FORECASTING OF CONCRETE STRENGTH DURING THE HARDENING PROCESS BY MEANS OF ELASTIC WAVE METHOD

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"FORECASTING OF CONCRETE STRENGTH DURING THE HARDENING PROCESS BY MEANS OF ELASTIC WAVE METHOD"** was prepared by **CHIN WAI ZHEN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering at Universiti Tunku Abdul Rahman.

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Date : 6 May 2019

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In a nutshell, this final year project has enhanced my view and understanding regarding the effectiveness and potential of NDT in the engineering world which is able to contribute to the development of construction field in future.

ABSTRACT

Many compressive strength tests of a concrete involve the destruction of concrete samples or existing structures, and the effective method for predicting the compressive strength of the concrete is the main focus of the research. The compressive strength of concrete is generally acquired by conducting destructive tests that will cause the concrete to undergo failure, and for this research, the strengths when the concrete samples fail for different experimental factors are the desired compressive strength values. For the purpose of maintaining the serviceability and integrity of concrete, several non-destructive tests (NDT) have been studied in the literature review and one of the NDT methods has been proposed to achieve the objectives of studying and observe the changes undergo by the elastic wave on the cube specimen and discovering the suitable wave properties for performing correlation with the strength of concrete. Since NDT methods do not involve destruction of specimens, the strength properties of the specimens can be evaluated accurately. This project utilizes a specific method of non-destructive test that is known as the impact echo test to forecast the compressive strength development of concrete that utilizes the change in properties of a type of elastic wave that propagates within the concrete. It is shown how the parameters of the elastic wave that is adopted can be applied to correlate with the development of compressive strength of concrete in 28 days, and how the equations and the patterns of the correlations can be used to predict the values of compressive strength of a certain concrete in future after 28 days. Graphs of P-wave amplitude, velocity and frequency are plotted against the compressive strengths for correlation. To conclude the research, the graph with the highest reliability and accuracy will be used as the final graph for the purpose of correlation with compressive strength of concrete.

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LIST OF SYMBOLS / ABBREVIATIONS

E_d	dynamic modulus of elasticity, GPa
f, f_c	compressive strength of concrete, MPa
M, E_c	Elastic modulus, GPa
v	wave velocity, m/s
v_d, μ	dynamic Poisson ratio
ρ	density, kg/m^3

AF	Atrial fibrillation
Al_2O_3	Aluminium Oxide
ASTM	American Society for Testing and Materials
BS EN	British Standard European
C_2S	Dicalcium Silicate
C_3A	Tricalcium Aluminate
C_3S	Tricalcium Silicate
C_4AF	Tetracalcium Aluminoferrite
CaO	Calcium Oxide
CAPO	Cut and Pull Out
Cl	Chloride
DT	Destructive test
Fe_2O_3	Iron Oxide
I.R	Insoluble Residue
LOI	Loss on Ignition
LOK	Punch-out
MgO	Magnesium Oxide
NDT	Non-destructive test
OPC	Ordinary Portland Cement
RC	reinforced concrete
SiO_2	Silicon Oxide
SO_3	Sulphur Trioxide
SSD	Saturated surface dry
UPV	ultrasonic pulse velocity
w/c	water-cement

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Concrete is a type of material which serves as the important essence in almost every type of typical construction. It is a composite material that consists of elements of cement, water and aggregate. Nowadays, the application of concrete is significant as technology and innovation thrive to allow more efficient and effective use of concrete in the building industry, for example, the adding of admixture into concrete.

The fundamental usage of concrete is based on its compressive strength which is the main characteristic of concrete. This material is widely applied in construction due to its ability to resist loadings due to compression and thus sustaining all kinds of loadings in building structures. In order to assess the strength of the concrete, there are 2 types of concrete tests that are highly recommended. These two tests are known as the destructive test (DT) and the non-destructive test (NDT).

While carrying out the DT, concrete is generally destroyed to evaluate its strength properties. It is always essential to perform this test because of the importance of ensuring the quality and performance of the casted concrete for long-lasting characteristics. The process is rather simple and direct and results can be obtained without consuming much time. In general cases, these tests are compulsory for every construction process especially before the concrete is casted.

