NON-DESTRUCTIVE TESTING USING INFRARED IMAGE FOR THE MEASUREMENT OF COMPRESSIVE STRENGTH OF IBS CONCRETE PANEL

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ABSTRAK

Kajian ini berkenaan tentang mencipta kaedah ujian tidak terganggu untuk panel konkrit terutamanya konkrit IBS. Ujian tersebut adalah untuk menguji kekuatan mampatan konkrit tanpa menggangu bentuk sebenar struktur. Terdapat dua objektif dalam menjalankan kajian ini iaitu untuk menghasilkan satu alat ujian tidak terganggu dengan menggunakan analisis infra merah dan untuk menentukan korelasi antara kekuatan mampatan dan pengagihan haba pada konkrit. Kaedah tradisi dan yang sedang digunapakai adalah menggangu bentuk sebenar struktur dengan memampatkan spesimen sehingga ia mencapai tahap kekuatan maksimum. Kaedah ini akan memberi impak negatif kepada struktur antaranya ia akan mengalami kejatuhan integriti disebabkan penggantian semula struktur yang mungkin mempunyai kekuatan yang berbeza. Ia juga memberi kesan kepada nilai astetik kerana struktur tersebut telah ditebuk. Kaedah ini dimulakan dengan menyediakan sampel kiub konkrit bersaiz 150mm x 150mm x 150mm yang melibatkan konkrit gred 20, gred 25, gred 30, gred 35 dan gred 40 dimana setiap gred mempunyai sembilan sampel yang akan menjalani ujian pada hari ke-7, hari ke-28 dan hari ke-56. Ujian yang terlibat adalah ujian tidak terganggu iaitu gambaran terma infra merah dan ujian terganggu iaitu ujian kekuatan mampatan. Alat yang digunakan di dalam kajian ini adalah kamera terma infra merah yang akan menghasilkan gambar kontur terma. Ujian terganggu akan dijalankan sejurus selepas gambaran terma infra merah untuk mendapatkan kekuatan konkrit. Kesemua gambaran terma infra merah akan dianalisis di dalam perisian MATLAB dan AutoCAD untuk mendapat bacaan sebenar kekuatan mampatan daripada ujian tidak terganggu. Data yang dikumpul daripada gambar kontur infra merah akan di analisis untuk mendapatkan kolerasi antara kekuatan mampatan dan pengedaran haba didalam konkrit dengan mengukur diameter kontur berwarna putih, kuning dan oren yang terhasil pada imej kontur terma. Keputusan mendapati konkrit dibawah gred 25 tidak sesuai digunakan didalam kaedah ini sebagaimana bacaan untuk gred 20 tidak relevan kerana bacaannya tidak meningkat secara seragam jika dibandingkan dengan gred konkrit yang lain. Keputusan untuk gred konkrit yang lain menunjukkan bacaan meningkat sepertimana kekuatan yang meningkat yang boleh diklasifikasikan pekali kolerasi yang baik dan boleh diterima kerana pekali korelasi untuk bacaan kontur berwarna putih, kuning dan oren adalah masing-masing 0.83, 0.97 dan 0.98 yang menunjukkan kesemua bacaan hampir mencapai pekali korelasi terbaik iaitu 1. Alat pengukur kekuatan konkrit yang dihasilkan boleh digunakan didalam Sistem Pengukuran Kekuatan Konkrit dengan hanya memuat-naik imej kontur terma didalam perisian itu dan jalankan ia untuk mendapatkan bacaan kekuatan daripada julat bacaan diameter kontur. Kesimpulannya, kaedah alternatif baru untuk ujian tidak terganggu adalah kaedah yang boleh diterima untuk mencari kekuatan konkrit secara tidak terganggu. Korelasi antara kekuatan mampatan dan pengedaran haba juga telah ditentukan dan ia menunjukkan semakin tinggi kekuatan konkrit, semakin tinggi kadar pengedaran haba pada konkrit.

ABSTRACT

This study is about developing a non-destructive testing method for the concrete panels especially for IBS concrete. The testing is for measuring the compressive strength of concrete without destructing the structure. There are two objectives for this study which is, to develop a non-destructive test measurement tool by using infrared analysis and to determine the correlation between compressive strength and heat distribution of concrete. The conventional and present method is destructing the structure where the concrete specimen will be compress until it achieves the maximum strength. This method will give the negative impacts to the structure that may be less in integrity due to the replacement of the structure where it may be has a different strength. It also may be less in aesthetic value because the structure had been cored. The method starts with making the samples of concrete cube sized 150mm x 150mm x 150mm which involving grade 20, grade 25, grade 30, grade 35 and grade 40 where each grade comes with nine samples that will be undergo testing at the age of 7th day, 28th day and 56th day. The testing involved are the non-destructive testing which is infrared thermal imaging and the destructive testing which is compressive strength test. The tools that have been use for non-destructive testing is infrared thermal camera which produce the thermal contour image. The destructive testing will be done right after the infrared thermal imaging to get the strength of the concrete. The thermal contour image then have been analysed into the software which are MATLAB and AutoCAD to get the non-destructive testing compressive strength reading. The collected data of infrared contour image then will be analysed to make the correlation of compressive strength and heat distribution of concrete between the different grades of concrete by measuring the diameter of the white, yellow, and orange colour of the contour produced by thermal contour image. The result found that the concrete below grade 25 are not suitable to use for this method as the reading of grade 20 is not relevant because the reading was not ascending as compared to the other grades of concrete. The result for the other grades of concrete show the ascending order of readings which can classify a good and an acceptable correlation coefficient because the reading of diameter for white, yellow and orange colour contour were 0.83, 0.97 and 0.98 respectively which are all near to the best fit reading which is 1. The tool of measuring the strength of concrete can be use in the Concrete Strength Measurement System that have been made just by uploading the thermal contour image into the software and run it to get the strength reading by their range reading of contour diameter. This study concludes that the new alternative method of non-destructive testing is an acceptable method to find the strength of concrete non-destructively. The correlation between compressive strength and heat distribution of concrete has been determined and it shows that the higher the strength of the concrete, the higher the heat distribution takes place in it.

Keywords: Concrete, Non-destructive Testing, Infrared Thermal Imaging,
Compressive Strength

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LIST OF SYMBOLS

(O)	Orange
(W)	White
(Y)	Yellow
Fc	Compressive Strength
R^2	Correlation Coefficient

LIST OF ABBREVIATIONS

DT	Destructive Testing
ETIM	Engineering Technology (Infrastructure Management)
FRP	Fibre-reinforced Polymer
IBS	Industrialised Building System
IR	Infrared
IRH	Impact Rebound Hammer
mm	Millimetre
MPa	Mega Pascal
NDT	Non-destructive Testing
OPC	Ordinary Portland Cement
PPE	Personal Protective Equipment
RC	Reinforced Concrete
RH	Rebound Hammer
UPV	Ultrasonic Pulse Velocity

CHAPTER 1

INTRODUCTION

1.1 Background

Industrialised Building System (IBS) is a process where the components of the building are fabricated, transported and erected on site. In construction industry, there is a typical way to measuring the compressive strength of the concrete on-site by coring which is expensive and sometimes it is hard to implement in certain cases. A destructive testing (DT) is widely used in construction to measure the characteristics of the concrete but this method will be the conventional way in this era of technology.

A non-destructive Testing (NDT) is the process of identifying, assessing, inspecting and evaluating the materials without destroying the actual state or shape of the materials. Usually the testing will be handling by the specific tools to get the result of the materials' characteristic. There are three types of NDT for concrete that often being used to identify the characteristic of the concrete. The first one is Ultrasonic Pulse Velocity (UPV) test to determine the uniformity of the concrete within structure. The second one is Rebound Hammer test to identify the compressive strength of the concrete at the certain point of the surface. The third one is Cover meter which is reinforcement bar locater test.

This study will produce the new method of non-destructive testing which is infrared thermal imaging. NDT method is used for hardened concrete or the building to get the characteristics of the structure in the same time to maintain the actual shape of building. Infrared imaging is the simple way yet it is practical and accurate as compared to other NDT method.

1.2 Problem Statement

As applying the current method of compressive strength measurement of concrete, there are some problems existed in completing the action. This technique will gives the negative impact of the building especially the old building because the method to identify the compressive strength is using the core sampling and testing. The method of this test is by coring the specific part of the building and taking the sample to the laboratory to make a testing for the compressive strength. This method will make the building less in aesthetic value as the surface of the concrete is been cored to direct assessing the compressive strength. It is also make the structure less in integrity as the strength of replacement after coring may be different in strength. For another usage of NDT which is rebound hammer and UPV, the spot for applying those method are very tiny so that the results will less accurate. Therefore, this study has produced the new alternative method of non-destructive testing which is infrared thermal imaging analysis. This new NDT method can outturn the comparison of compressive strength testing and heat distribution of concrete.

1.3 Objectives

The objectives of this project defined as follows:

i. To develop a non-destructive test measurement tool by using infrared analysis

ii. To determine the correlation between compressive strength and heat distribution of concrete

1.4 Scopes of Study

This study focused on measuring the compressive strength of concrete by using the new method of non-destructive testing which is Infrared Thermal Imaging. Infrared imaging produced a contour of the picture to know the heat level of the concrete as well as representing the compressive strength by analysing the percentage of contour size in the picture. The analysis has been computerized to state the strength of the concrete depending on the percentage contour produce by the infrared image. After computerizing the data analysis, this tool can directly show the strength after taking the picture of the concrete and upload it into the software.

This study needs several devices to get the compressive strength reading. The devices that used in this study are FlirOne Thermal Camera and Android Smart Phone as the camera has to connect to Android device to get the thermal image. The grades of concrete that will be tested in this study are grade 20 (G20), grade 25 (G25), grade 30 (G30), grade 35 (G35) and grade 40 (G40). The specimen of concrete is in the cube shape as the mould used in this study is a cube mould that is 150mm x 150mm x 150mm in size.

1.5 Significance of Study

Infrared thermal imaging is one of the techniques that is not being used for determining concrete strength in construction industry yet. This is an alternative NDT that much easier as compared to the other technique of measuring compressive strength. The technique can give the similar result of testing but in an easier way that does not really costly. It also can save time as the technique can only be made for approximately 5 minutes only to get the result. This alternative method can minimize the structural disruption caused by coring process. The tools and procedure required are easier than the compressive strength machine. The tools used are not required to direct contact to the object which is concrete structures. The thermal camera can take the picture of the concrete structures in several millimetres and kilometres as long as the heat imposed is as enough as required. This study can show the heat distribution in the concrete as well. As the density of every sample of the concrete cube is different depending on their strength, the heat distribution will also have a different movement and it affects the time taken as well as the measurement of heat movement. As the important variables of every construction management are cost, time and quality, this new technique of NDT seems very suitable to develop because this technique is considering all of those important variables. It saves cost, reduces time taken and maintains the quality of the structure.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Infrared Thermal Imaging is the method that is proposed to the testing of concrete which is compressive strength. This method will use the new devices which are infrared thermal camera to get the thermal image of the concrete after applying some heat. Instead of using the current method of compressive test which is coring, this Infrared Thermal Imaging gives more advantages which are more practical, more portable, saving times and cheaper. The tools that required in this method are Infrared Thermal Camera, Torch and Android Device to connect to the camera. The concrete sample must be heated by the torch at some level of heat, and then the picture of the concrete is taken using the thermal camera. The reading then will be analysed (Muhamad Azani Yahya, 2006) and computerized to set the strength of the concrete. The devices of this method are small and can be carried around to the place of the building. It also does not have to make a hole to the building which is coring. It means, Infrared Thermal Imaging method will not going to affect the physical state of the building. It will not damaging the point of the testing. It just has to apply the heat to the targeted spot and take the thermal image of the structure. The thermal image then will be analysed in the software.

2.2 Industrialised Building System

Industrialized Building System (IBS) is the system of construction that is built in the factory by using the pre-fabricated components. They have three major groups' categories which include frame of post beam system, panel system, and box system. The frame structure is defined as the structure that carrying load through the beams and girders to columns and to the ground. The panel system is where the load is distributed through a large floor and wall panels. The box system includes those systems that employ three-dimensional modules (or boxes) for fabrication of habitable units are capable of withstand load from various directions due to their internal stability (Wah Peng et al. 2003). In construction industry, IBS is a practical system as it helps the phases of construction being better way to meet the client's requirement as compared to the conventional method which produces waste based on construction players and researchers (Yahya and Shafie 2012). In Malaysia, the IBS usage can make the construction industry to be more matured since it is the modern method. IBS method which is pre-fabricated on site and built in the factories gives more cost saving and high quality as the labour intensity will be reduced and construction standardization (Yahya and Shafie 2012). There are benefits using IBS besides cost saving and offers high quality; boost the productivity, complete rapidly and tidier construction sites in contrast to the conventional methods (Abd. Hamid et al. 2008). IBS system can only be use and worth to construction project if the major benefits are valuable as compared to conventional system (Wada et al. 2006)

Even though the potential of IBS promotes benefits, research show that 15% of building projects using IBS system in 2003 and it increased by 10% in 2006 (Abd. Hamid et al. 2008). It means most of the construction industries are still confuse about adopting IBS. One of the main reasons for the confusion in adopting IBS is that they refuse to look for the benefits of IBS because there is lack of information to make the adoption (Abd. Hamid et al. 2008). Contractors assume IBS is not the best system as compared to conventional according to various projects characteristics and sources of resource (CIDB 2007).

2.3 Concrete

Concrete is an engineering material that sparked the properties of rock and is a combination of particles closely bound together. It blends aggregates, normally natural sand and gravel or crushed rock. These are bound together by a hydraulic binder for example, Portland Cement and activated by water to form a dense semi homogenous mass.

Because of its general characteristics, concrete is sometimes referred to as artificial rock. Concrete is very strong in resisting compression. In use where tensile stresses have to be accommodated reinforcement is incorporated into the concrete to absorb tension. Concrete is the most widely used construction material. It allows flexibility in structural form as it can be moulded into multiplicity of shapes.

2.3.1 Cement

A cement is a binder, it is used for hardens and adhere to other material in construction to bind them together. It seldom used on its own. It usually mix and bind together with fine aggregate to produce mortar for masonry, or with sand and gravel aggregates to produce concrete.

Usually, cement used in construction industry are inorganic, it often based with lime and calcium silicate, and can be characterized as being either hydraulic or non-hydraulic, depending upon the ability of the cement to set in the presence of water.

Non-hydraulic cement will not set in wet conditions or underwater; rather, it sets as it dries and reacts with carbon dioxide in the air. It is resistant to attack by chemicals after setting.

Hydraulic cements (e.g., Portland cement) set and become adhesive due to a chemical reaction between the dry ingredients and water. The chemical reaction results in mineral hydrates that are not very water-soluble and so are quite durable in water and safe from chemical attack. This allows setting in wet condition or underwater and further protects the hardened material from chemical attack.

2.3.2 Aggregate

Aggregate in building and construction is a material used for mixing with cement, bitumen, lime, gypsum, or other adhesive material to form mortar or concrete. The aggregate gives volume, stability, resistance to wear or erosion, and other desired physical properties to the finished product. Aggregates that commonly used are sand, gravel, crushed or broken stone, boiler ashes (clinkers), broken blast-furnace slag, burned clay and burned shale. Fine aggregate usually consist of crushed stone, sand, or crushed screenings. Coarse aggregate consists of gravel, slag, fragments of brok en stone and other coarse substances (Britannica, 2015).

2.3.3 Water-Cement Ratio

Three simple ingredients can be blended and proportioned numerous ways to make concrete; aggregate, cement and water. In concrete, the single most significant influence on most or all of the properties is the amount of water used in the mix.

In concrete mix design, the ratio of the amount of cement used (both by weight) is called the water cement ratio (w/c). These two ingredients are responsible for binding everything together. The water to cement ratio, or w/c ratio, largely determines the strength and durability of the concrete when it is cured properly. The w/c ratio refers to the ratio of the weights of water and cement used in the concrete mix. A w/c ratio of 0.4 means that for every 100 lbs of cement used in the concrete, 40 lbs of water is added.

The simplest way to think about the w/c ratio is to think that the greater the amount of water in a concrete mix, the more dilute the cement paste will be. This not only affects the compressive strength, it also affects the tensile and flexural strengths, the porosity, the shrinkage and the colour.

The more the w/c ratio is increased (that is, the more water that is added for a fixed amount of cement), the more the strength of the resulting concrete is reduced. This is mostly because adding more water creates a diluted paste that is weaker and more susceptible to cracking and shrinkage. Shrinkage leads to micro-cracks, which are zones of weakness. Once the fresh concrete is placed, excess water is squeezed out of the paste by the weight of the aggregate and the cement paste itself. When there is a large excess of water, that water bleeds out onto the surface. The micro channels and passages that were created inside the concrete to allow that water to flow become weak zones and micro-cracks.

Using a low w/c ratio is the usual way to achieve a high strength and high quality concrete, but it does not guarantee that the resulting concrete is always appropriate for countertops. Unless the aggregate gradation and proportion are balanced with the correct amount of cement paste, excessive shrinkage, cracking and curling can result. Good concrete results from good mix design, and a low w/c ratio is just one part of a good mix design.

2.4 Methods of Non Destructive Testing

Nowadays, the non-destructive testing (NDT) is considered as a good importance in terms of engineering and practical value (Jain et al. 2013). The available NDT can give many characteristics in concrete which is elastic modulus, compressive strength, impermeability, hardness, durability and many others using different method of NDT (Wheen 1974).

NDT gives the advantages of using it which is reducing the labour consumption as the most NDT tools are portable and efficient. A constriction of labour consumption of preparation phase, a smaller amount of structural damage, a destructive testing (DT) of concrete compression strength is possibly do not need to be applied which is cores. The less expensive testing tools can be applied as compared to core testing (Jain et al. 2013).

The other advantage using NDT is obviously not damaging the building component and not affecting the structural performance. In addition, NDT makes the rapidity and simplicity of in use as the result is readily and rapidly available on site immediately after the test is conducted (Hobbs and Tchoketch Kebir 2007).

The concrete structures are necessarily made a test after it is hardened to get the characteristics and to investigate whether the structure is match with its designed use as well as determine whether the standard cube test fail to meet the required strength of concrete. In this situation, NDT plays the important roles and it is useful in determining whether the concrete is uniform and the strength when compared with cores sampling and other destructive test such as load testing that is more expensive. Therefore, the NDT method is adopted will give the accurate and effective results (Testing n.d.).

The technology of NDT is gained obviously important in these modern industrial phases for deducting the time and enhancing the productivity and safety. These days, various types of NDT methods have been introduced which is rebound hammer and ultrasonic pulse velocity.

2.4.1 Rebound Hammer

In the early 1980s, there is a survey conducted in Canada and the United States of concrete testing laboratories revealed that although its limitations, the rebound hammer (RH) was the most frequent used for non-destructive test method by those surveyed (Wada et al. 2006). RH is applicable to determine uniformity of concrete, to describe regions in a structure of bad quality or deteriorated concrete, and to determine the strength development. For a particular concrete mixture, the rebound number is affected by certain factors such as moisture content of the test surface, the method used to obtain the test surface (type of form material or type of finishing), and the depth of carbonation. These factors need to be considered in preparing the strength relationship and interpreting test results (Carino 2001).

