete test pieces used in this experiment. Delamination of all concrete test pieces locates in a depth of 1cm from the surface. Delamination of the left-hand piece is very thin and others are 0.5cm, 1.0cm and 1.5cm depths of delamination as shown in the figure. These concrete test pieces were placed at the parking area in front of the Engineering II on campus and concrete surface temperature of damaged area and sound area were collected from 5/29/2013 to 6/1/2013.

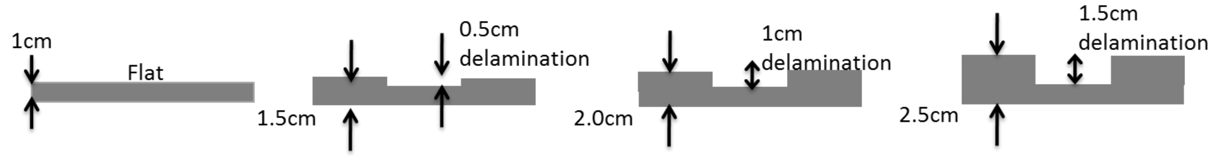


Figure 120: Concrete Test Pieces of Different Volume of Delamination

Figure 121 shows the temperature variation of damaged area of concrete test pieces of all four types. Although, it is expected that there is regularity in temperature variation of damaged area along with delamination volume, there seems to be no regularity in this graph. However, when looking at the temperature variation of each concrete test piece, one thing was found.

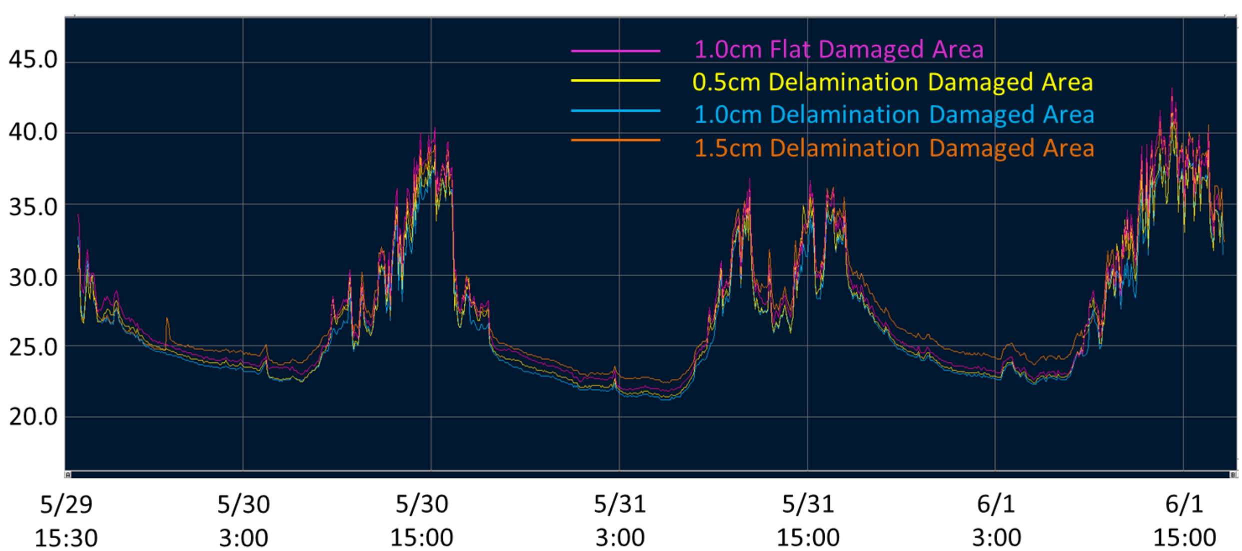


Figure 121: Temperature Variation of Damaged Area in Terms of Delamination Volume

Figures 122-125 show the result of each concrete test piece. All results shows that the temperature of damaged area heats up faster than that of sound area and cools down faster that of sound area according to the general concept. When comparing these four graphs, it is found that the temperature differential between damaged area and sound area increase with the increasing delamination volume, when the temperature cools down during nighttime. From this finding, it can be said that it is easier to detect larger delamination during nighttime.