For the alternative method of NDT, it gives a rather remarkable way of accessing the concrete. It has the main advantage of obtaining the properties of concrete rapidly without destroying the specimen at a moderate cost. This method puts less concern on the powered performance of the concrete while focuses heavily on the evaluation of physical characteristics (Breysse, 2012). This special method provides a more suitable way of assessing the strength of existing constructions.

Nowadays, the use of NDT is encouraged due to its effectiveness in achieving the purposes of examining both the external and internal state as well as the current condition of the concrete structures, particularly in completed buildings. The process of acquiring the characteristics of the specimen as well as existing structures utilizes the application of ultrasonic and sonic as the facilitators of the test (Sack & Olson, 1995). Besides, some methods of NDT adopt the radar as well as infrared technology to achieve investigation on properties that is impossible with the naked eye.

1.2 Problem Statement

Before the concrete is used for any type of application, it is compulsory to test its strength properties, generally by the use of DT. The assurance of concrete quality and performance is achieved by testing the specimens. For ordinary circumstances, the application of normal concrete compression test on obtaining the compressive strength of concrete is regarded as convenient and rapid.

However, this may not be the ideal approach for every case. Some of the disadvantages include the need to destroy the concrete tested to the extent of bearing cracks which greatly impacts the lifespan of the evaluated structure (Shankar & Joshi, 2014). Due to this particular issue, the complete evaluation of concrete until day 90 has to be done using several concrete cube specimens since the samples have to undergo failure every time when a test is conducted. This means that a total amount of 4 to 5 samples are necessary to be destroyed for this purpose, which demonstrates a waste of resources and money just to obtain one set of result completely. This discrepancy is enough to cause a disruption in the accuracy of the results obtained due to the fact that different samples of concrete with the same dimensions and composition are used to acquire the complete results. As a result, the cumulative changes in the strength of the concrete throughout the curing process cannot be monitored or examined.

With the intention of achieving better monitoring of concrete compressive strength for the main purpose of forecasting the strength values of concrete in the future, the alternative method of NDT comes into play. Utilizing elastic wave for that objective in the elastic wave method is the best way to carry out the strength prediction development on a single sample of concrete without having to exert any force or pressure on it. This option serves as a great solution to monitor the quality and change of properties of concrete of existing structures without causing disruption to the concretes by just evaluating the properties of elastic waves during propagation (Gu et al., 2006). More importantly, the data obtained plays an important role in establishing a relationship to connect the wave information with the strength data of the sample tested (Hannachi and Guetteche, 2012). Furthermore, it is relatively low cost and much more effective as compared with the ordinary DT methods. Thus, the goal of predicting concrete compressive strength in future can be accomplished.

1.3 Aim and Objectives

For this entire research conducted, the aim is to perform a correlation of concrete strength at 28 days with the informal parameters from elastic wave data.

The objectives that are required to achieve to fulfil the aim of this research:

1. To study and observe the changes undergo by the elastic waves on the concrete cube specimen throughout the period of 1 day, 7 days and 28 days.
2. To identify and discover the appropriate characteristics of the elastic wave to be used to perform correlation with the strength of concrete.

1.4 Research Questions

The research question for this research is, what is the outcome of the research that can contribute to the construction industry. The features of safety and cost-effective benefits associated with NDT methods have boosted their recognition as well as their emerging usage. Various on-site procedures have been devised for the purpose of conducting an evaluation on concrete while building structures as well as eliminating issues concerning the weakening of structures. However, the insufficient teamwork between construction engineers with NDT experts is still obvious and raised concerns among the researchers (Helal, Sofi and Mendis, 2015).

Therefore, it is proposed that an average correlation graph that links the wave and strength values should be formulated to allow the process of compressive strength prediction to be effectively conducted, which enables the aim to be accomplished. In this case, when the strength data is obtained along with the wave data at 28 days, it is very possible to utilize this information to predict the concrete strength at 56 days or as far as 90 days with this unique graph. With this, the evaluation of concrete structures in existing constructions can be done effectively without having to wait as well, which saves time.

1.5 Scope and Limitation of the Study

For this research conducted, this study mainly places its concern on the areas related to the various utilization of non-destructive test (NDT) methods as means of assessing the compressive strength of concrete. This scope of the study is necessary to facilitate the process of determining the optimum elastic wave data in predicting the concrete strength.