The use of different hammer in the same test which takes three different readings can give the different rebound numbers. Therefore, tests should be made with the same hammer in order to compare results. If more than one hammer is to be used, perform tests on a range of typical concrete surfaces so as to determine the magnitude of the differences to be expected (Carino 2001).

Figure 2.1: The Schmidt Rebound Hammer

Figure 2.1 shows the hammer that consists of spring loaded mass that slides on a plunger. To test the compressing spring, the plunger must be pressed on the surface until it releases by itself made the mass to impinge on the plunger with compressed spring energy (Wheen 1974).

There are factors other than strength and age affected the hardness readings which is high-alumina cements can give the strengths up to 100 per cent higher than ordinary portland cements. Other than that, super-sulphated cements can give values 50 per cent lower than ordinary Portland cement. The surface differences for similar cements cause only minor variations (up to 10 per cent) in the strength values (Wheen 1974).

2.4.2 Ultrasonic Pulse Velocity (UPV)

UPV is the non-destructive test method which determines the velocity of compression stress waves (P-waves). The waves' velocities traveling in a solid material lean on the density and elastic properties of material. The elastic stiffness is relating to the quality of some materials, therefore, measurement of UPV in such materials can often be used to indicate their quality as well as to measure their elastic properties (Kewalramani and Gupta 2006).

Every cube which prepared for the ultrasonic pulse velocity test is as stated in BS EN 12504-4:2004. The pulse velocity should be measured between moulded faces for cubes. For each specimen, there are at least three sided of space should be measured it is between top and bottom and the mean value recorded. The correlation curve will be constructing after the mean pulse velocity and mean strength obtained from each three identical cubes (Kewalramani and Gupta 2006).

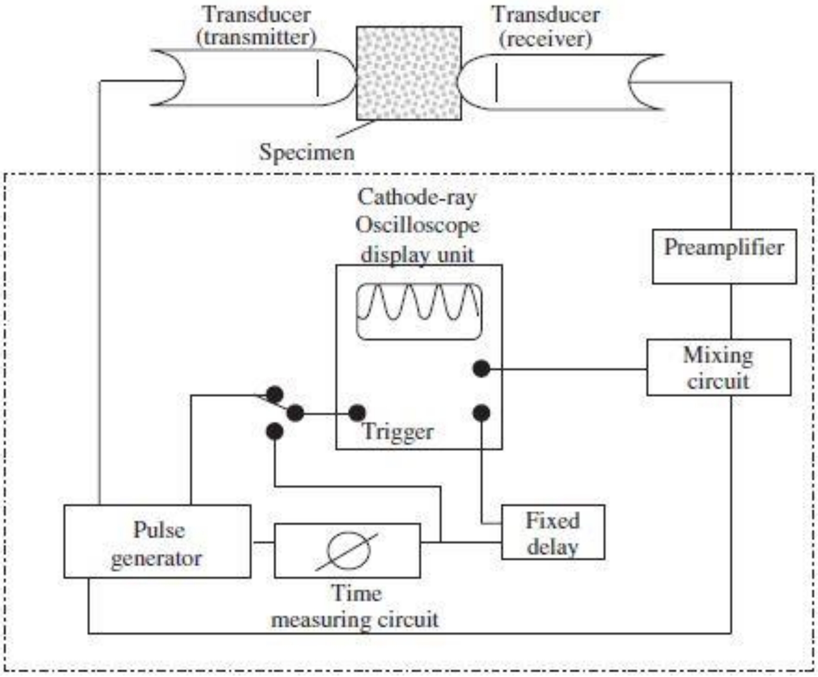


Figure 2.2: Schematic diagram of pulse velocity testing using circuit (adapted from ASTM C586)

The UPV test method employs the principle of measuring the travel velocity pulses trough a material medium. The pulse velocity equipment consists of an emitter (generating transducer) from which ultrasonic pulses are transmitted, a receiver (or receiving transducer) where the pulses are received, and a device for indicating the time of travel from the transmitter to the receiver. Piezoelectric and magneto-strictive types of transducers may be used, the latter being more suitable for the lower part of the frequency range (Kewalramani and Gupta 2006).

The ultrasonic pulse is created by applying a rapid change of potential from a transmitter-driver to a piezoelectric transformation element that causes it to vibrate at its fundamental frequency. The transducer is placed in contact with the material so that the vibrations are transferred to the material. The vibrations travel through the material and are picked up by the receiver. The wave velocity is calculated using the time taken by the pulse to travel the measured distance between the transmitter and the receiver. The concrete surface cannot be very rough, it is required to smoothen and level an area of the surface where the transducer is to be placed. The transducers are held tight on the surfaces of the specimens, and the display indicates the time of travel of the ultrasonic wave (Kewalramani and Gupta 2006).

2.4.3 Infrared Thermal Imaging

Infrared radiation will be absorbed by most material over a wide range of wavelengths, it will cause the higher in their temperature. Infrared energy emits all objects with a temperature greater than absolute zero, and even glowing objects usually emit far more infrared energy than visible radiation. Thermal imaging is a technique for changing a thermal radiation pattern, which is cannot be seen through the human eye, into a visual image. To accomplish this, an infrared camera is used to measure and produced the emitted infrared radiation from an object. Since this radiation is depended on the object surface temperature, it makes it possible for the camera to calculate and display this temperature. However, the camera produce the measurement of radiation does not only depend on the temperature of the object, but it also depends on the emissivity and its absorption by the atmosphere (Clark, McCann, and Forde 2003).

Three fractions composing with infrared radiation received by an infrared sensor from a heated body surface: the body radiation emitting, the surface that reflecting the surrounding infrared radiation and the infrared emission of the atmosphere layer between infrared camera and body (Datcu et al. 2005) .

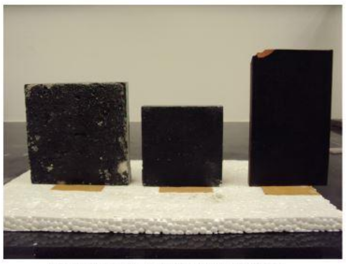
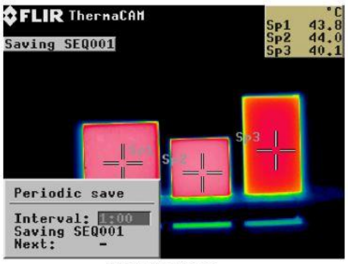
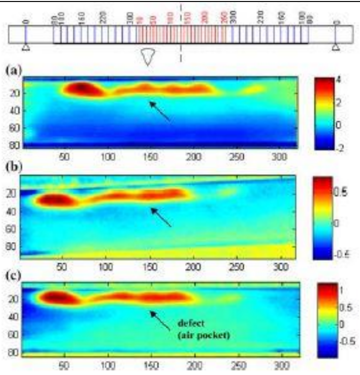
Advantages of using thermography (Datcu et al. 2005)

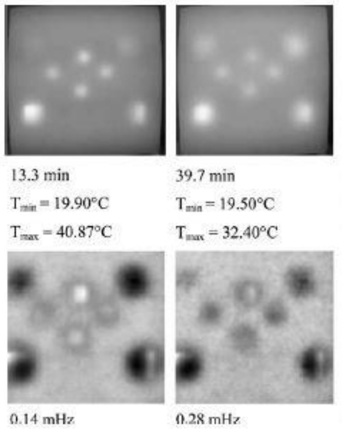
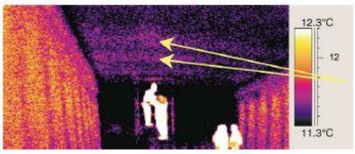
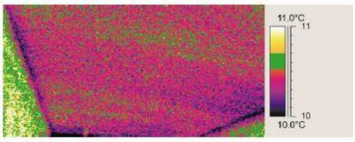
i. Remote sensing 1. There is no direct contact needed between the camera and the object under investigation. The distance of separation to allow measurement for the potential object is between a few millimetres to several kilometres. it is possible to use for both day and night .
ii. Large monitoring capacity. Thermal imaging cameras are capable to monitor the temperature at many different points within a scene simultaneously.
iii. Fast response rate. Thermal imaging equipment is able to detect and monitor rapid temperature fluctuations to an accuracy of ±0.08ºC.
iv. Portability. Thermal imaging equipment is lightweight and can easily be transported.

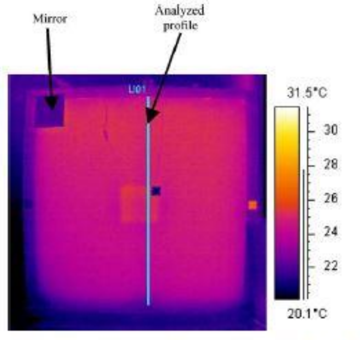
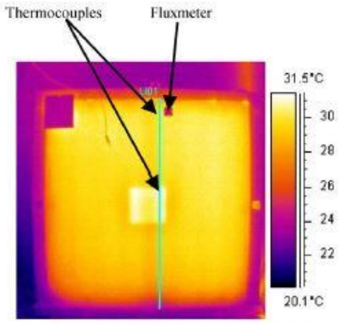
2.4.4 Summary of Literature Review

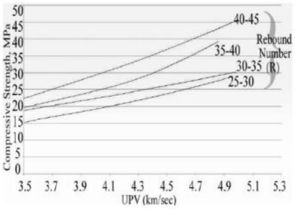
The summaries of literature review show the relevant research or study that using almost the same method to find the quality and the characteristic of the concrete. There are many NDT method use but in different techniques to find the characteristics of the concrete.

Table 2.1: Summary of Literature Review

Author	Method	Purpose	Findings
Janet F.C. Sham, Tommy Y. Lo, Shazim Ali Memon, 2012	Continuous Surface Temperature Monitoring (CSTM)	Investigate the noctumal sensible heat release characteristics by building fabrics. (e.g.: concrete, marble, ceramic)	 *(a) Three samples of building finishes*  *(b) Thermal image*
M.R. Valluzzi, E. Grinzato, Pellegrino, C. Modena, 2009	IR thermography	Interface analysis of FRP laminates externally bonded to RC beams.	

Ch. Maierhofer, et al, 2006	Impulse-thermography	Investigations of the near surface region of various structures. (e.g.: voids, honeycomb, cracks)	
M.R. Clark, D.M. McCann, M.C. Forde, 2003	Infrared Thermography	Detect defects and anomalies in various civil engineering structures.	 Fig. 6. Infrared image looking down a span while tap testing wa undertaken.  Fig. 7. Same infrared image as Fig. 4 but a tighter temperature range.  Fig. 8. An image of all three areas of delamination in this span.

Stefan Datcu, Laurent Ibos, Yves Candau, Simone Mattei, 2005	Infrared Thermography(quantitative thermal scanning)	Building wall surface temperature measurements.	 Fig. 6. Wall surface infrared image for a heat generation rate of 24 W/m^2 (non-corrected apparent temperatures).  Fig. 7. Wall surface infrared image for a heat generation rate of 48 W/m^2 (non-corrected apparent temperatures).
Manish A. Kewalramani, Rajiv Gupta, 2005	Ultrasonic pulse velocity through artificial neural network (ANN)	Prediction of compressive strength of concrete based on weight and UPV for two different concrete mixture namely M20 and M30.	The prediction done using ANN shows a good degree of coherency with experimentally evaluated compressive strength for both shapes and sizes of concrete specimens considered.
Samia Hannachi, Mohamed Nacer Guetteche, 2012	Combined method of UPV and RH	Determine the concrete quality by applying regression analysis models between compressive strength of in situ concrete on existing structure and the NDT	The analysis for cores gives correlations that are not really satisfactory, it is because the quality and means of implementation of concrete which are often inadequate, in terms of social housing programs often attributed to small companies

		values.	without major resources.
Akash Jain, A. Kathuria, A. Kumar, Y. Verma, K. Murari, 2013	Combined method of NDT (UPV and Rebound number)	Assessment of strength of concrete with greater accuracy.	Dependency on just one test method (RH or UPV test) will not give accurate result. The correlation between UPV, rebound number and compressive strength were given. 
N. Testing	Rebound Hammer and Ultrasonic Pulse Velocity	Develop a combined method to estimate the compressive strength of concrete in structures very accurately.	Moisture in concrete affects the predicted strength based on these two methods, the effect of moisture on predicted strength can be eliminated. For low strength concrete, the rate of change of compressive strength respect to rebound number is very low. But it increases with the increase of strength and pulse velocity.
R. J. Wheen, 1974	Various of Non-Destructive Testing of Concrete	The characteristics of compressive strength, elastic modulus, durability, hardness, impermeability,	Successful use of non-destructive test methods requires the training of special technical staff. The strength of the methods, in general, lies in quality control procedures and

		and many others required in different applications.	comparative testing of concretes.
Brian Hobbs, Mohamed Tchoketch Kebir, 2006	UPV and impact rebound hammer (IRH)	Laboratory investigation for reinforced concrete building.	The use of combined methods produces results that are more reliable and closer to the true value when compared with the use of the methods separately. An acceptable level of accuracy was achieved for strength estimation of concrete.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section discussed about the methodology for the study. The method used in the study is a typical method for concrete field which includes several steps before getting the reading of compressive strength.

The progress starts with literature review that is collection of any information and knowledge about the study. The findings focus more on the concrete such as the material that will be used in the concrete, the procedures to produce the concrete, the testing involved with fresh and harden concrete and anything related with concrete. It is begin with the mix design of the concrete.

The material preparation of the concrete depends on the mix design that can decide the value to prepare the material. It involves in determining the type of cement use, the size of aggregate, the water content, the type of grade of the concrete to produce and the day for concrete to achieve the 100% strength.

After the concrete is mixed, the fresh concrete then will be cast into the mould and take out after 24 hours. Then it will go to curing phase which the concrete is submerged under water to develop the strength. The hardened concrete will be tested for the compressive strength using Non-Destructive Test (NDT) and Destructive Test (DT) method. The reading and result then will be analyse and come out with recommendation for the future improvement.

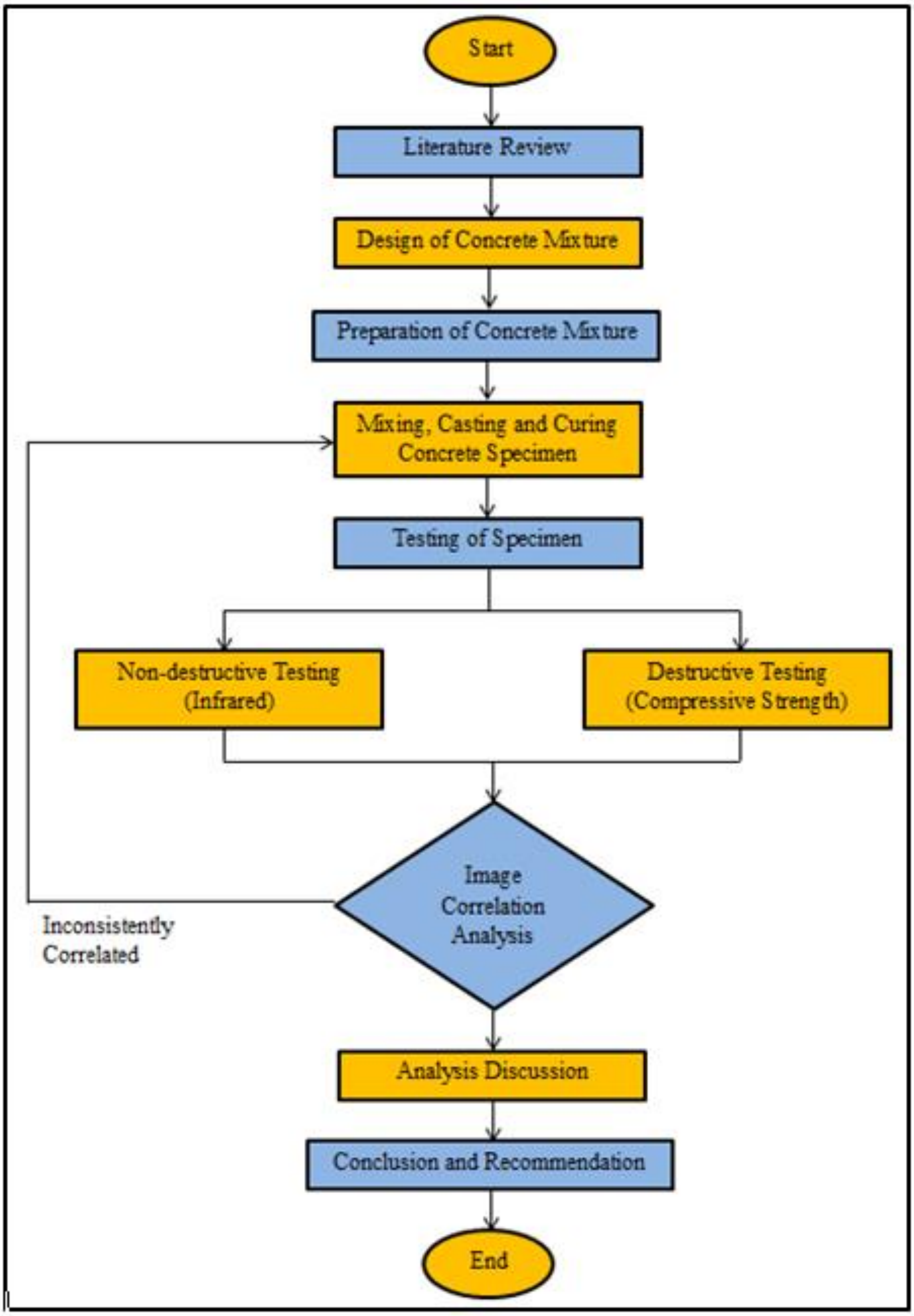


Figure 3.1: Methodology Flowchart

Figure 3.1 shows the flowchart of the methodology that will be done in this study. The methodology involving the laboratory works. It means that there are precautions to be taken which are always wear Personal Protective Equipment (PPE) in handling laboratory works. For example safety shoes, safety goggle and dust mask.

3.2 Material Preparation

The material preparation of the study starts after the design calculation is made. The design calculation must follow the specifications to get the acceptable value for the materials to prepare. The design form can be referring to Appendix A. After the calculation is made, the first step is prepared the material, tools and apparatus. The materials used are cement, sand, aggregate and water. There is specific ratio for the particular grade of concrete. The ratio will express by number for example 1:2:4 which is one part is the cement, two parts is the fine aggregate and four parts is the coarse aggregate. The water-cement ratio is usually shown by mass.

The cement use for this study is Ordinary Portland Cement (OPC) complies with MS 522 JKR Standard Specification Building Works 2005 which consider as conventional trial mix without any added admixtures. The aggregate used in this study is the uncrushed fine aggregate and crushed coarse aggregate with maximum size of 20mm. The coarse aggregate is sieved with sieve analysis before proceed to mixing phase.