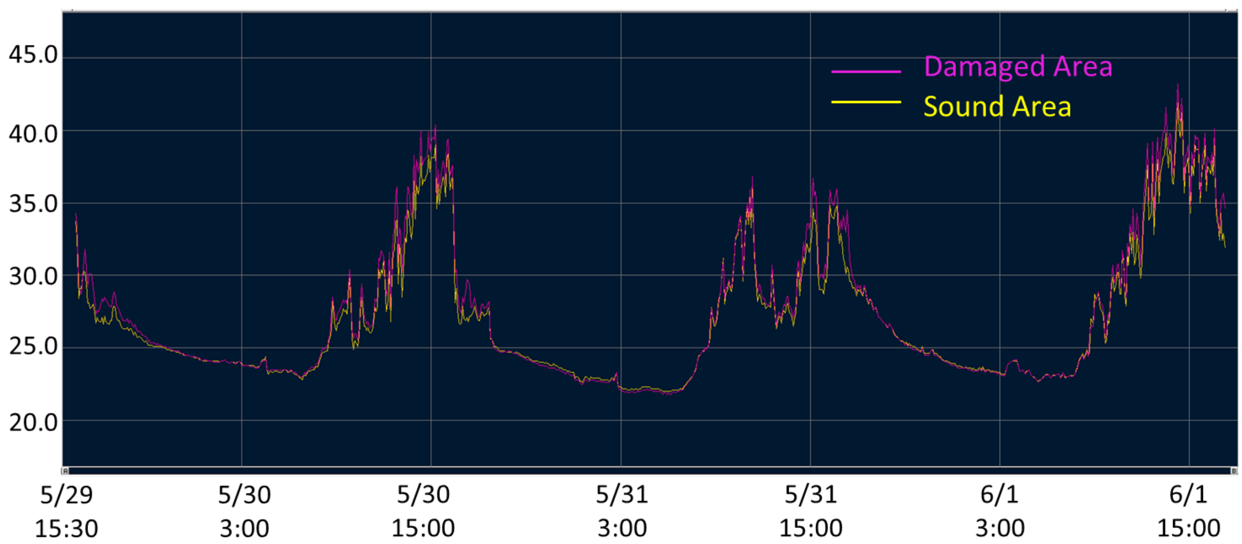


Figure 122: Temperature Variation of 1cm Thick Concrete Test Piece

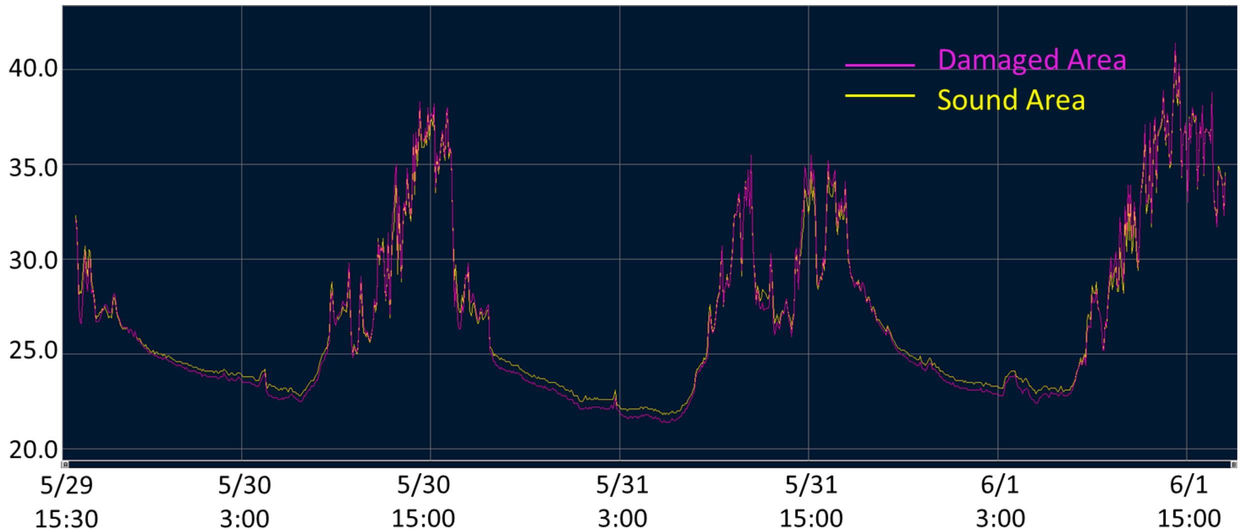


Figure 123: Temperature Variation of 0.5cm Depth Delamination Concrete Test Piece