Apart from that, this particular research is limited by 2 factors. These factors are the water content which affects the water-cement ratio and the aggregate, either coarse or fine aggregate. For the experimental part, it involves the casting as well as the curing of ordinary normal weight concrete cubes without the use of admixtures. While controlling the 2 variables, the experimental objective is to obtain results for the concrete strength and also the elastic wave data at day 7 and day 28.

Furthermore, this experiment adopts the use of a type of wave to conduct the NDT test. It is generally known as the compression wave, or sometimes P-wave to conduct the respective correlation with concrete strength. In this process, it is required to collect various P-wave data, for example, the velocity and amplitude of the wave to perform the analysis that generates the correlation graph. Last but not least, the ideal parameter that works best in predicting concrete strength will be identified through multiple comparisons between the data accumulated.

1.6 Significance of Study

The final outcome produced from this research and experiment conducted will be used as guidance for experts and professionals from the related field as well as reference for current or future studies about the non-destructive test (NDT) using elastic waves. It is also a good way of promoting awareness of the importance of this type of NDT test in the construction industry as it clearly benefited over the ordinary DT test. The fact that this particular elastic wave test is able to obtain concrete strength properties while retaining the integrity and the functionality of the concrete structure proves that this study is relevant for better economical approach and safety when it comes to assessing the concrete compressive strength characteristics.

1.7 Layout of Report

This report consists of 5 chapters in total. The first chapter provides a brief introduction about concrete and the significant Non-Destructive Test (NDT), problem statement, aims and objectives, research question, scope and limitation of the study, significant of study, the layout of the report and lastly summary of chapter 1.

For chapter 2, it is the literature review that concerns about the factors affecting concrete strength as well as the methods accessible in NDT for concrete strength evaluation. All the information is gathered from relevant and published sources such as journals, articles, websites etc. This topic also stresses about the use of P-wave as the primary wave for the elastic wave method using tool PXie-1073.

Chapter 3 talks about the methodology used to carry out the experimental test. This chapter comprised of the procedure of obtaining the desired concrete mix proportions, material preparation, investigate and examine the outcomes produced from the informational wave data during the test and perform correlation of the data with the compressive strength information of normal weight concrete.

In the fourth chapter, the contents are all about the end results as well as the discussions made based on the results. As the test is carried out with various concrete proportion from the specified manipulating factor, optimum parameters of the wave are collected for analysis and a graph is formulated which aids in the prediction of strength by utilizing the elastic P-wave. The discussions conducted dive into the issues as well as the improvements that can be made to yield more accurate results for the concrete strength forecasting.

Lastly, the final chapter which is chapter 5 consists of Conclusion and Recommendation that sum up the whole research according to the aim and the listed objectives of this research.

1.8 Summary of the Report

Chapter one of this project places its focus on the general overview of the study which involves the factors that affect the formation and the compressive strength of concrete, DT and NDT, and elastic waves. This research will serve as an important source for achieving the aims and objectives which can contribute to solving the problems and produce better alternatives for the construction industry in the future. This chapter also gives information about the limitation and scope of the research as the area of study is only on the forecasting of ordinary concrete strength using data obtained from elastic waves, and the significance of the outcome is discussed as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is a composite material that is useful to be applied to various building works in the construction field. The main ingredients of concrete are the cement, aggregate and water. For ordinary cases, ordinary Portland cement (OPC) is usually the type of cement used in the formation of concrete. This type of cement is widely regarded as one of the most groundbreaking technological product that is ever invented by humans in history (Shi, Jiménez and Palomo, 2011). This cement is responsible for all types of building constructions that contributes to the new image of various cities in the 20th century. Due to this creation, concrete is largely utilized and a series of tests are being devised to assess it for strength capacity determination.

Among all the available types of tests, destructive test (DT) is known as the most common classification for assessment of concrete strength. This old-fashioned method is very useful in obtaining the strength data in terms of compressive, in addition to another two important values of flexural and tensile strength (Akhtar, 2013). Despite its convenience and practicability in testing the concrete, these tests are still associated with some drawbacks such as the test results cannot be determined instantly. The test involves the destruction of the test specimen, partially or entirely breaking down of its composition to extract the important information.