Table 3.1: Sieve Analysis Result

BS SIEVE SIZE (mm)	**PASSING (%)**	**UPPER LIMIT**	**LOWER LIMIT**
37.5	99.95	100	100
20	78.48	100	90
16	48.38	100	75
10	10.75	90	55
5	0.12	59	35
2.36	0.06	30	8
2	0.02	10	0

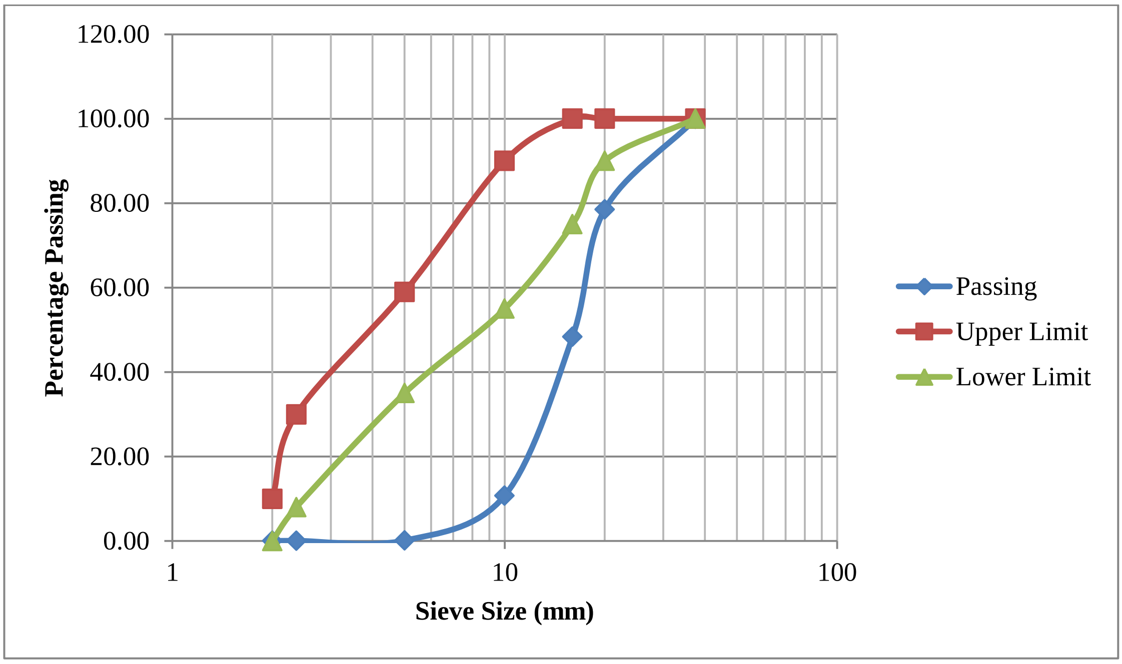


Figure 3.2: Graph of Sieve Analysis

3.3 Mixing, Casting, Curing

In this study, the concrete that will be mix consists of five different types of grade which starting from G20, G25, G30, G35 and G40. Each grade is prepared for nine cube sample sized 150mm x 150mm as the testing needs three specimen per testing to get the average value. The material prepared then will be mix together following the requirement and it will be put in the concrete mixer machine.

Figure 3.3: Slump Test

Before the fresh concrete is put in the mould, the mix will undergo a testing which is slump test to know the workability of the mix concrete. The mixed concrete then will be cast in the cube mould to get the shape of specimen.

Figure 3.4: 150mm x 150mm x 150mm Cube Mould

The concrete mould is made of UPV. Before the concrete is cast into the mould, the mould must be spread a lubricant to avoid concrete get stuck when it is harden. The harden concrete must be taken out after 24 hours of casting. The harden concrete then is put under water to undergo curing process.

Figure 3.5: Concrete specimen after casting into the mould

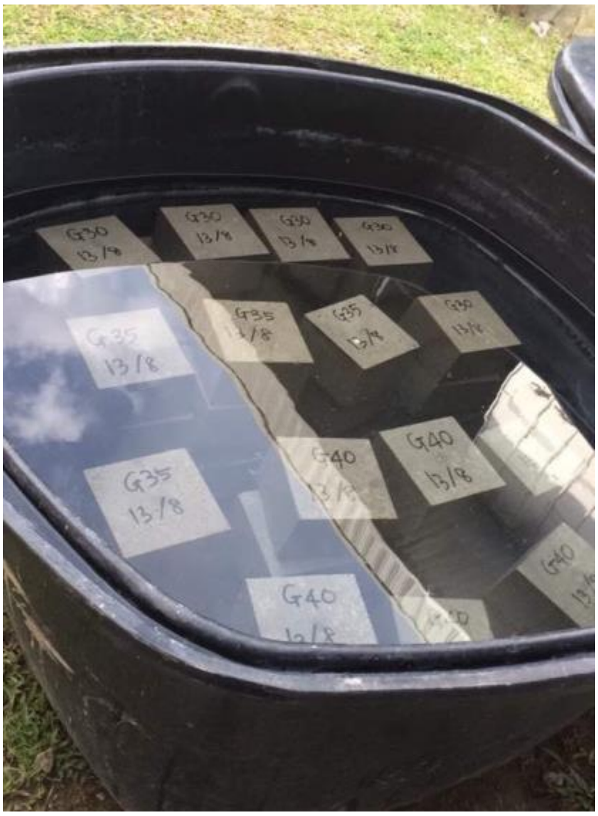


Figure 3.6: Concrete curing process

Curing process is the state that the concrete is submerged under water for the development of strength and durability. The curing method used for this study is ponding and immersion method. The water that will be used to be put the concrete cube must be cooler than the temperature of the concrete. The typical temperature of concrete is between 27ºC to 35ºC as measured by ASTM C 1064-86.

3.4 Infrared Image Sampling

Infrared image sampling is the image that is produced by infrared thermal camera. In this study, the camera model used is FlirOne Infrared Thermal Camera for Android. The camera must be connected to the android device which is android mobile phone version 6.0 and above to support the application of FlirOne from Android PlayStore.

Figure 3.7: FlirOne Infrared Thermal Camera

Figure 3.2 shows the Infrared Thermal Camera used in this study. The camera will produce the thermal image which has the colour contour according to the temperature of heat. This camera model is just for Android model.

After the concrete specimen reach to day 7, 28 and 56, it will be tested for compressive strength using NDT method. NDT that will be conducted is the new method which is Infrared Thermal Imaging. The DT method is compressive strength test.

Figure 3.8: Compressive Strength Test Machine

The Infrared Image will be taken after the heat is applied to the surface of the specimen. The reading will be taken in three faces of the specimen to get the average reading. The heat will be applied by torch for particular time. After that, the picture of the specimen is immediately taken to get the image of heat contour.

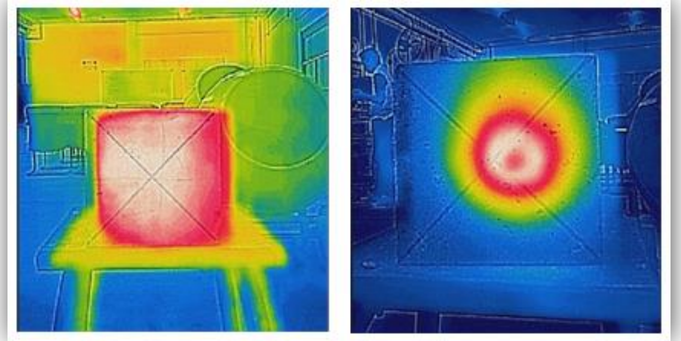


Figure 3.9: Thermal image before and after heat being applied

Figure 3.3 show the state of concrete surface in thermal image before and after heat applied by using thermal camera. The camera will detects minimum heat -20ºC and maximum heat 120ºC. After heat being applied, the camera focuses on the dominant heat which will produce the contour image to see the heat distributions.

Figure 3.10: Torch

Figure 3.4 shows the torch that used to apply heat on the concrete surface. The heat will be applied for only five second to get the best contour of heat distribution. The picture of thermal image then will be taken after 25 second heat applied

Figure 3.11: Heat Applied

3.5 Thermal Contour Image Analysis

Thermal contour analysis is the process made after the image is being captured by the thermal camera. The image produced by the camera is a thermography image which is false colour that shows different temperature for different colours. The different colours represent the level of the temperature which will be classified according to the grade of the concrete. The classification includes the percentage of the contour colour. The contour produced by the camera will be different as the strength of the concrete is different. The heat applied to the concrete is the same level of heat and the same number of time. So, the contour produced is depending on the grade of the concrete.

There are at least three contours with different colours and heat will be produced by the camera for each surface of the concrete which are white colour in the centre, yellow colour after white and orange colour after yellow. Each of the diameter reading of the contour will be taken and get the average. The result then will classify the strength of the concrete.

3.6 Compressive Strength Test

Compressive strength is one of the important characteristics that must be recorded and analysed before proceed to the next action for the concrete. The strength of concrete plays very important role because when the concrete or the structure achieve the allowable strength then the structure must be sustain according to the requirement on the design phase.

There are several methods to recognize the strength of the concrete which is divided into two method; NDT and DT. NDT consists of Rebound Hammer (RH) test and Ultrasonic Pulse Velocity (UPV) test while, DT consists of compressive strength test. These methods have different procedure to get the compressive strength reading.

The new method to recognize the compressive strength that will be produced in this study is categorized in NDT method which is Infrared Thermal Imaging. This method can be considered as the simplest yet precise. It is very practical as the size is just as small as a hand palm.

3.7 Thermal Distribution Analysis

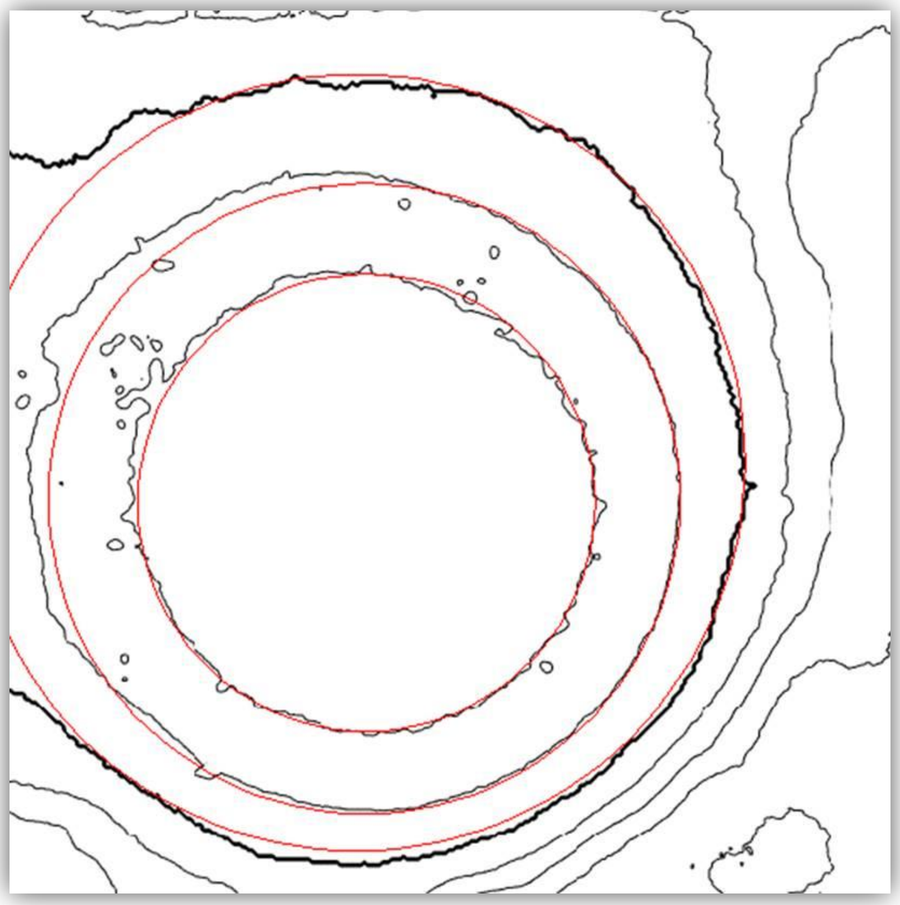


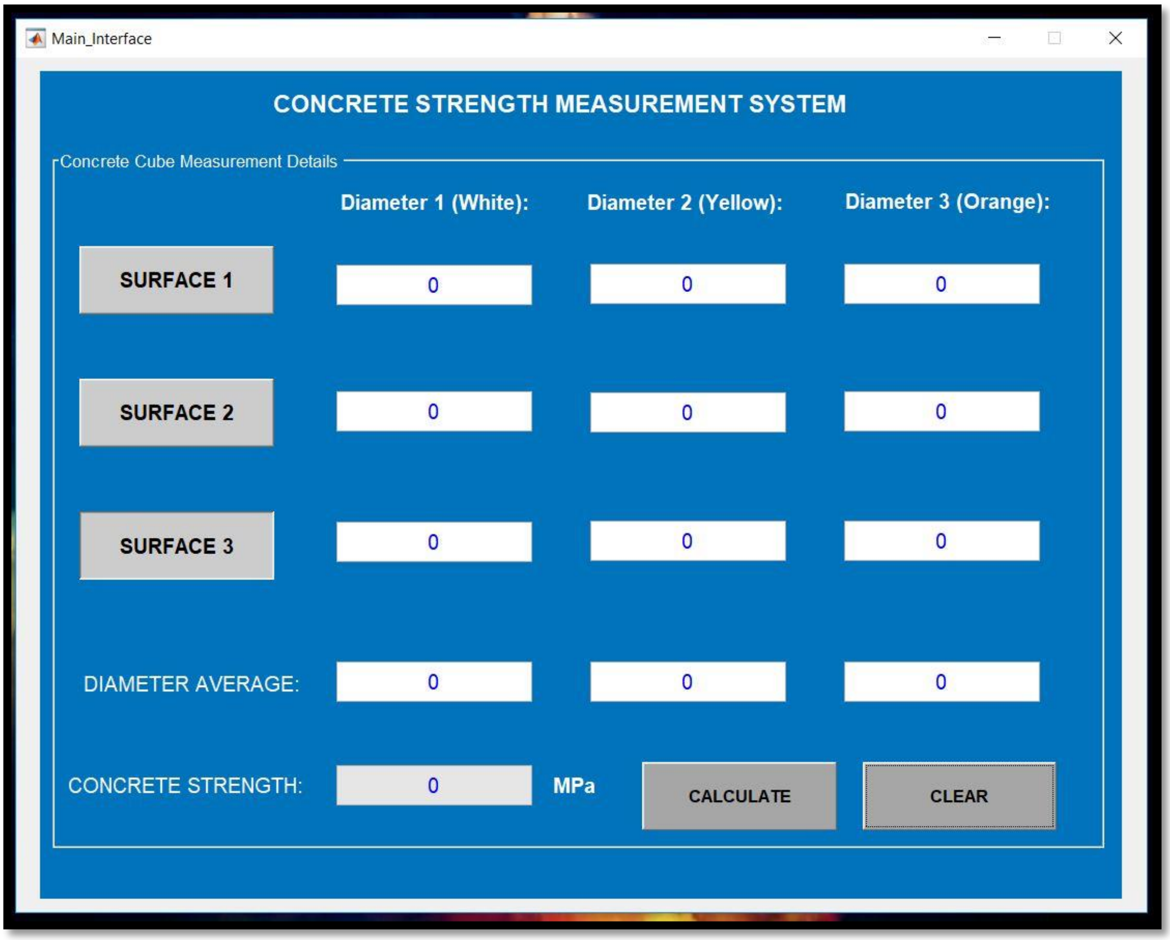
Figure 3.12: Define circle from AutoCAD

Figure 3.4 shows how the circles diameter is determined. The first step is resizing and scaling the image into the actual size as concrete cube specimen which is 150mm x 150mm. There is an option in AutoCAD to determine diameters by using 3-points circle. The circle then placed on the actual circle where the points must be in the most dominant and accurate circle. The diameter then determined for every specimen where each cube is defined for three surfaces. Then, the average is calculated to get the precise reading.

3.8 User Manual for Measurement Tool

The measurement tool is made up from MATLAB software that has been developed by the source code. The data that has been analysed in the software is the diameter for every contour colour of the heat distribution. The range of diameter for every grade of concrete has been set based on the result gained from the laboratory. These are step by step user manual for this measurement tool.

Step 1: Open the tool to get the interface.



Main_Interface

CONCRETE STRENGTH MEASUREMENT SYSTEM

Concrete Cube Measurement Details

	Diameter 1 (White):	Diameter 2 (Yellow):	Diameter 3 (Orange):
SURFACE 1	0	0	0
SURFACE 2	0	0	0
SURFACE 3	0	0	0
DIAMETER AVERAGE:	0	0	0

CONCRETE STRENGTH: 0 MPa

Figure 3.13: The interface of measurement tool

The interface shows the details of needed to determine the strength of concrete. Surface 1, surface 2, and surface 3 represent the sample cube of concrete. Each grade of concrete cube needs to use three specimens to get the average of the diameter readings. Every specimen need to determine three type of diameter which is diameter 1 represents white colour contour, diameter 2 represents yellow colour contour and diameter 3 represents orange colour contour. It is also to get the average reading of diameter.

Step 2: Click on the ‘surface 1’ button to insert the diameter.

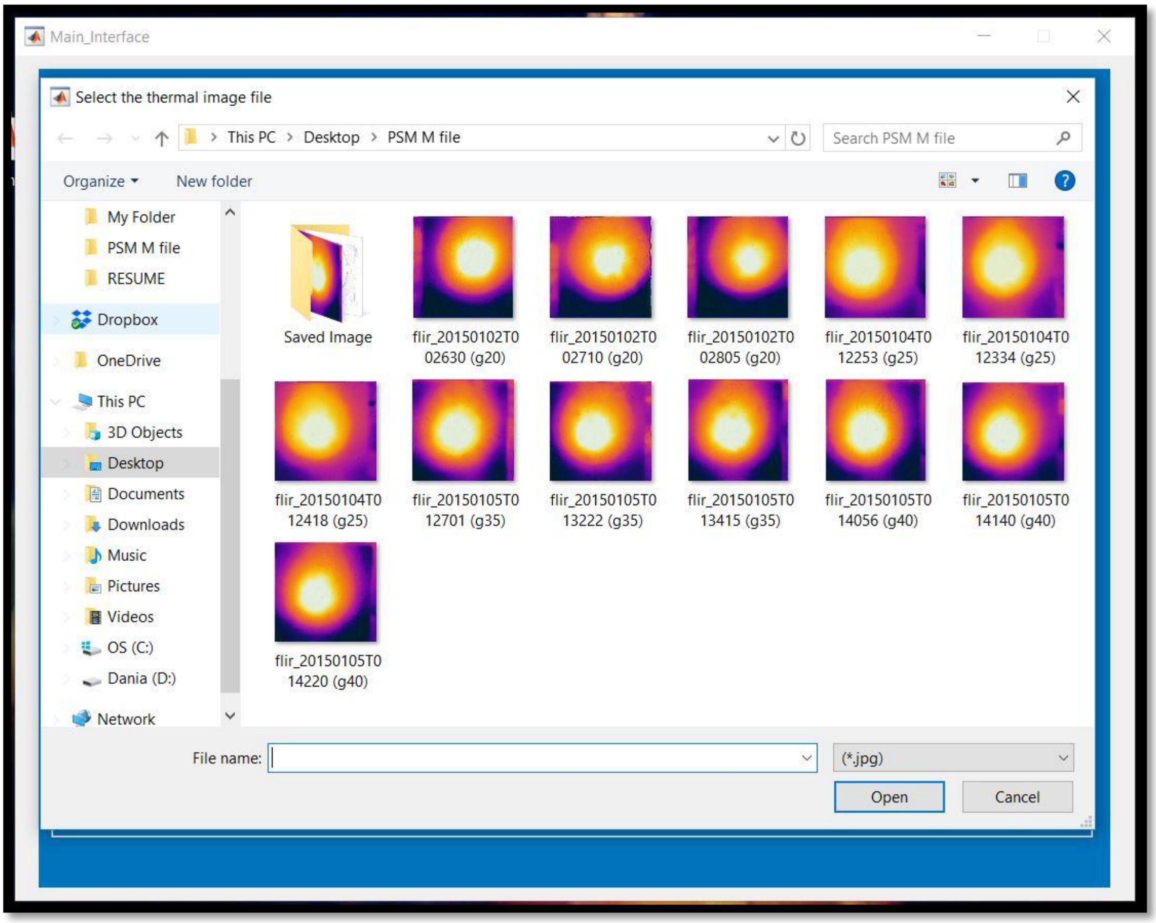


Figure 3.14: Image Folder

The image folder will pop-up to allow user to choose which image contour to determine first depending on the grade of concrete that stated at the end of the name of image. (e.g.: g35)

Step 3: select the diameter of the contour using three-point circle at contour plot image.