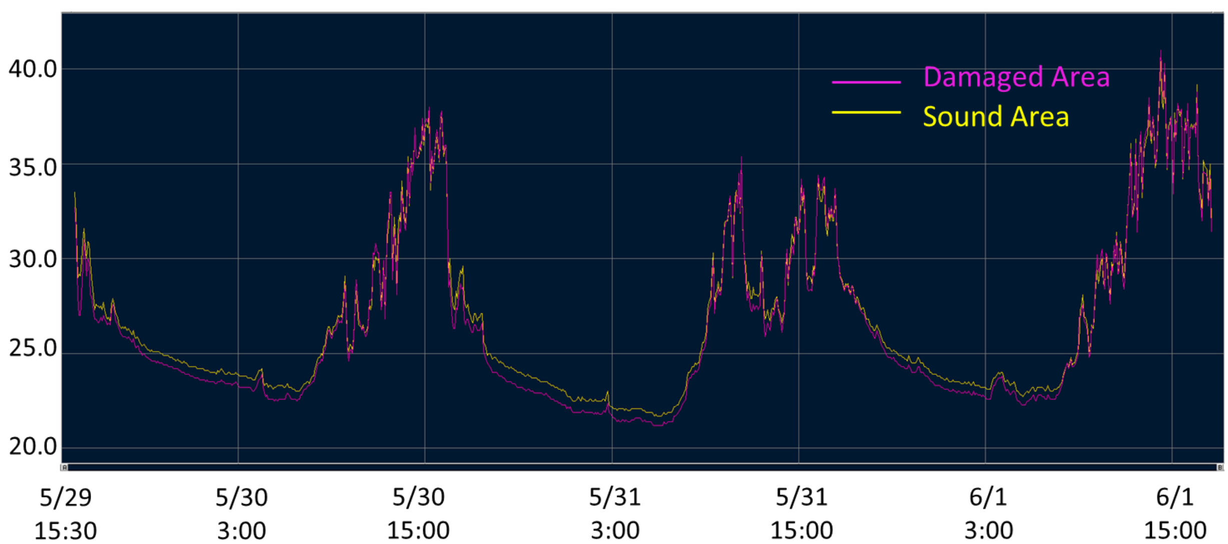


Figure 124: Temperature Variation of 1.0cm Depth Delamination Concrete Test Piece