Apart from that, another group of test known as the non-destructive test (NDT). These tests are usually regarded as applications involving examination of the ingredient as well as constituents of the concrete sample which generally serve the purpose of identifying the properties and assist in locating any possible or existing defects while retaining the whole structure which prevents damages inflicted on the sample (Gholizadeh, 2016). Several NDT tests that are used these days include ultrasonic pulse velocity evaluation method, thermographic assessment (Kroeger, cited in Gholizadeh, 2016), radiographic testing and rebound hammer test.

To provide an overview, both destructive and non-destructive test are characterized by their unique way of evaluation and engineering distinctiveness. Table 2.1 shows the brief comparison of both DT and NDT tests.

Table 2.1: Comparison of DT and NDT of Concrete (Godfrey & Henry, 2016)

Destructive Test (DT)	**Non-destructive Test (NDT)**
1. Tests usually simulate one of more service conditions. Consequently, they tend to measure serviceability directly and reliably.	1. Tests usually involve indirect measurements of properties of no direct significance in service. The correlation between these measurements and serviceability must be proved by other means.
2. Tests are usually quantitative measurements of load for failure, significant distortion or damage, or life to failure under given loading and environmental conditions. Consequently, they may yield numerical data useful for design purposes or four establishing standards or specifications.	2. Tests are usually quantitative and rarely quantitative. They do not usually measure load for failure or life to failure even indirectly. They may, however, reveal damage of expose the mechanisms of failure.
3. The correlation between most destructive test measurements and the material properties being measured (particularly under simulated service loading) in most observers may agree upon the results of the test and their significance with respect to the serviceability of the material or part.	3. Skilled judgement and test or service experience are usually required to interpret test indications. Where the essential correlation has not been proven, or where experience is limited, observers may disagree in evaluating the significance of test indications.
4. Destructive tests are not usually convenient to apply to parts in service. Generally, service must be interrupted and the part permanently removed from service.	4. Non-destructive tests may often be applied to parts in service assemblies without interruption or service beyond normal maintenance or idle periods. They involve no loss of serviceable parts.
5. With parts of very high material or fabrication cost, the cost or replacing the parts destroyed may be prohibitive. It may not be feasible to make an adequate	5. Acceptable parts of very high material or fabrication costs are not lost in non-destructive testing. Repeated testing during production or service is feasible

number and variety of destructive tests.	when economically and practically justified.

2.2 Factors that Impact the Compressive Strength of Concrete

The most important properties that define the capability and characteristic of the concrete are the compressive strength properties. Its strength properties are the key to ensure the effective and practical use of concrete in the construction processes. For every type of constructions, different compressive strength values are required according to the structure’s function, shape, architecture, size etc. Each part of the building structure such as beam, slab and column has theirs own strength requirements to achieve upon casting them.

While knowing that concrete strength is arguably one of the most vital aspects in determining the quality of the concrete cast, there is a specific configuration that needs to be achieved while producing the mixture from the necessary ingredients. This is done so that the mixture can possess an appropriate duration for setting and thus lead to the desired compressive strength at the end of the process (Abolpour, Afsahi and Hosseini, 2015). In order to ensure the strength is within the expected range, compressive strength tests are conducted on the sample cast.

With the intention to attain the best possible quality of concrete, focuses should be put on the designing of concrete mix. For this particular purpose, it is important to know that the determination of relative proportions of cement, aggregate and amount of water plays a significant role. In other words, the mixture proportion is regarded as the prerequisite of achieving the characteristic strength of the concrete cast, provided that it possesses the preferred workability and toughness. Therefore, the identification of the factors that will affect the compressive strength of the concrete is a very critical process for quality assurance.

The influential aspects that considerably affect the compressive strength of concrete are the cement content and characteristics, the proportion of water to cement, types of aggregate used and its qualities, etc (AbdElaty, 2014). In this section, the factors discussed are cement, aggregate, water quality, water-cement ratio, compaction and curing.

2.2.1 Cement

Cement quality plays a vital part in contributing to the compressive strength of the concrete cast. It is also known as the binder of the concrete mixture. The properties of the cement have a major impact on the final presentation of the concrete formed as part of the strength quality of the sample is derived from the cement paste.