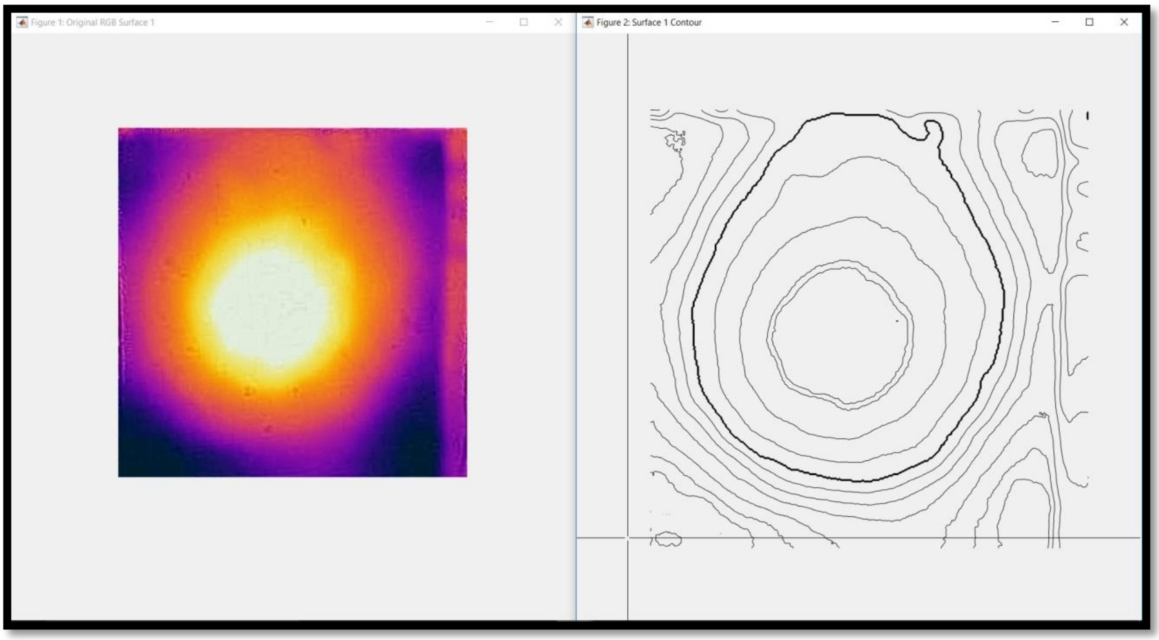
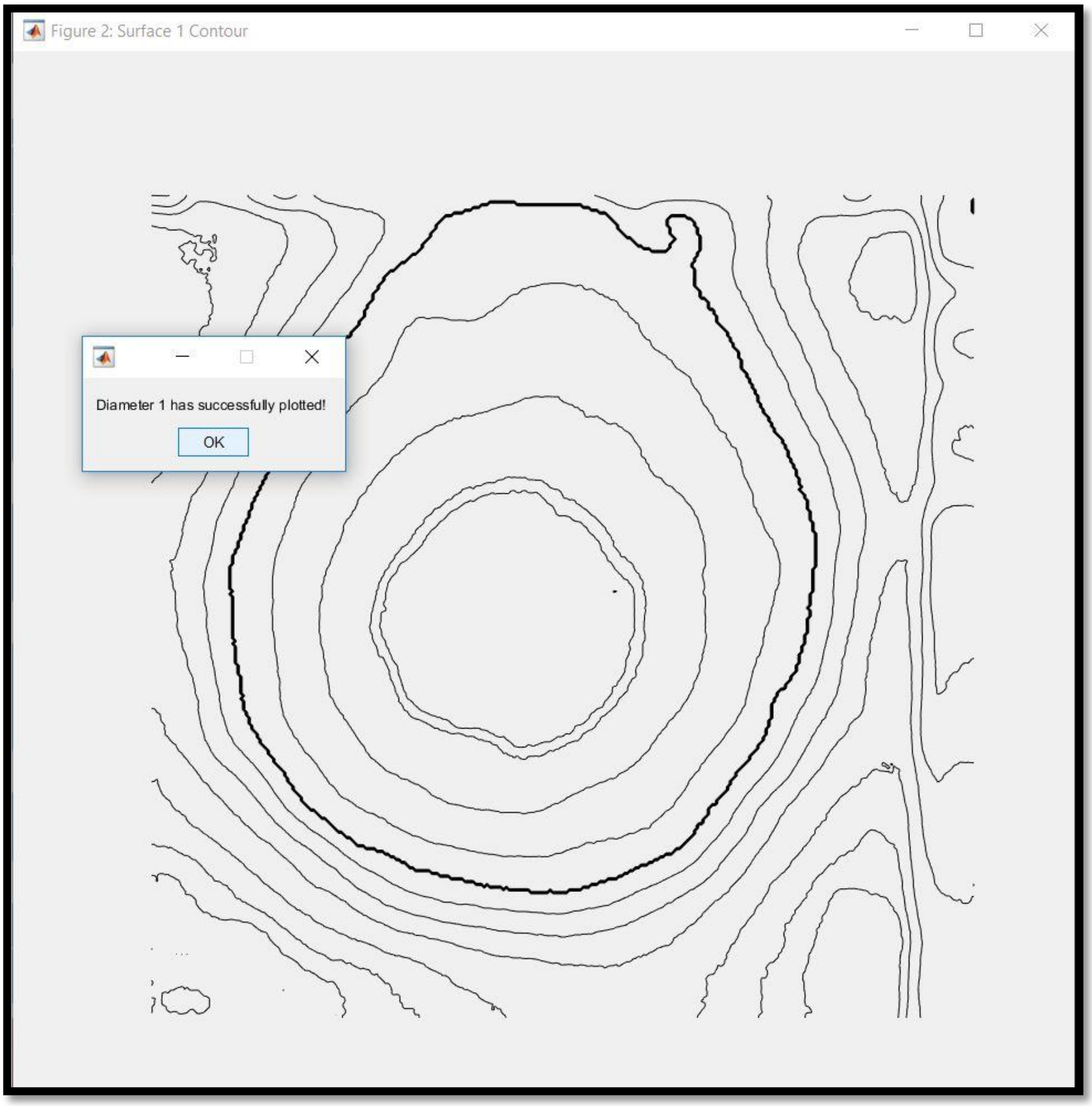


Figure 3.15: The contour plot of the contour image

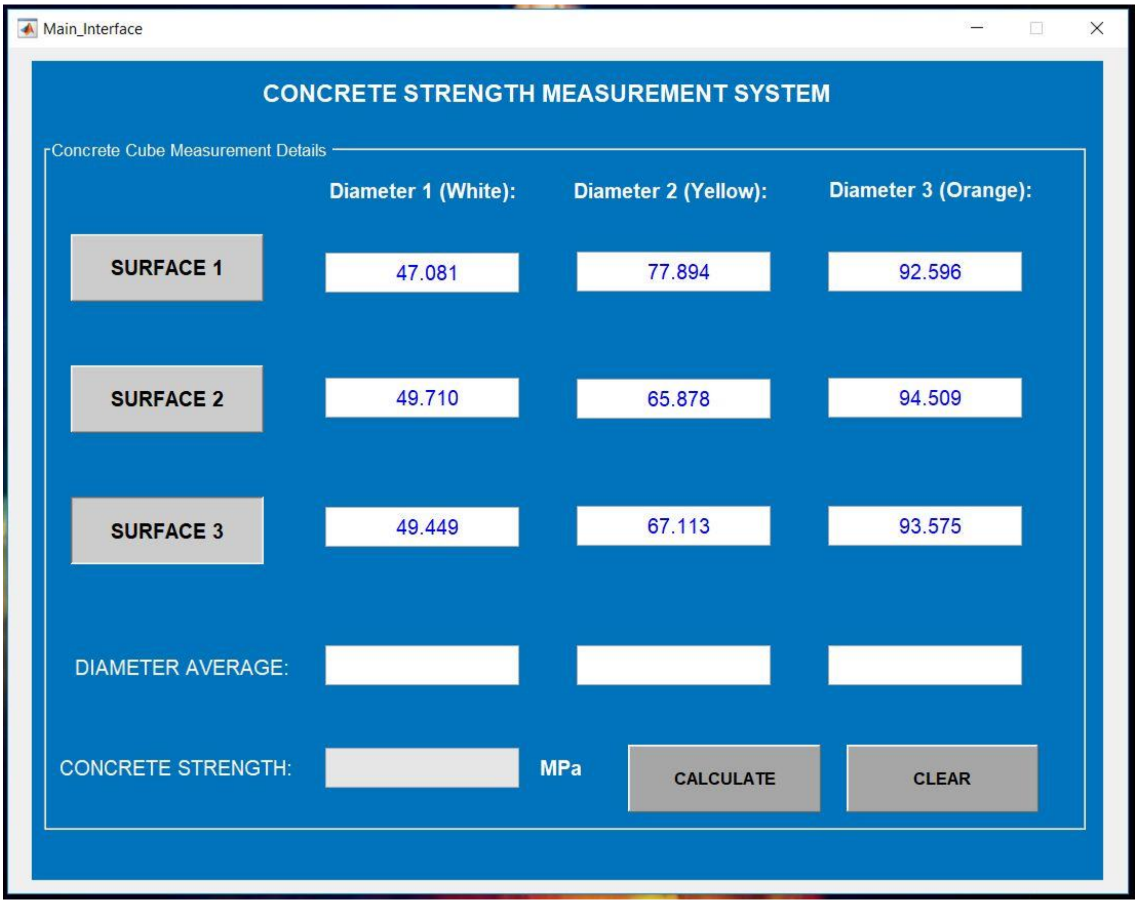
The contour plot image will appear once the image from the folder is chosen. It is for determining the diameter from the clearer version of contour image. Every contour image needs three reading of diameter which is the white colour contour, yellow colour contour and orange colour contour. The user just needs to click at the three points on every contour line to get the diameter. After selecting the diameter, the pop-up of successful will appear to let user know the point was enough selected.



Diameter 1 has successfully plotted!

Figure 3.16: Pop-up of three point circle successfully plotted

Step 3: Repeat step 2 for ‘surface 2’ and ‘surface 3’



CONCRETE STRENGTH MEASUREMENT SYSTEM

Concrete Cube Measurement Details

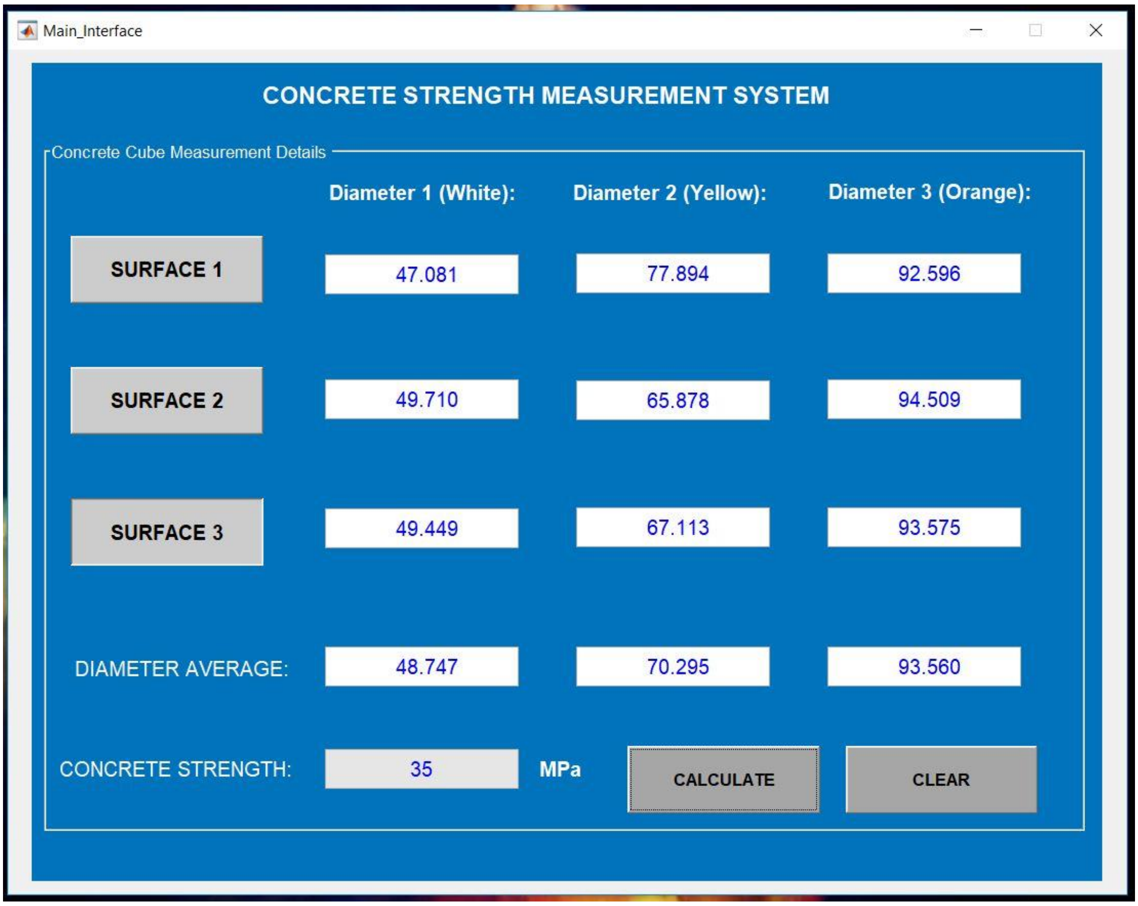
	Diameter 1 (White):	Diameter 2 (Yellow):	Diameter 3 (Orange):
SURFACE 1	47.081	77.894	92.596
SURFACE 2	49.710	65.878	94.509
SURFACE 3	49.449	67.113	93.575
DIAMETER AVERAGE:			

CONCRETE STRENGTH: MPa

Figure 3.17: The full-filled of diameter reading

The step 2 is repeated for the surface 2 and surface 3 by using the different image of the same grade.

Step 4: Click “CALCULATE”



CONCRETE STRENGTH MEASUREMENT SYSTEM

Concrete Cube Measurement Details

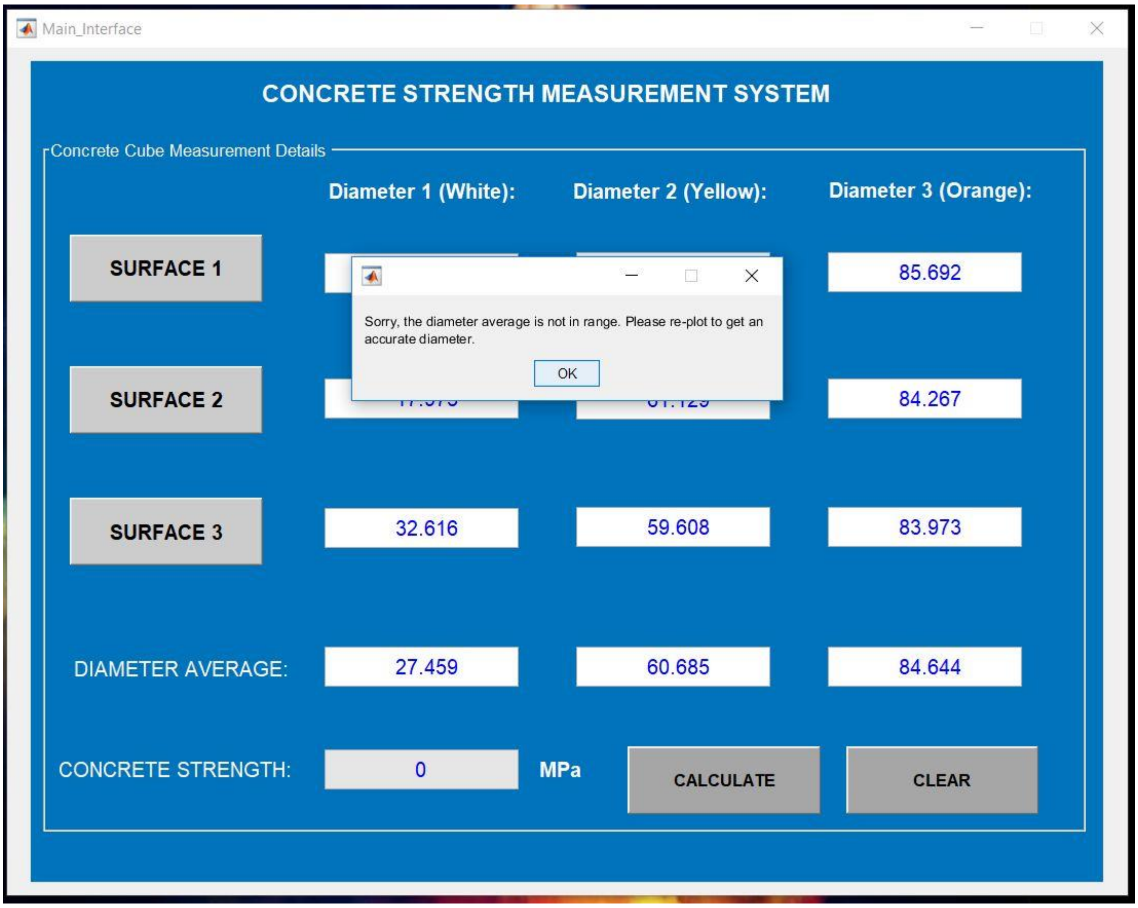
	Diameter 1 (White):	Diameter 2 (Yellow):	Diameter 3 (Orange):
SURFACE 1	47.081	77.894	92.596
SURFACE 2	49.710	65.878	94.509
SURFACE 3	49.449	67.113	93.575
DIAMETER AVERAGE:	48.747	70.295	93.560

CONCRETE STRENGTH: 35 MPa

Figure 3.18: The result of concrete strength

After the diameter of the contour has been full filled, the user has to click on the “CALCULATE” button to get the average reading and concrete strength result. The result of concrete strength based on the range that has been set from the average reading of the diameter then will appear.