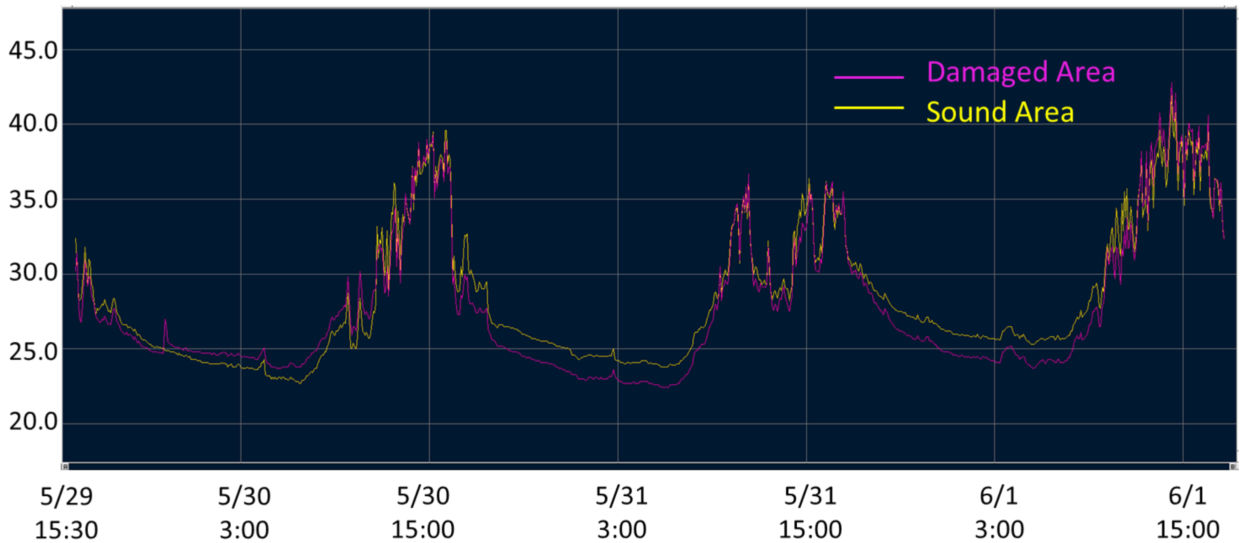


Figure 125: Temperature Variation of 1.5cm Depth Delamination Concrete Test Piece

CHAPTER SIX: CONCLUSION AND RECOMMENDATION

As a result of pilot project in Melbourne, the validity of image-based technologies using high resolution digital images (HRDI) and infrared thermography image (IRTI) was presented by comparing the results of inspection at an in-service bridge obtained from these technologies with the results obtained by a qualified bridge inspector at the same time. There is a need to be close the object when an inspector conducts bridge inspection, for example visual inspection and hammer sounding test. Sometimes it can be difficult to be close to the object. For example, when a bridge is over a river, a snooper truck is needed. Additionally, visual inspection and hammer sounding test are time-consuming, since inspectors need to inspect large area little by little. High resolution digital image technology detects cracks on concrete surface that generally obtained by close-up visual inspections and infrared thermography technology detects voids, delamination and spalling of concrete subsurface condition that generally obtained by sounding test using hammer. Therefore, the combination of these technologies can cover both of visual inspection and hammer sounding test. Furthermore, there is no need to be close to the object, but just to take photographs of the objective using digital camera or high definition video and infrared camera. Therefore, it makes general inspection by inspector efficient by inspecting large area at one time using these technologies and screening the area that need visual inspection and hammer sounding test. That is to say, these technologies can help inspectors with identifying the area that need close-up inspection and future monitoring.

However, since the accuracy of damage identification using infrared thermography image is greatly affected by ambient temperature variation, suitable temperature condition to enable detection is essential. Applicable duration for infrared thermography technology is the period when there is temperature differential of concrete surface of damaged area and sound area. In order to examine the applicable duration, there is a need to visit the bridge and attach special concrete plates to the object (bridge) and also monitor the concrete surface temperature prior to the inspection. This work can be time and effort. Then, in this research, predicting the temperature variation without visiting the bridge was investigated. As a result, as for the bridge deck top, pressure along with temperature affect the prediction equation of concrete surface temperature. Prediction equations of concrete surface temperature were created using influential factors and the results of experiments, and temperature variations of concrete surface obtained from prediction equations were compared with the temperature variation obtained from actual collected data. As a result, same durations that are applicable to inspections by infrared thermography technology are obtained. Therefore, it is said that prediction equations obtained from the experiment enable to find out the appropriate duration for IRTI.

In addition to this experiment, another experiment to investigate what kind of difference is obtained in terms of delamination volume. As a result, it is found that the temperature differential between damaged area and sound area increase with the increasing delamination volume, when the temperature cools down during nighttime. From this finding, it can be said that it is easier to detect larger delamination during nighttime.

Recommendation

In this research, experiment using concrete test pieces was conducted at an in-service bridge in a certain period. However, this experiment should be conducted through a whole year, since the temperature variation differs seasonally. In addition to that, this experiment should be conducted at some other bridges. As a result, prediction formulae would be more accurate. Furthermore, the weather data was obtained from a website four times a day, which are at 12:00am, 6:00am, 12:00pm and 6:00pm in this research. However, it would appear that if frequency is increase, the created prediction formulae would be more accurate.

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