The degradation course experienced by the concrete is governed by the characteristics of the toughened blend of cement. Researches prove that the period when the cement paste undergoes maturity and change in its configuration, as well as the arrangement of pores, determine whether the final product will go through any reduction in its strength properties in a complex manner (Janotka and Nürnbergerová, 2005). Therefore, considerations have to be made on the selection of quality cement as well as the conditions while mixing it with aggregate and water.

2.2.2 Aggregate

Aggregate is a very critical element in forming the compressive strength of concrete. For instance, the size, shape and texture of the aggregate are both key factors to focus on. The strength assessment of concrete, as well as the design carried out on the quality concrete mix, are largely influenced by the shape feature of the selected aggregate. Crumbling and lengthened aggregate particles possess a greater specific surface area. This quality is extremely effective in producing a cement mixture that is associated with greater demand (Molugaram, Shanker and Ramesh, 2014).

While conducting studies on coarse aggregate, it is mentioned that the favourable percentage of coarse aggregate content that gives the casted concrete with high strength values is in the range between 36% and 40%. It is disadvantageous if the concrete contains coarse aggregate content that is higher than 40% as it can decrease the concrete strength (Cetin and Carrasquillo, 1998). Besides, an experiment proves that the increase of fine aggregate supply efforts in the formation of concrete with higher compressive strength due to the nature of fine aggregate as a noteworthy strengthening element, particularly in lean mixtures (Kronlöf, 1994).

2.2.3 Water Quality

Furthermore, water quality is another factor that significantly affects the quality of concrete and its strength. Observations have been done to evaluate the existing concrete and it is discovered that the degradation of the strength of concrete is caused by the salt ions such as sulphate and chloride ions (Kumar, 2000). These important findings further show that water that contains salt ions are not suitable to be used for producing concrete mixture for casting. The chemical reactions experienced by these reactive particles can disrupt the desired chemical composition of concrete and reduces the compressive strength.

2.2.4 Water-Cement Ratio

Moreover, another critical parameter that has a direct effect on how the concrete acquires its compressive strength is the water-cement ratio. From the numerous experiments done by researchers in the past, they displayed a significant pattern which shows that the strength of the hardened cement paste can be regarded as the direct influence to the compressive strength of the casted concrete sample. From this relationship, the controlling factor is known as the ratio of water to cement, the w/c (Popovics and Ujhelyi, 2008).

By analysing the data obtained, the variations of concrete illustrate different strength properties. For example, greater ratio of w/c gives concretes with reduced strength values while this is not the case when the w/c ratio is raised gradually, which in turns produce specimens with greater structural strengths. Therefore, it is reasonable to conclude that the greater porosity in the cement paste is due to the greater value of w/c ratio, producing a weaker concrete.

Several formulas have been devised for the purpose of providing estimation on the compressive strength of concrete based on the information extracted from the experiments with w/c ratio as the controlling aspect. One of the earliest formulas that were ever formulated for this correlation is the Abrams' formula. This formula is based on the rules created by Abrams to link the related parameters together. The specific rule is widely regarded as the Abrams' Law (Abrams, 1918).

The famous Abrams' formula is illustrated in the equation below.

$$f = A/B^{w/c} \quad (2.1)$$

where:

f =compressive strength of concrete, N/mm^2

w/c =water-cement ratio

A and B = empirical parameters acquired by fitting the curve to the practical information from experiment and are not governed by the strength and proportion of water to cement.

To attain the w/c ratio that is suited for the strength development of concrete, a particular test known as the slump test is carried out for the samples of concrete blending mix with the same fraction of mixture in the range of 0.33 and 0.36 (Yasar, Erdoğan, and Kılıç, 2004). When the optimum fraction of water to cement is identified, it is used to produce the ideal concrete specimens.

2.2.5 Compaction of Concrete

The compaction done to concrete is also another important process that essentially decides the value of compressive strength. It is necessary because the steps conducted join the aggregate constituent parts together while consistently eliminating the air contained within the concrete, which is able to enhance density and leads to better compressive strength (Civil Blog, 2018). For reinforcement concrete structures, this particular practice is able to execute a big manipulation on the main concrete in addition to the degree to which the steel structures bond and contact with the interacting main concrete, which in turns changes how composite structure performs in a building system (Han and Yao, 2003).

In the development of a concrete, the cement that undergoes chemical response which involves hydration turns into a cementitious compound. This concrete is ruled by a system of solids and pores, whereas the pores exist due to poor effort done towards compaction (Kumar and Bhattacharjee, 2003). Thus, the process of compaction of concrete should not be taken lightly.