If the average reading is not in the range of diameter that has been set, the concrete strength reading will not appear and there will be a pop-up that tells the reading is not in range. It will ask to point the three point circle again.



	Diameter 1 (White):	Diameter 2 (Yellow):	Diameter 3 (Orange):
SURFACE 1			85.692
SURFACE 2			84.267
SURFACE 3	32.616	59.608	83.973
DIAMETER AVERAGE:	27.459	60.685	84.644

CONCRETE STRENGTH: 0 MPa

Sorry, the diameter average is not in range. Please re-plot to get an accurate diameter.

Figure 3.19: The error of the reading

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Compressive Strength

Compressive strength testing is the very last step for laboratory works because it is the destructive testing that makes the concrete crack and destroyed.

Table 4.1: Compressive Strength of Concrete for day 7

Concrete Compressive Strength (MPa)	
Grade	**Day 7**
20	19
25	22
30	22
35	22
40	36

Table 4.1 shows the compressive strength of concrete for day 7. Concrete strength should achieve 60% to 70% strength after seven days. These readings show that all grades of concrete have achieved the target strength. For concrete grade 20, the strength is 19MPa which is 95% strength has achieved. For grade 25, the strength is 22MPa which is 88% strength has achieved. For grade 30, the strength is the same like grade 25 which is 22MPa and it is 73% strength has achieved as well as grade 35, the strength is 22MPa which is 63% strength has achieved. It can be considered as the weakest of all because the strength growth is the slowest at this age. For grade 40, the strength is 36MPa which is 90% strength has achieved.

Table 4.2: Compressive Strength of Concrete for day 28

Concrete Compressive Strength (MPa)	
Grade	**Day 28**
20	28
25	33
30	34
35	34
40	42

Table 4.2 shows the compressive strength of concrete for day 28. The compressive strength reading for day 28 supposedly must be achieved 100% strength. These readings show that most of the readings have achieved and exceeding the 100% strength. For concrete grade 20, the strength reading is 28MPa which has exceeded 40% from 100% strength reading. For grade 25, the strength reading is 33MPa which 32% more than 100% strength reading. For grade 30, the strength reading is 34MPa which is 13% more from the targeted reading. For grade 35, the strength reading is not achieved yet as the strength is 34MPa. The last one, the strength reading for grade 40 is 42MPa which is more 5% than the 100% strength reading.

Table 4.3: Compressive Strength of Concrete for day 56

Concrete Compressive Strength (MPa)	
Grade	**Day 56**
20	34
25	39
30	39
35	41
40	48

Table 4.3 shows the compressive strength of concrete for day 56. All of the compressive strength readings after 56 days are exceeding the 100% strength as the

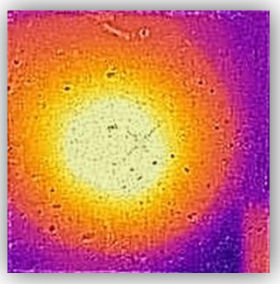
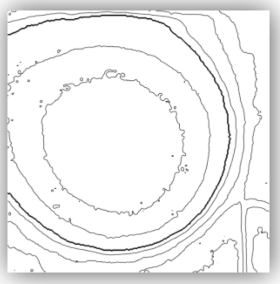
concrete strength continuing the strength growth and it will stop when it achieves the maximum strength.

The strength growth of concrete is depends on the design of material at the first stage before starting the laboratory works. The design material is for stating how much the particular material should be used for mixing the specific grade of the concrete. As all of the compressive strength reading exceeding the 100% strength, there are because of there are material used at the mixing stage of the concrete is exceed for example the cement paste. But the specimen still can be use as long as the targeted strength has achieved.

4.2 Correlation between Thermal Contour Image and Contour Plot

As the concrete cube going through the new alternative way of non-destructive testing which is Infrared Thermal Imaging, the thermal contour image will be transferred into a contour plot using MATLAB to get the clear image for accurate readings.

Table 4.4: Correlation between Thermal Contour and Contour Plot

GRADE	THERMAL CONTOUR	CONTOUR PLOT
20		

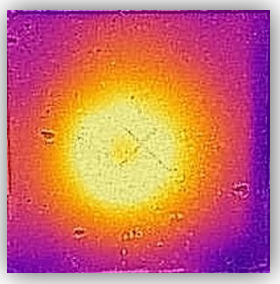
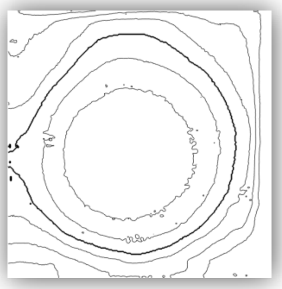
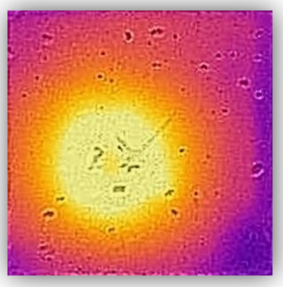
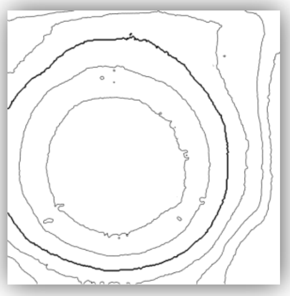
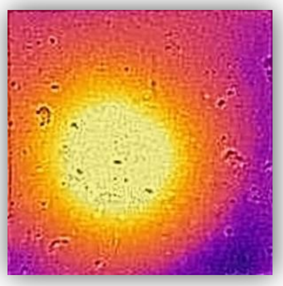
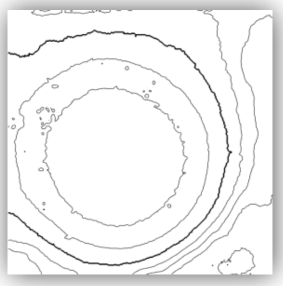
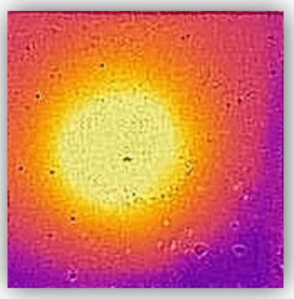
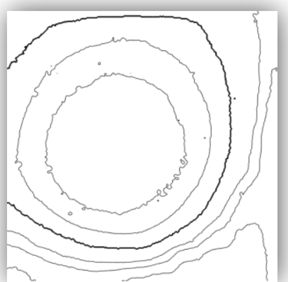
25		
30		
35		
40		

Table 4.3 shows the sample of thermal contour image produced by thermal camera and contour plot that is produced by MATLAB. There a slightly difference in the diameter of the circles for every grade of concrete. It can see that the higher the

strength of the concrete, the higher the reading of the circles diameter. This means that if the concrete or materials are high in density, the heat distribution will drive faster.

The uses of contour plot give more accurate reading of diameter. This is because the contour plot has the real line that can be seen clearly as compared to thermal contour. There is just a slightly different in the reading of the diameter that makes this study have to use the precise data to avoid error.

Table 4.5: Diameter Reading for Contour Plot

Grade	**Diameter (mm)**		
	White	**Yellow**	**Orange**
20	78	107	131
25	74	102	124
30	78	105	127
35	78	106	131
40	79	110	136

Table 4.5 shows the diameter reading for every contour plot. As the thermal image has various types of colours that represent the heat distributions, this study focuses only on the first three colours from the centre of the surface. The colours are; white colour that considered as the hottest, followed by yellow colour which is the second circle, and the orange colour which is the biggest circle that would been taken the diameter reading.

The reading of the diameter increased directly proportional to the grade of concrete starting from grade 25 to grade 40 concrete. For the below grade 25, the reading is not into the trend that would considered not relevant to use this method. This is because of all the diameter readings does not show the good heat distribution as the concrete cube has less density as compared to the others.

4.3 Generation of Equation

The generation of equation is from the scatter graph produced by the data. The graph has the regression line that shows the correlation coefficient (R^2) and the linear equation based on the line. The correlation coefficient is the formula to find the trend of the regression line. The best value of R^2 is 1 which considered as the best fit of the line.

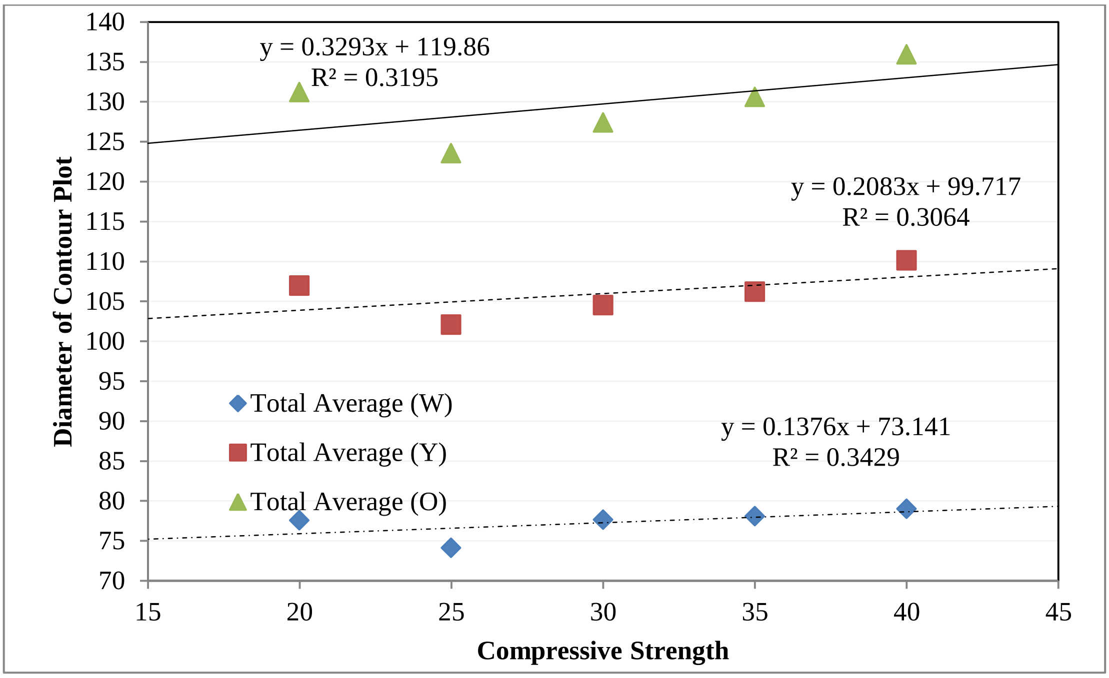


Figure 4.1: Correlation between the Compressive Strength and the Diameter of Contour Plot

Figure 4.1 shows the relationship of the strength and the diameter reading of the specimen. As it seen in the figure, the correlation coefficient is not as the reading is not even nearest to 1. As this method is not relevant for the concrete below than grade 25, the reading of concrete grade 20 would be excluded from the analysis.

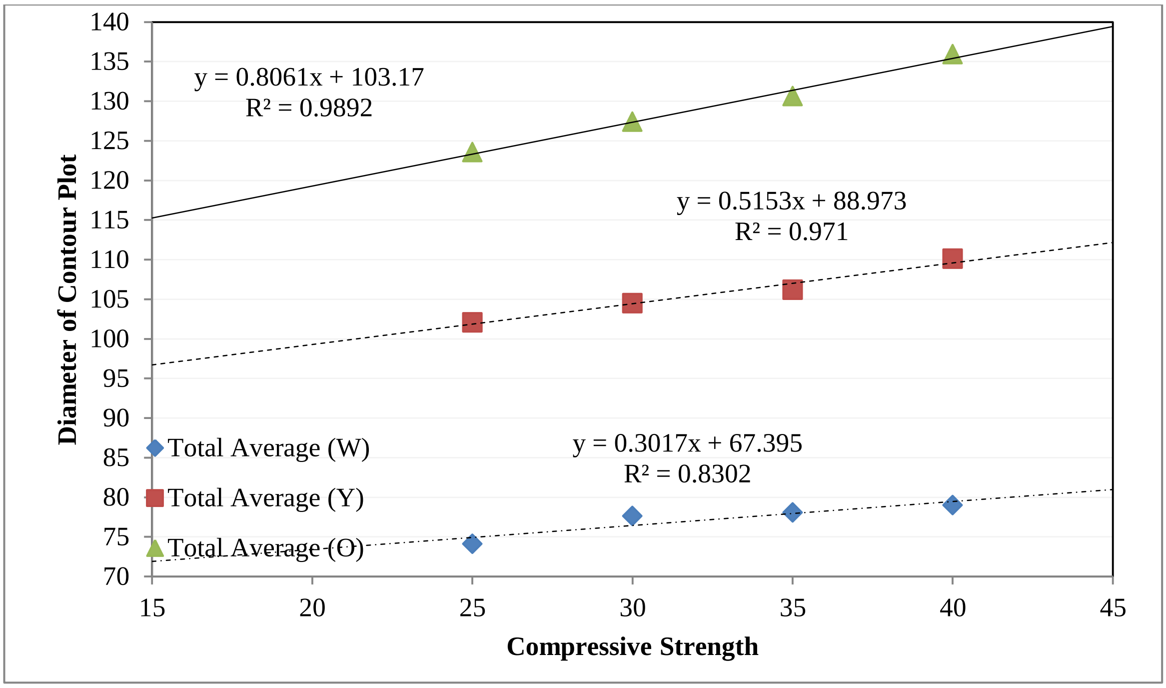


Figure 4.2: The Correlation between Compressive Strength and the Diameter of Contour Plot without Grade 20 Data

Figure 4.2 shows the regression line that has been excluded grade 20 data as the method is not suitable for it. The correlation coefficient shows the reading that is relevant and nearest to 1. It is not equal to 1 because the increasing variables are not uniform. However the regression lines are acceptable because it is near to the best fit. The linear equation can be found on the graph.

$$f_c = \left(\frac{d}{0.3017} - 223\right) \qquad 4.1$$

Where:

fc = Compressive Strength (MPa)

d = Diameter of thermal contour (mm)

Equation 4.1 shows the example of linear equation that has been simplified to find compressive strength for the diameter reading of white colour circle. The formula would be used for all the three colours of image contour to find correlation between compressive strength and heat distribution of concrete.

Table 4.6: Simulation of Compressive Strength with and without grade 20

Grade	Average Strength (MPa)	Grade	Average Strength (MPa)
20	34	20	-
25	24	25	24
30	31	30	31
35	34	35	34
40	40	40	40

Table 4.6 shows the final reading of the correlation between compressive strength and the heat distribution of concrete with grade 20 and without grade 20 reading. These compressive strengths are from the average of all the diameter readings. The reading of grade 20 shows 34MPa which has high difference from the actual strength of concrete. For the grade 25 concrete, the compressive strength is 24MPa which has less 1MPa to achieve the real strength. For the grade 30 and 35 concrete, the compressive strengths are 31MPa and 34MPa respectively which have more than 1MPa from the real strength. For the grade 40 concrete, the reading is just as accurate as the real strength. These readings have only 1MPa different in reading.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The conclusions for this study according to the objectives are as follows:

i. The first objective of the study which is to develop non-destructive test measurement tool by using infrared analysis is achieved as the tool (software system) of the measurement tool has been tested. It is a simple way to get the concrete strength non-destructively. It also saving time, saving cost and maintains the quality of the structure because the test does not need to take the sample of the structure to the laboratory. The tool can be use on site just by taking the thermal image at the targeted spot to upload into the MATLAB software that has been develop by source code and get the reading of the concrete strength.

ii. The second objective is to determine the correlation between compressive strength and heat distribution of concrete. The correlation is determined by the diameter of the heat contour to form the regression line. The regression line produced the reading of correlation coefficient. All the reading of the correlation coefficient from the results are considered as an acceptable reading because they are near to the best fit reading which is 1. It shows that, the higher the concrete compressive strength, the faster the heat distribution spreading in the concrete cube.

5.2 Recommendations

These recommendations are for the future works to improve the study and findings:

i. Heat all the specimens into the oven for 24 hours before the testing is conducted to let it dry equally.

ii. The time taken of applying the heat by the torch at the centre of concrete surface must be reduced to get the better contour images.

iii. Do not use the dark colour pen to mark and label the specimen as it affects the contour plot output.

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APPENDIX A

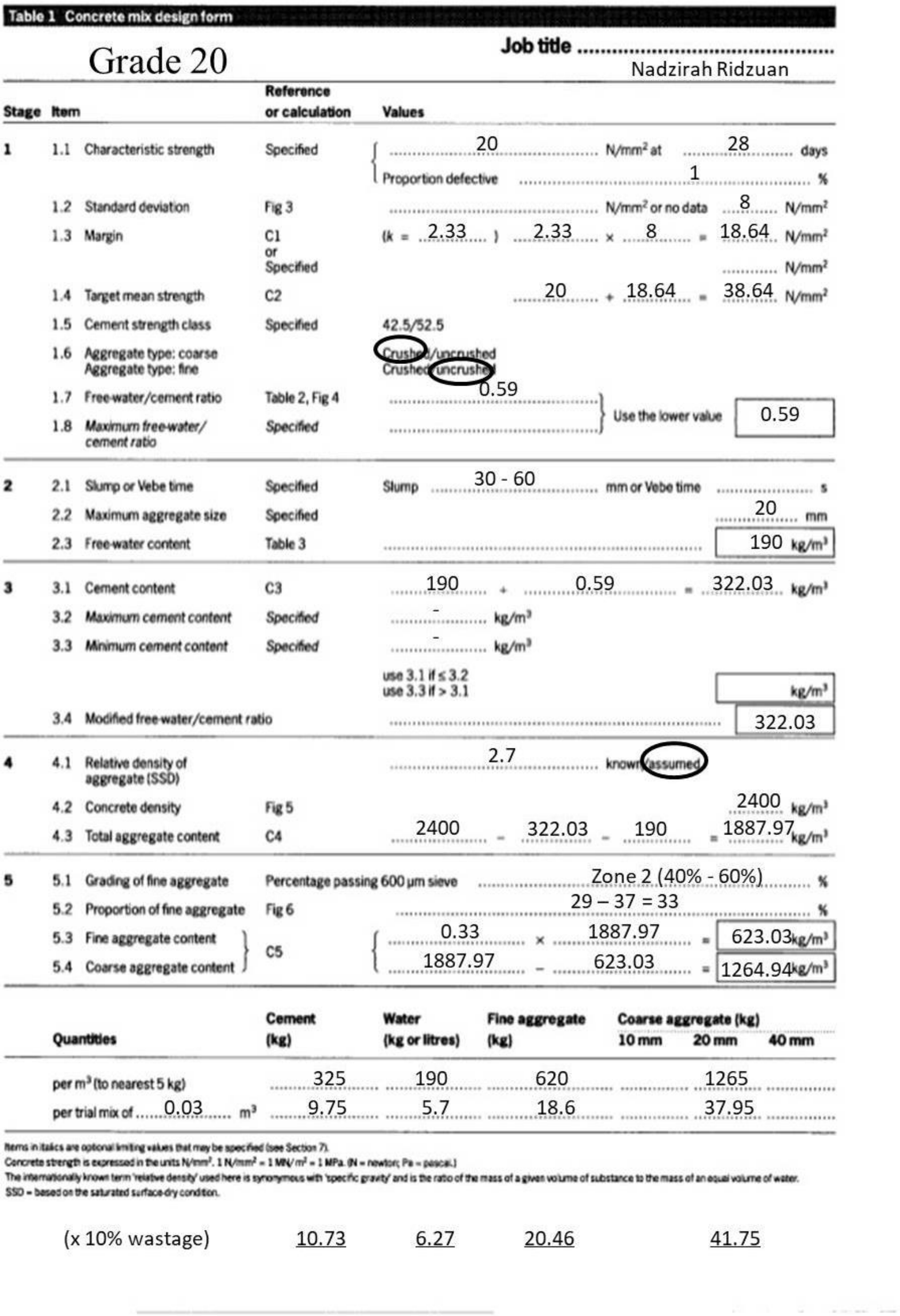


Table 1 Concrete mix design form

Grade 20

Job title Nadzirah Ridzuan

Stage	**Item**	**Reference or calculation**	**Values**
1	1.1 Characteristic strength	Specified	20 N/mm² at 28 days Proportion defective 1 %
	1.2 Standard deviation	Fig 3	N/mm² or no data 8 N/mm²
	1.3 Margin	C1 or Specified	(k = 2.33) 2.33 × 8 = 18.64 N/mm² N/mm²
	1.4 Target mean strength	C2	20 + 18.64 = 38.64 N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse Aggregate type: fine		[✓ Crushed]/uncrushed Crushed/[✓ uncrushed]
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.59 } Use the lower value 0.59
	1.8 *Maximum free-water/cement ratio*	*Specified*	
2	2.1 Slump or Vebe time	Specified	Slump 30 - 60 mm or Vebe time s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	190 kg/m³
3	3.1 Cement content	C3	190 ÷ 0.59 = 322.03 kg/m³
	3.2 *Maximum cement content*	*Specified*	- kg/m³
	3.3 *Minimum cement content*	*Specified*	- kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 kg/m³
	3.4 Modified free-water/cement ratio		322.03
4	4.1 Relative density of aggregate (SSD)		2.7 known/[✓ assumed]
	4.2 Concrete density	Fig 5	2400 kg/m³
	4.3 Total aggregate content	C4	2400 − 322.03 − 190 = 1887.97 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	Zone 2 (40% - 60%) %
	5.2 Proportion of fine aggregate	Fig 6	29 – 37 = 33 %
	5.3 Fine aggregate content	C5	0.33 × 1887.97 = 623.03 kg/m³
	5.4 Coarse aggregate content	C5	1887.97 − 623.03 = 1264.94 kg/m³

Quantities	**Cement (kg)**	**Water (kg or litres)**	**Fine aggregate (kg)**	**Coarse aggregate (kg) 10 mm**	**20 mm**	**40 mm**
per m³ (to nearest 5 kg)	325	190	620		1265	
per trial mix of 0.03 m³	9.75	5.7	18.6		37.95	
(x 10% wastage)	10.73	6.27	20.46		41.75	

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Figure A.1: Mix Design for Grade 20

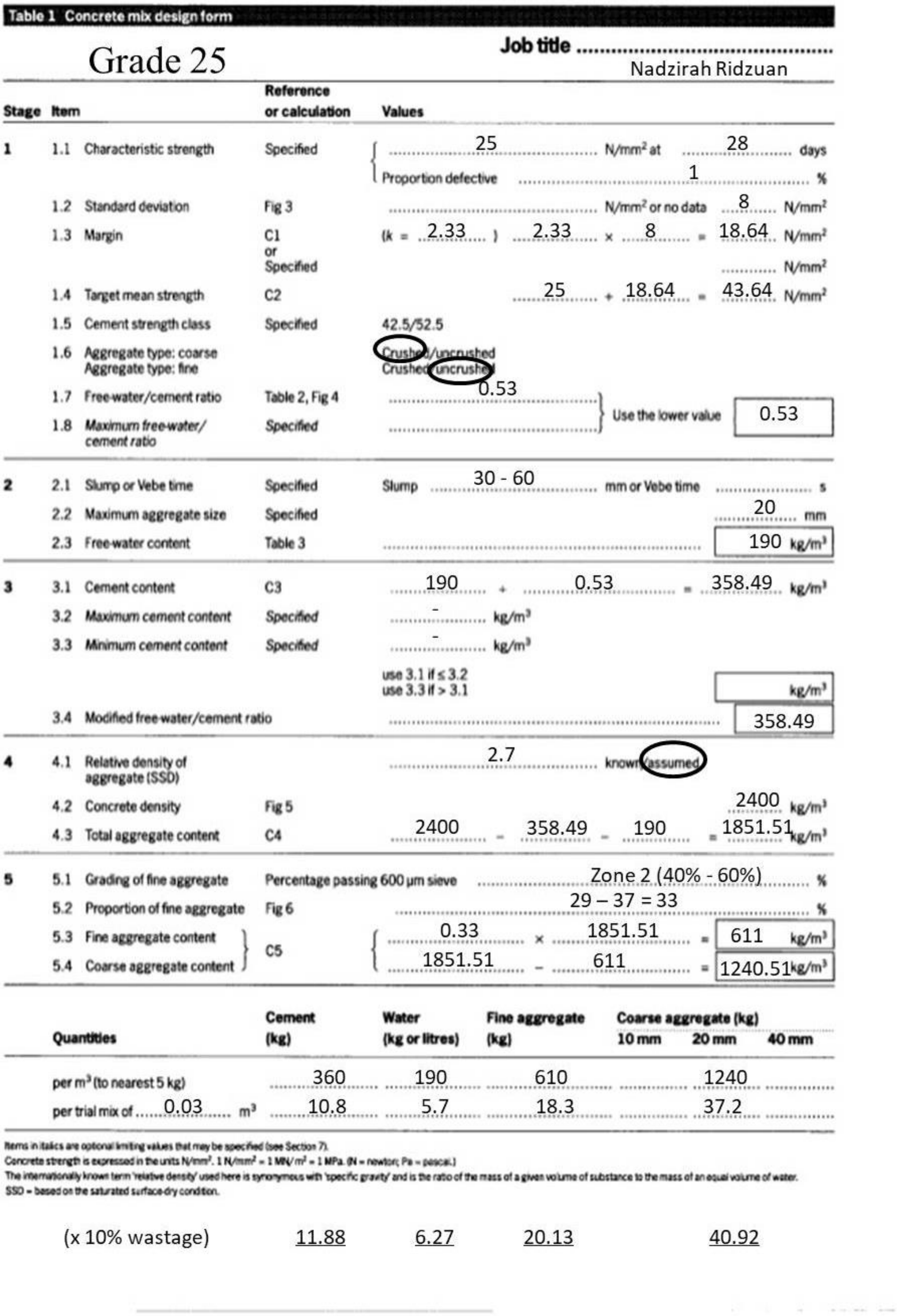


Table 1 Concrete mix design form

Grade 25

Job title Nadzirah Ridzuan

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	25 N/mm² at 28 days Proportion defective 1 %
	1.2 Standard deviation	Fig 3	N/mm² or no data 8 N/mm²
	1.3 Margin	C1 or Specified	(*k* = 2.33) 2.33 × 8 = 18.64 N/mm² N/mm²
	1.4 Target mean strength	C2	25 + 18.64 = 43.64 N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse Aggregate type: fine		[✓ Crushed]/uncrushed Crushed/[✓ uncrushed]
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.53 } Use the lower value 0.53
	1.8 *Maximum free-water/ cement ratio*	*Specified*	
2	2.1 Slump or Vebe time	Specified	Slump 30 - 60 mm or Vebe time s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	190 kg/m³
3	3.1 Cement content	C3	190 ÷ 0.53 = 358.49 kg/m³
	3.2 *Maximum cement content*	*Specified*	- kg/m³
	3.3 *Minimum cement content*	*Specified*	- kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 kg/m³
	3.4 Modified free-water/cement ratio		358.49
4	4.1 Relative density of aggregate (SSD)		2.7 known/[✓ assumed]
	4.2 Concrete density	Fig 5	2400 kg/m³
	4.3 Total aggregate content	C4	2400 − 358.49 − 190 = 1851.51 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 μm sieve	Zone 2 (40% - 60%) %
	5.2 Proportion of fine aggregate	Fig 6	29 – 37 = 33 %
	5.3 Fine aggregate content	C5	0.33 × 1851.51 = 611 kg/m³
	5.4 Coarse aggregate content	C5	1851.51 − 611 = 1240.51 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	360	190	610		1240	
per trial mix of 0.03 m³	10.8	5.7	18.3		37.2	

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

(x 10% wastage)	11.88	6.27	20.13		40.92	

Figure A.2: Mix Design for Grade 25

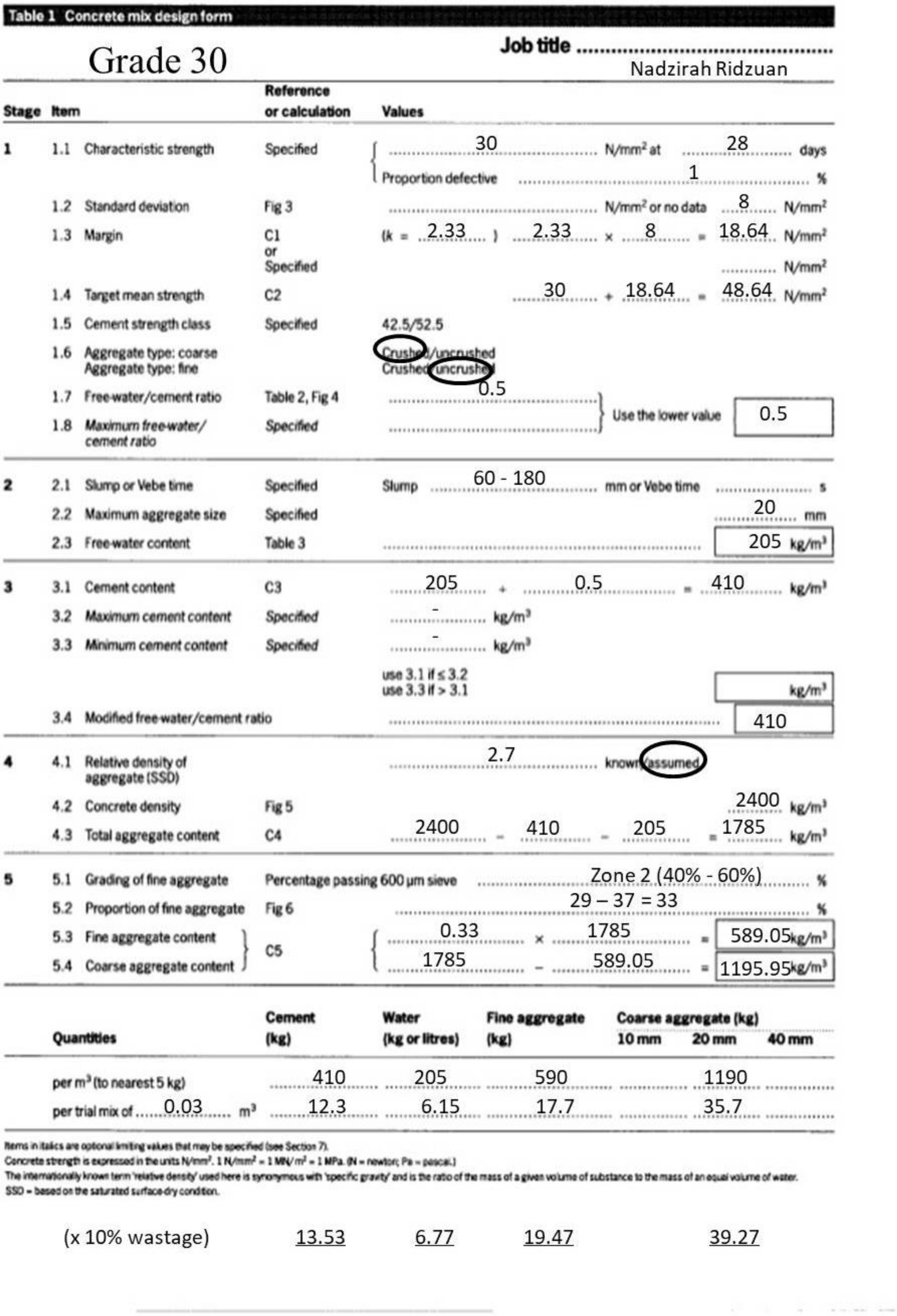


Table 1 Concrete mix design form

Grade 30

Job title Nadzirah Ridzuan

Stage	**Item**	**Reference or calculation**	**Values**
1	1.1 Characteristic strength	Specified	30 N/mm² at 28 days Proportion defective 1 %
	1.2 Standard deviation	Fig 3	N/mm² or no data 8 N/mm²
	1.3 Margin	C1 or Specified	(k = 2.33) 2.33 × 8 = 18.64 N/mm² N/mm²
	1.4 Target mean strength	C2	30 + 18.64 = 48.64 N/mm²
	1.5 Cement strength class	Specified	42.5/52.5
	1.6 Aggregate type: coarse Aggregate type: fine		[✓ Crushed]/uncrushed Crushed/[✓ uncrushed]
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.5 } Use the lower value 0.5
	1.8 Maximum free-water/cement ratio	*Specified*	
2	2.1 Slump or Vebe time	Specified	Slump 60 - 180 mm or Vebe time s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	205 kg/m³
3	3.1 Cement content	C3	205 ÷ 0.5 = 410 kg/m³
	3.2 Maximum cement content	*Specified*	- kg/m³
	3.3 Minimum cement content	*Specified*	- kg/m³
			use 3.1 if ≤ 3.2 use 3.3 if > 3.1 kg/m³
	3.4 Modified free-water/cement ratio		410
4	4.1 Relative density of aggregate (SSD)		2.7 known/[✓ assumed]
	4.2 Concrete density	Fig 5	2400 kg/m³
	4.3 Total aggregate content	C4	2400 − 410 − 205 = 1785 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 μm sieve	Zone 2 (40% - 60%) %
	5.2 Proportion of fine aggregate	Fig 6	29 – 37 = 33 %
	5.3 Fine aggregate content	C5	0.33 × 1785 = 589.05 kg/m³
	5.4 Coarse aggregate content	C5	1785 − 589.05 = 1195.95 kg/m³

Quantities	**Cement (kg)**	**Water (kg or litres)**	**Fine aggregate (kg)**	**Coarse aggregate (kg) 10 mm**	**20 mm**	**40 mm**
per m³ (to nearest 5 kg)	410	205	590		1190	
per trial mix of 0.03 m³	12.3	6.15	17.7		35.7	

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

(x 10% wastage)	13.53	6.77	19.47	39.27

Figure A.3: Mix Design for Grade 30

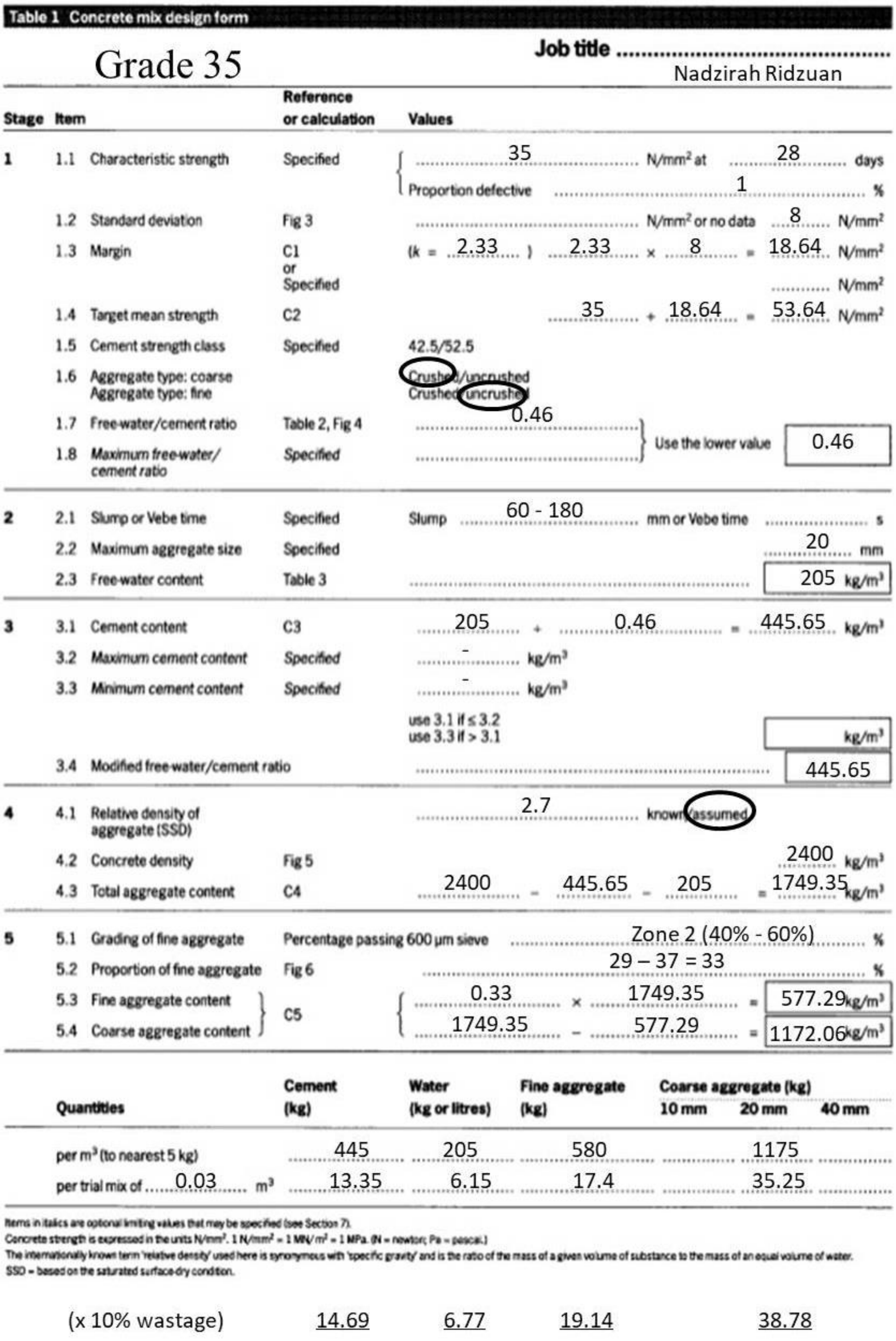


Table 1 Concrete mix design form

Grade 35

Job title Nadzirah Ridzuan

Stage	**Item**		**Reference or calculation**	**Values**
1	1.1	Characteristic strength	Specified	35 N/mm^2 at 28 days Proportion defective 1 %
	1.2	Standard deviation	Fig 3	N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1 or Specified	(k = 2.33) 2.33 × 8 = 18.64 N/mm^2 N/mm^2
	1.4	Target mean strength	C2	35 + 18.64 = 53.64 N/mm^2
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		[✓ Crushed]/uncrushed Crushed/[✓ uncrushed]
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.46
	1.8	*Maximum free-water/ cement ratio*	*Specified*	Use the lower value 0.46
2	2.1	Slump or Vebe time	Specified	Slump 60 - 180 mm or Vebe time s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	205 kg/m^3
3	3.1	Cement content	C3	205 ÷ 0.46 = 445.65 kg/m^3
	3.2	*Maximum cement content*	*Specified*	- kg/m^3
	3.3	*Minimum cement content*	*Specified*	- kg/m^3
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 kg/m^3
	3.4	Modified free-water/cement ratio		445.65
4	4.1	Relative density of aggregate (SSD)		2.7 known/[✓ assumed]
	4.2	Concrete density	Fig 5	2400 kg/m^3
	4.3	Total aggregate content	C4	2400 − 445.65 − 205 = 1749.35 kg/m^3
5	5.1	Grading of fine aggregate	Percentage passing 600 μm sieve	Zone 2 (40% - 60%) %
	5.2	Proportion of fine aggregate	Fig 6	29 – 37 = 33 %
	5.3	Fine aggregate content	C5	0.33 × 1749.35 = 577.29 kg/m^3
	5.4	Coarse aggregate content	C5	1749.35 − 577.29 = 1172.06 kg/m^3