It is noted that the compaction process is not only useful for strength development of ordinary concrete but to other variations as well such as the semi-dry concrete block. To illustrate this, high means of concrete compaction that is combined with optimum w/c ratio is able to yield improved durability and utility as well as enhanced features (Ling, 2012). Past studies also make a valid assumption that greater durability could mean greater the strength value of concrete (Al-Amoudi et al., 2009). Although this is not always the case, it is true to a certain extent.

2.2.6 Curing of Concrete

Curing is the preservation work done on the moisture content and specimen temperature while the specimen is still in its early age, which serves the objective to ensure proper progression of the concrete characteristics including the strength of concrete (NRMCA, 2000). The significance of this technique is further emphasized when materials that possess cementing properties are combined with the ordinary concrete, such as fly ash and blast furnace slag with granular properties while come into contact with warm and dehydrated surroundings as soon as casting is finished (Ramezanianpour and Malhotra, 1995).

Several experiments that are done on other concrete variations such as structural lightweight concrete shows that poor curing has a minor impact on it compared to ordinary concrete for the first month of coverage due to the “internal water” contained within the permeable aggregate particles (Al-Khaiat and Haque, 1998). Nevertheless, inadequate curing effort poses a decisive influence on the strength-maturity in a long-term manner for structural lightweight concrete.

2.3 Destructive Test

In order to assess the quality of the concrete cast, tests are required to be performed to obtain the compressive strength of the concrete. Typically, crushing of the specimen is necessary to acquire this important characteristic of concrete with the application of compression testing machine. These types of ordinary and traditional concrete strength test are classified under one category, which is known as the destructive testing (DT).

As indicated in the name itself, this regular test involves the destruction of concrete specimen until the failure is achieved. In contrast, the other type of concrete test called the non-destructive test retains the entire structure of the specimen (Samson and Omoniyi, n.d.). Some downsides identified from this ordinary testing method is that end results may require a longer time to complete and the apparatus used and the power supplied for this test may not be favoured in every single condition. Normally, this test will need 3 sets of the concrete sample to evaluate the test results for 7 days, 14 days and 28 days so that an analysis can be done for assessment of concrete strength characteristic.

There are 3 main types of destructive tests used for the evaluation of concrete, particularly in structures and buildings. They are the compression test, splitting tensile strength test and the flexural test (Feldman, cited in Dr. Sanjeev Kumar Verma, 2018).

2.3.1 Concrete Cube Test

The distinctiveness of concrete gets its impression from the value of the compressive strength that is obtained from testing any concrete cube. The results from a single test are adequate to provide a judgment on the validity of the casting process of the concrete (Mishra, 2018). Normally, for general construction site works, the average value of the compressive strength attained always differs in the range between 15 MPa and 30 MPa. The strength of concrete is influenced by a lot of aspects. Those factors identified are the fraction of water-cement, the strength of applied cement, the quality control while undergoing the manufacturing process of concrete etc.

The assessment for determining the strength of concrete is conducted on the cube but it has no problem for cylinder as well. A range of ordinary codes that is referred for compressive test of concrete specify any cube and cylinder specimen made of concrete as the standard test sample. For this test, two kinds of samples are prepared with the dimension of either 150 mm x 150 mm x 150 mm or 100 mm x 100 mm x 100 mm subjected to the size as well as the mass of aggregate utilized.

In general cases, assessments for the concrete cube are carried out at day 7 and day 28 except when certain conditions mention that it is compulsory to carry out particular initial tests (QEM Solutions, 2013). One of these tests is the limitation of a concrete shutter in a safe manner in a week earlier. Normally, one concrete cube will be evaluated for day 7 and two concrete cubes for day 28. However, the respective required standards, as well as the designs, will give some variations to the test. These concrete cubes are taken out from the finished curing process from the tank, left to dry and grit being got rid of, and then assessed with a standardized apparatus known as the compression machine (QEM Solutions, 2013). It can be moved out from within by experienced personnel or by a qualified test house. The cube samples are evaluated on the face at the upright position to the face used for casting. A continuous developing force is applied to the concrete cubes with the use of the compression apparatus until the failure is achieved. The maximum compressive strength of the tested concrete specimen is acquired from the displayed reading when the structure of the specimen stops working as usual during failure. Figure 2.1 shows the concrete cube being tested on a compression testing machine.