Quantities	**Cement (kg)**	**Water (kg or litres)**	**Fine aggregate (kg)**	**Coarse aggregate (kg) 10 mm**	**20 mm**	**40 mm**
per m^3 (to nearest 5 kg)	445	205	580		1175	
per trial mix of 0.03 m^3	13.35	6.15	17.4		35.25	

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm^2. 1 N/mm^2 = 1 MN/m^2 = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

(x 10% wastage)	14.69	6.77	19.14	38.78

Figure A.4: Mix Design for Grade 35

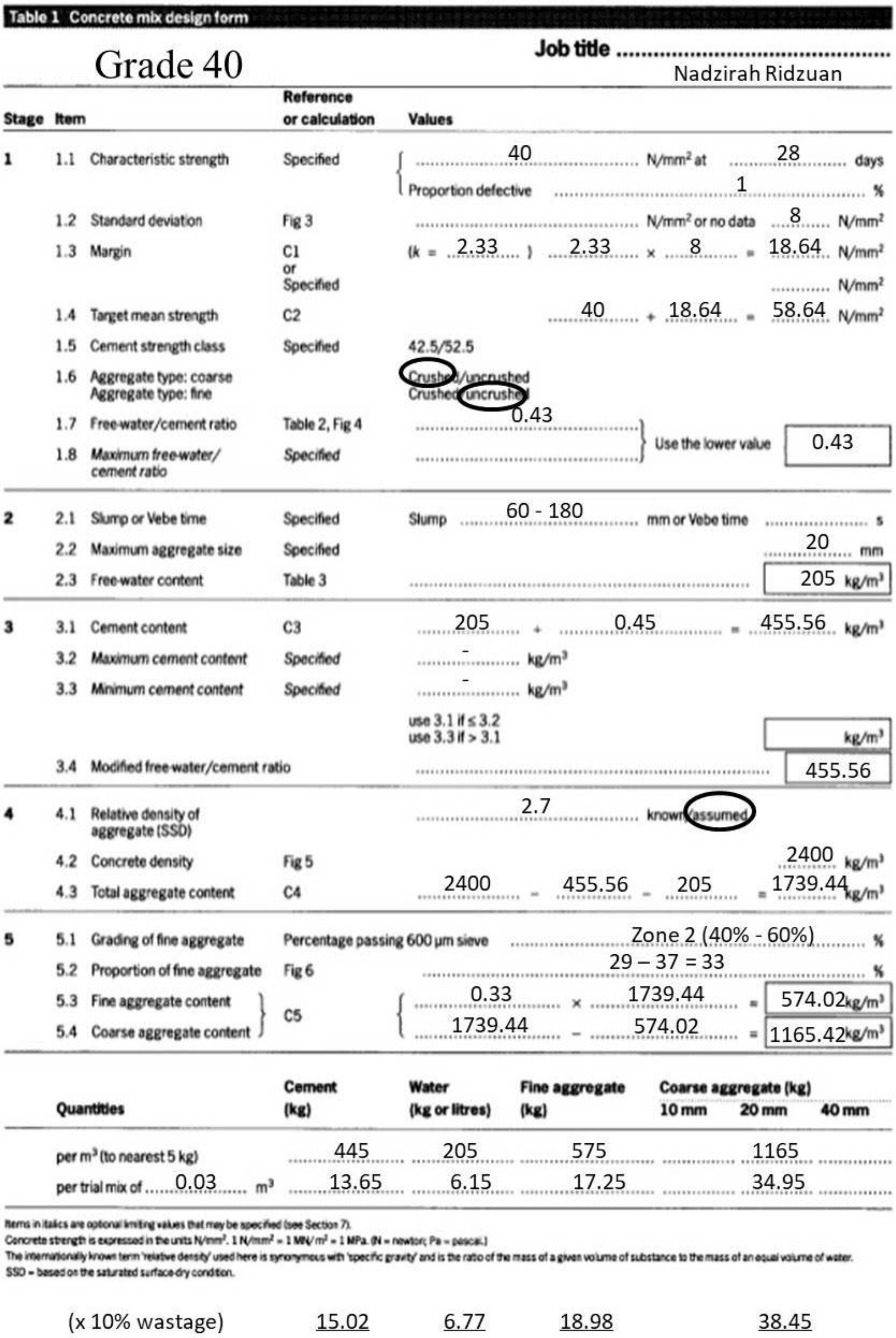


Table 1 Concrete mix design form

Grade 40

Job title Nadzirah Ridzuan

Stage	Item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	40 N/mm² at 28 days Proportion defective 1 %
	1.2	Standard deviation	Fig 3	N/mm² or no data 8 N/mm²
	1.3	Margin	C1 or Specified	(k = 2.33) 2.33 × 8 = 18.64 N/mm² N/mm²
	1.4	Target mean strength	C2	40 + 18.64 = 58.64 N/mm²
	1.5	Cement strength class	Specified	42.5/52.5
	1.6	Aggregate type: coarse Aggregate type: fine		[✓ Crushed]/uncrushed Crushed/[✓ uncrushed]
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.43 } Use the lower value 0.43
	1.8	*Maximum free-water/ cement ratio*	*Specified*	
2	2.1	Slump or Vebe time	Specified	Slump 60 - 180 mm or Vebe time s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	205 kg/m³
3	3.1	Cement content	C3	205 ÷ 0.45 = 455.56 kg/m³
	3.2	*Maximum cement content*	*Specified*	- kg/m³
	3.3	*Minimum cement content*	*Specified*	- kg/m³
				use 3.1 if ≤ 3.2 use 3.3 if > 3.1 kg/m³
	3.4	Modified free-water/cement ratio		455.56
4	4.1	Relative density of aggregate (SSD)		2.7 known/[✓ assumed]
	4.2	Concrete density	Fig 5	2400 kg/m³
	4.3	Total aggregate content	C4	2400 − 455.56 − 205 = 1739.44 kg/m³
5	5.1	Grading of fine aggregate	Percentage passing 600 µm sieve	Zone 2 (40% - 60%) %
	5.2	Proportion of fine aggregate	Fig 6	29 – 37 = 33 %
	5.3	Fine aggregate content	C5	0.33 × 1739.44 = 574.02 kg/m³
	5.4	Coarse aggregate content	C5	1739.44 − 574.02 = 1165.42 kg/m³

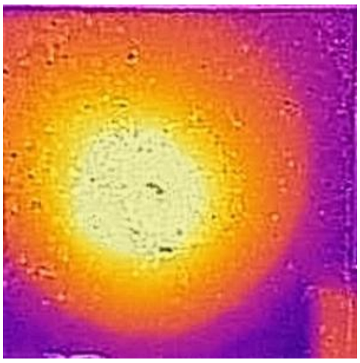
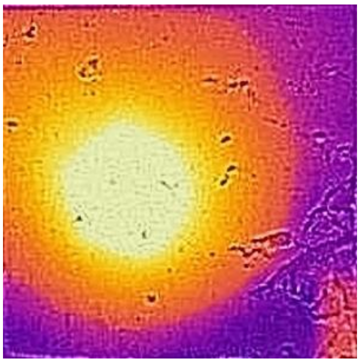
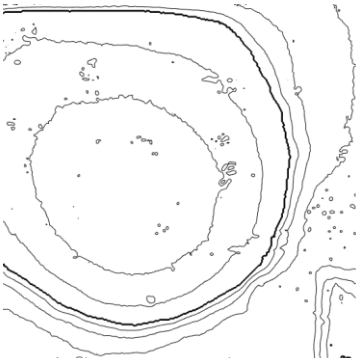
Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	445	205	575		1165	
per trial mix of 0.03 m³	13.65	6.15	17.25		34.95	
(x 10% wastage)	15.02	6.77	18.98		38.45	

Items in italics are optional limiting values that may be specified (see Section 7).
Concrete strength is expressed in the units N/mm². 1 N/mm² = 1 MN/m² = 1 MPa. (N = newton; Pa = pascal.)
The internationally known term 'relative density' used here is synonymous with 'specific gravity' and is the ratio of the mass of a given volume of substance to the mass of an equal volume of water.
SSD = based on the saturated surface-dry condition.

Figure A.5: Mix Design for Grade 40

APPENDIX B

Table B.1: Correlation between Thermal Contour and Contour Plot for Grade 20 Sample

SAMPLE	THERMAL CONTOUR	CONTOUR PLOT
1		
		

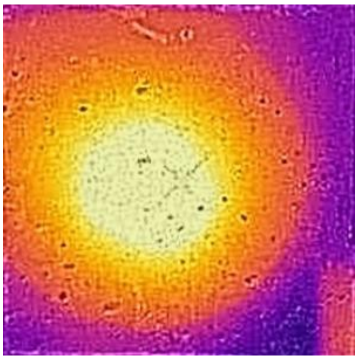
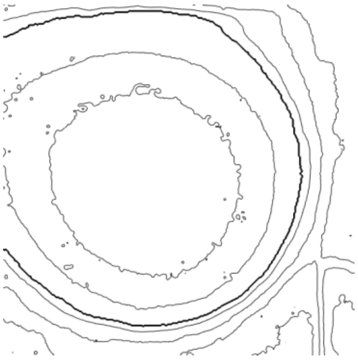
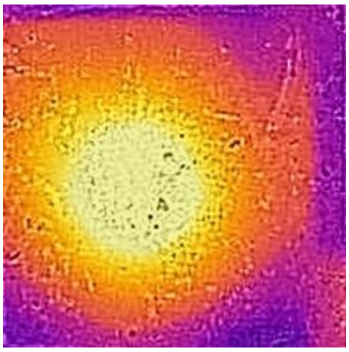
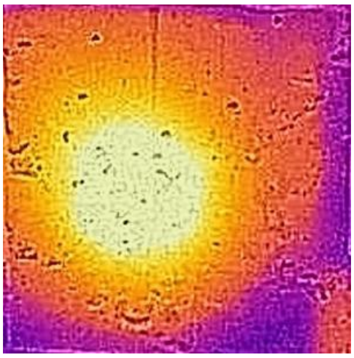
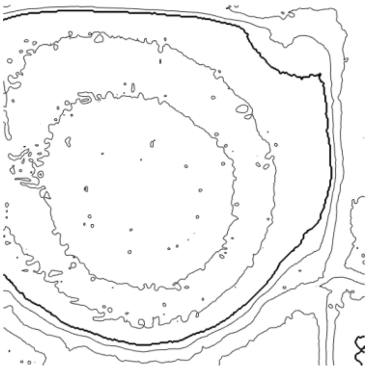
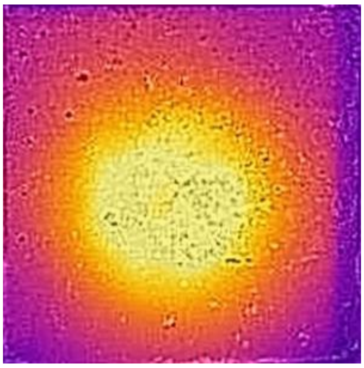
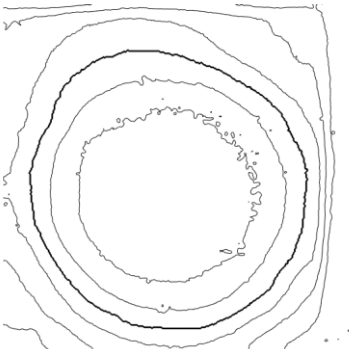
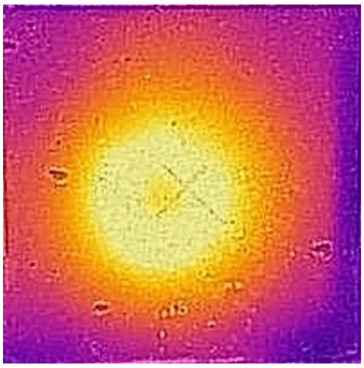
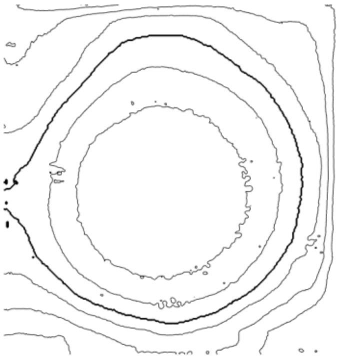
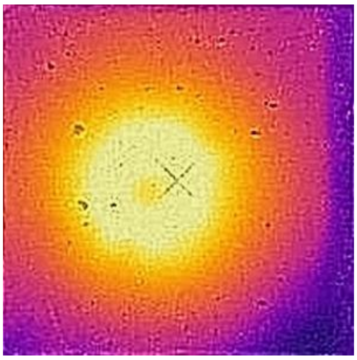
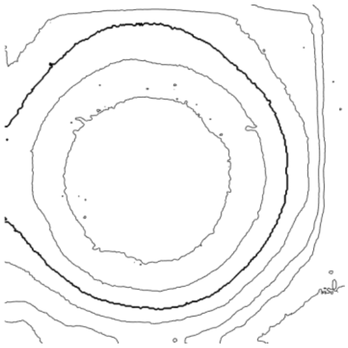
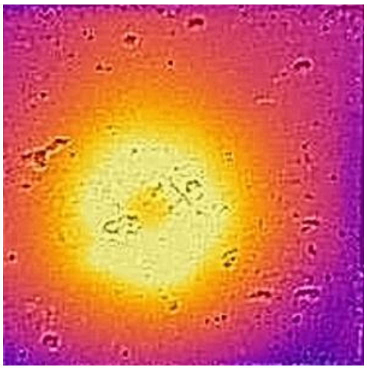
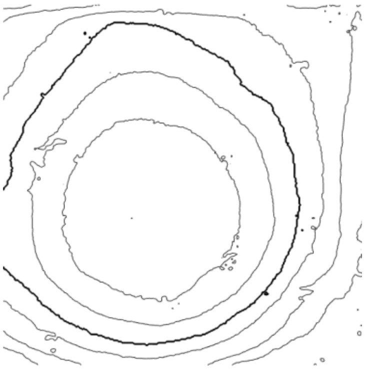
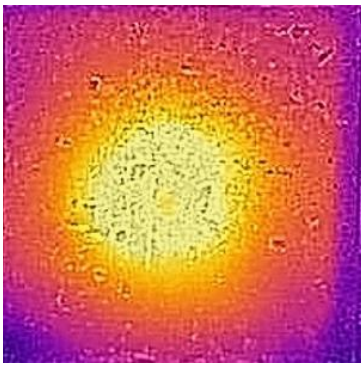
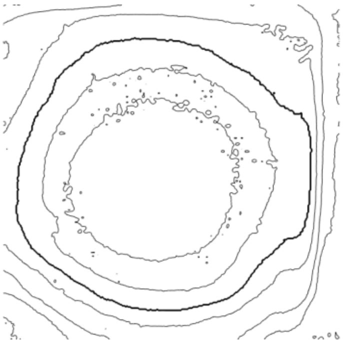
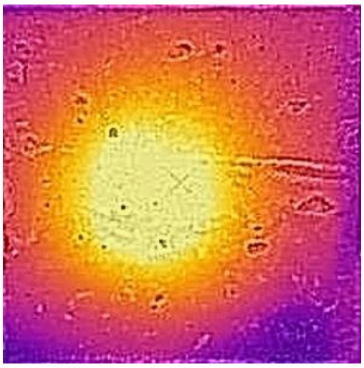
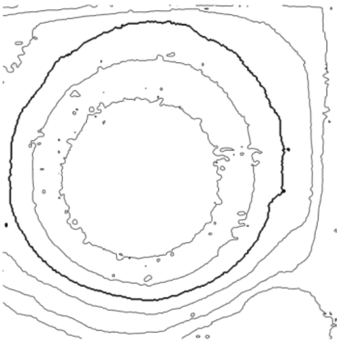
2		
		
		

Table B.2: Correlation between Thermal Contour and Contour Plot for Grade 25 Sample

SAMPLE	**THERMAL** **CONTOUR**	**CONTOUR** **PLOT**
1		
		
		

2		
		
		

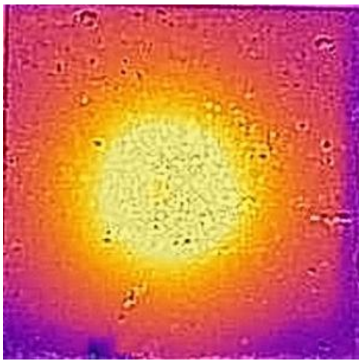
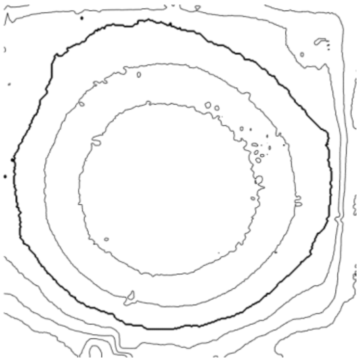
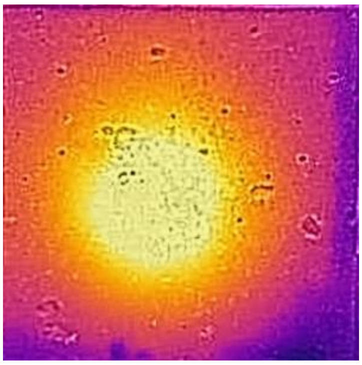
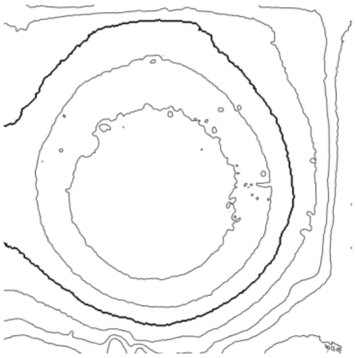
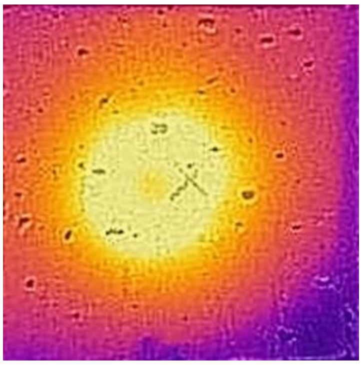
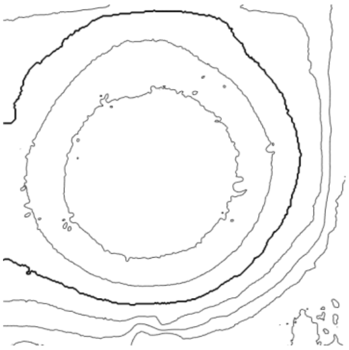
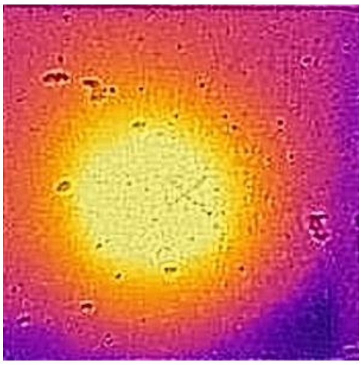
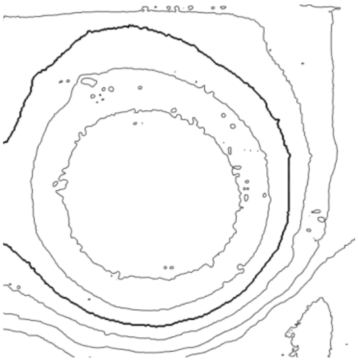
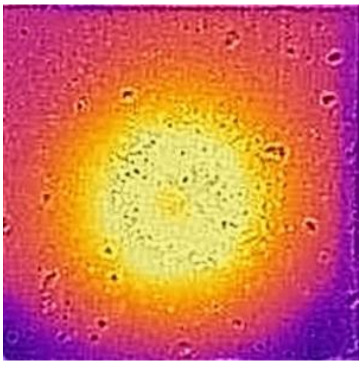
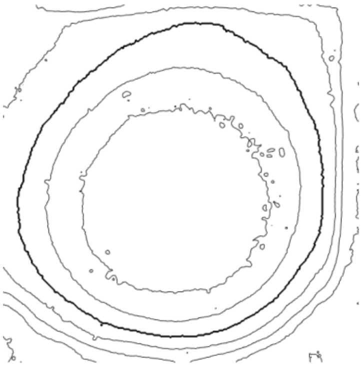
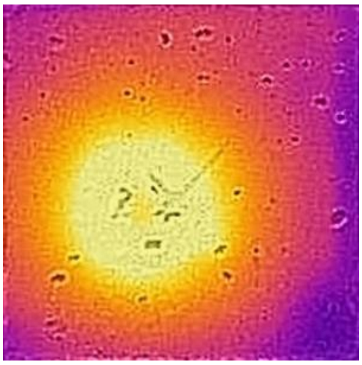
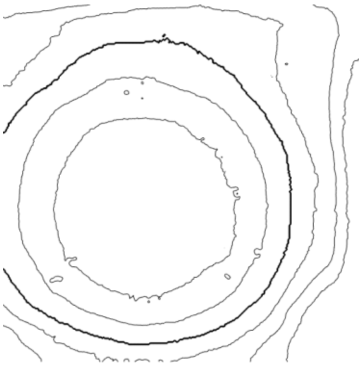
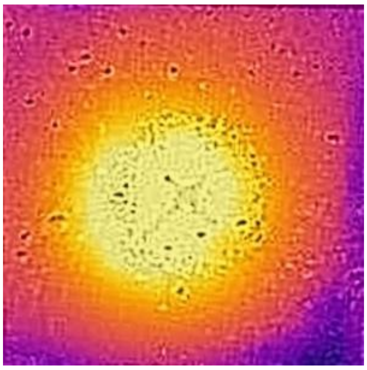
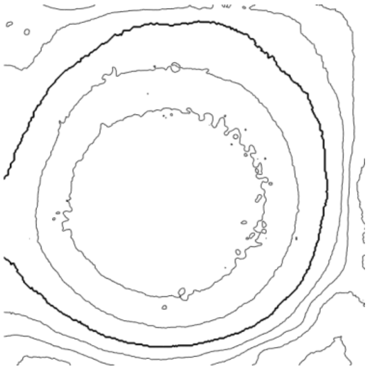
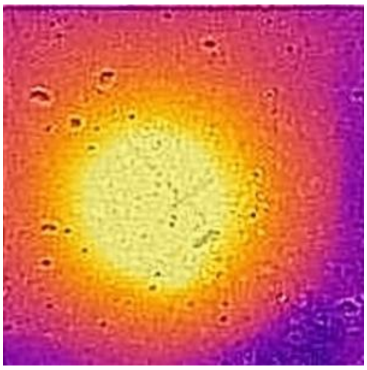
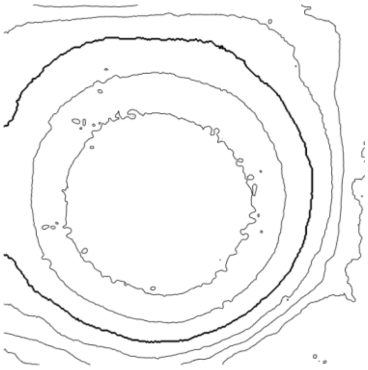
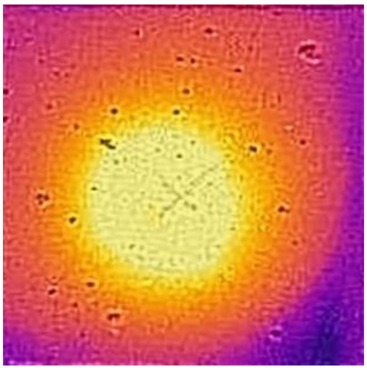
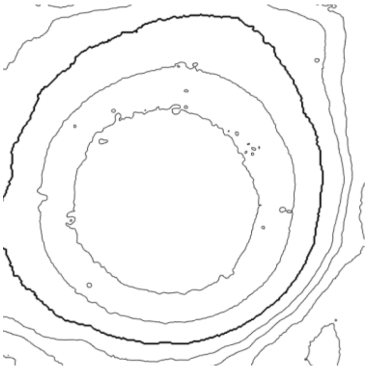
3		
		
		

Table B.3: Correlation between Thermal Contour and Contour Plot for Grade 30 Sample

SAMPLE	**THERMAL** **CONTOUR**	**CONTOUR** **PLOT**
1		
		
		

2		
		
		

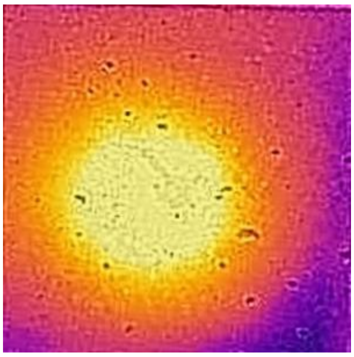
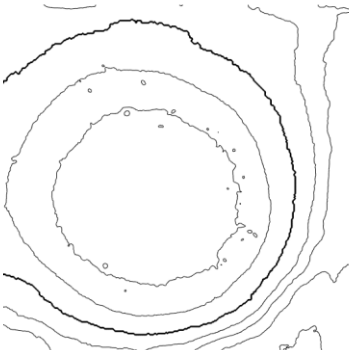
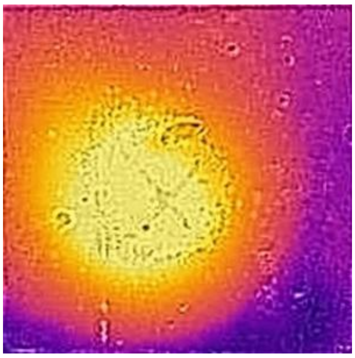
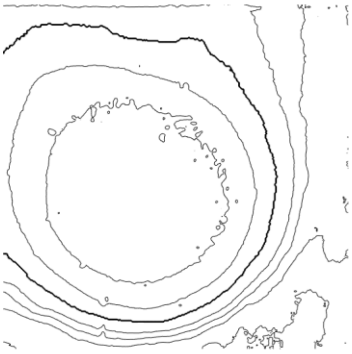
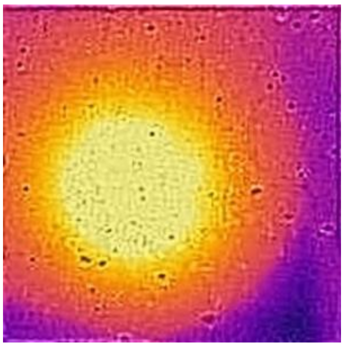
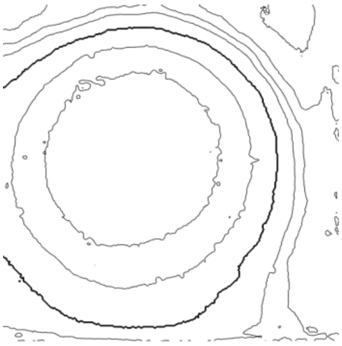
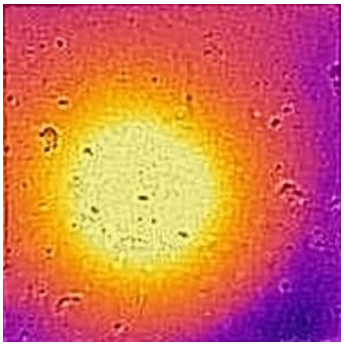
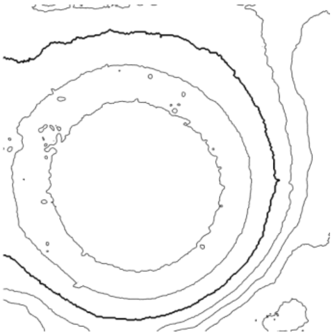
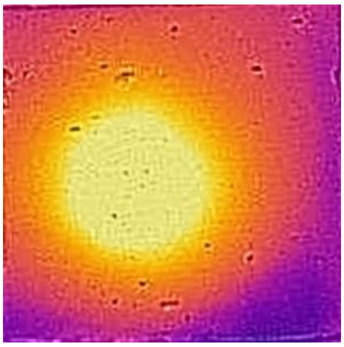
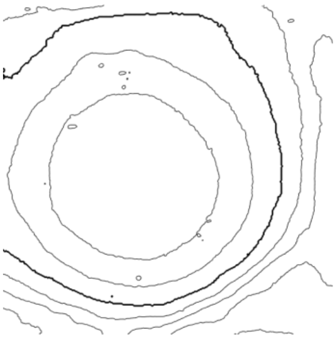
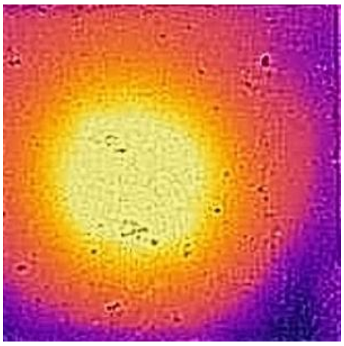
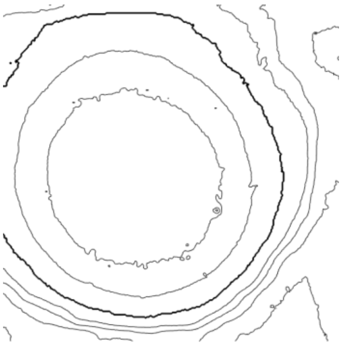
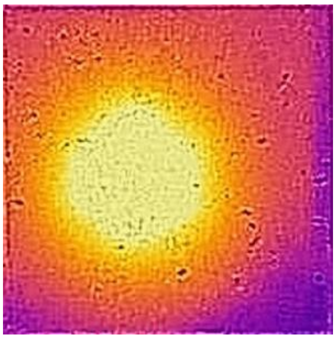
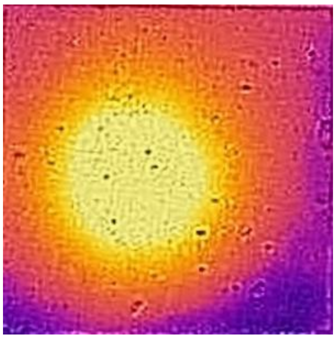
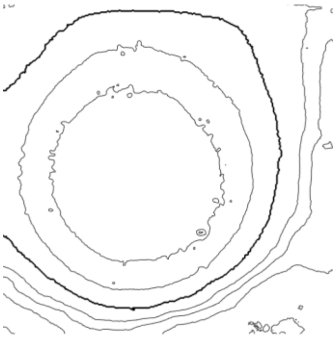
3		
		

Table B.4: Correlation between Thermal Contour and Contour Plot for Grade 35 Sample

SAMPLE	**THERMAL** **CONTOUR**	**CONTOUR** **PLOT**
1		
		
		

2		
		
		

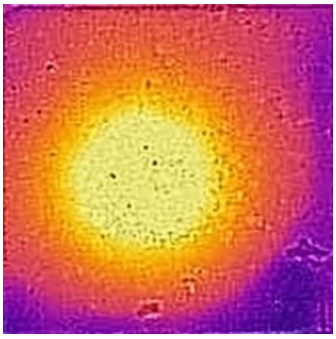
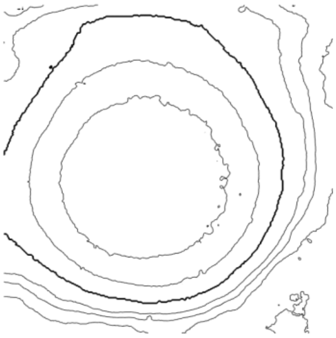
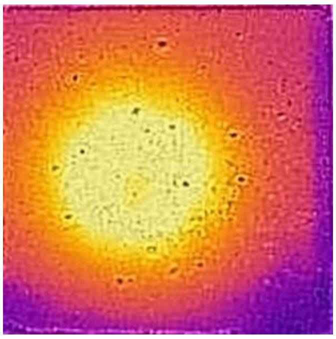
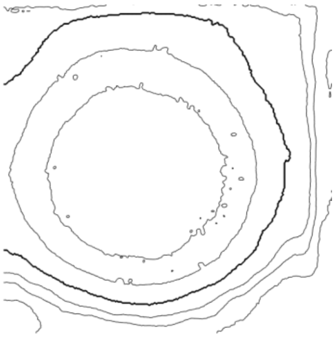
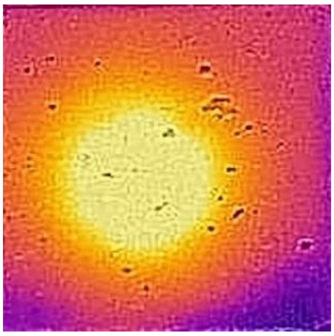
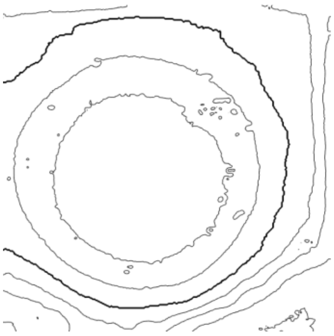
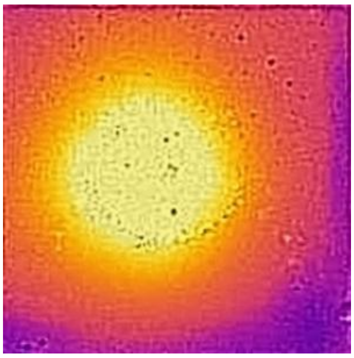
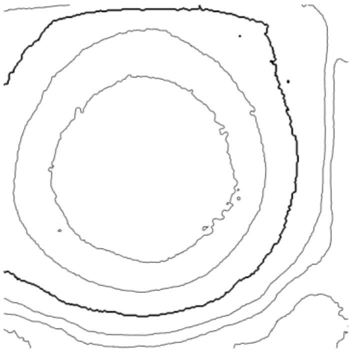
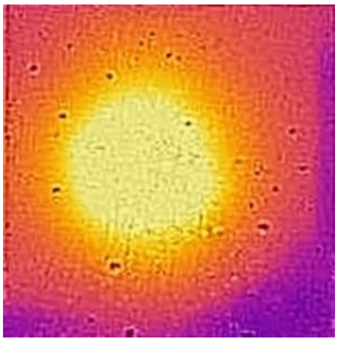
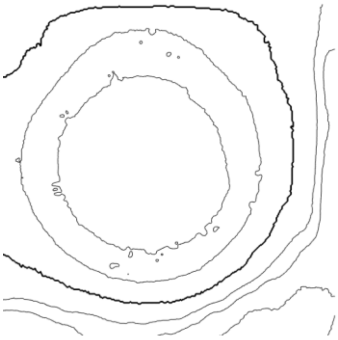
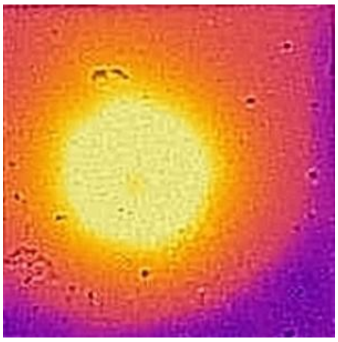
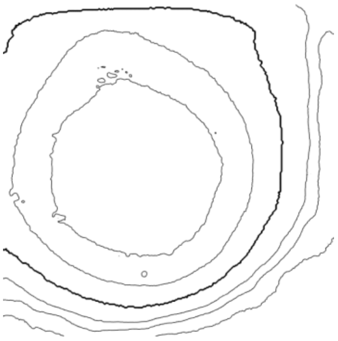
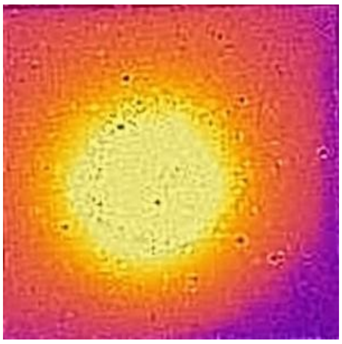
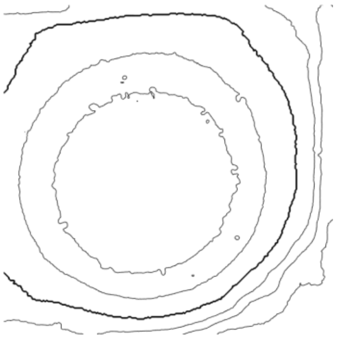
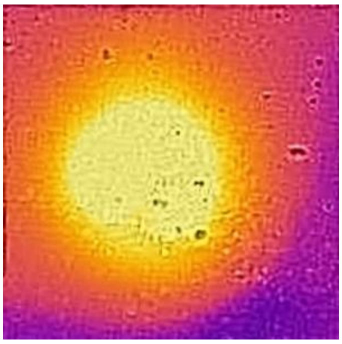
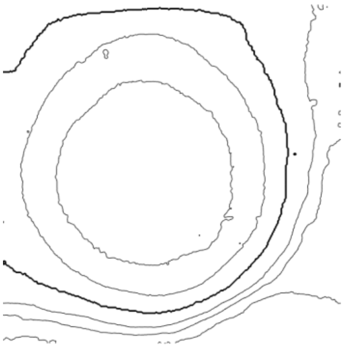
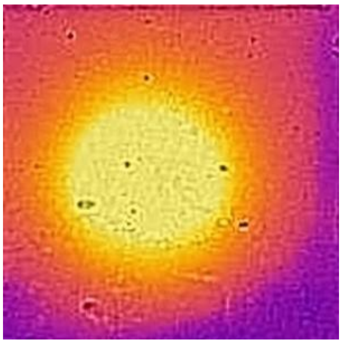
3		
		
		

Table B.5: Correlation between Thermal Contour and Contour Plot for Grade 40 Sample

SAMPLE	THERMAL CONTOUR	CONTOUR PLOT
1		
		
		

2		
		
		

3