Figure 2.1: Cube being tested on a compression testing machine (My Civil, n.d.)

In a research conducted to assess the properties of this cube test, a proposal test is made with the variation of getting rid of the platen friction as well as the end restraint of the concrete. If these removals are possible to achieve, then the final crushing strength of the cube specimen is supposedly unaffected by the length of the concrete cube samples provided that the effects caused by buckling are evaded (Hughes and Bahramian, 1965). The outcome of the test would be able to yield the true uniaxial compressive strength values which are free from errors.

The conclusion made from the test results shows that the ordinary compression test for concrete cubes is unable to show the “true” uniaxial compressive strength and chances of the establishment of connection linking the two obtained values were proved to be none. Besides that, it is proven that the ordinary test can be easily customized and improvised by the proposed usage of specialized pads to provide an estimation to the uniaxial strength of concrete comparable to the one provided by common prism or cylinder method (Hughes and Bahramian, 1965).

2.3.2 Splitting Tensile Strength Test on Concrete Cylinders

The tensile strength or the splitting tensile strength attained from concrete is common and essential for determining its characteristics. This tensile strength test for cylindrical concrete utilizes the equipment required to obtain the concrete strength due to the exerted tensile force. In general, this tensile strength can be regarded as a mechanical characteristic that serves as an element influenced by compressive strength (Akinpelu et al., 2017). Most of the concrete samples have high possibility to crack when tension is applied onto it. Therefore, the essentiality of carrying out this particular test for acquiring the load value when cracking occurs on the structure's members is undeniably crucial. In general, this test follows the procedure from ASTM C496 for measuring the tensile strength of concrete (Tabsh and Abdelfatah, 2009). It applies the use of compressive loadings that are situated diametrically opposite to each other exerting on the concrete cylinder sides, yielding the splitting tensile strength value.

For this test, it is highly recommended to adopt a dimension of 300 mm height x 150 mm diameter for the cylindrical concrete sample as a standard sample size. This sample is positioned at flat level between the surfaces of the test apparatus that would be subjected to loadings (Building Research, 2018). The loading process is stopped when the concrete fails along the diameter at the upright position while the load is exerted entirely and evenly throughout the length of the specimen. In order to ensure consistent allocation of load and to lower down the scale of the large compressive stresses close to the spot of assessment due to this load, additional materials such as shreds of plywood are utilized for that purpose with the compressive equipment (Building Research, 2018). The cylinders are separated by force into two parts along this flat plane as the existing Poisson's effect generates a tensile stress, causing this scenario to happen. Figure 2.2 shows the details of the splitting tensile test on a cylindrical concrete.

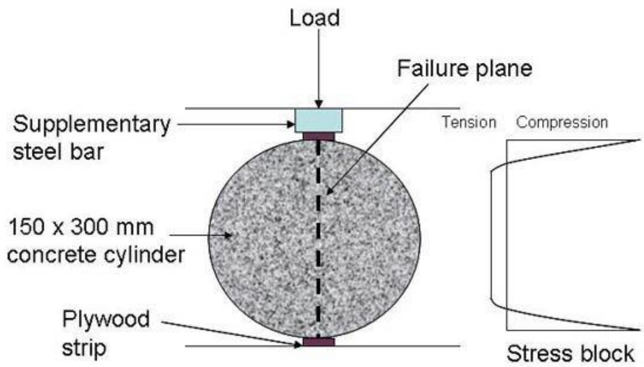

Figure 2.2: Splitting tensile strength test (Quantity Takeoff, 2018)

2.3.3 Flexural Strength Test

In this test, the main concern is to obtain the flexural strength of the concrete. This strength characteristic implements the theoretical fundamental of flexure that tensile stress is generated on one side of the neutral axis, while on the other hand another type of force known as the compressive stress is exerted as well (Ganjian, Khorami and Maghsoudi, 2009). When this condition applies, the test achieves the purpose of elimination of moment caused by acting compression provided that both tensile and compressive forces are joined as a unique combination of forces. Its growing attention received is the result of the established connection linking roadway construction with concrete. This is also due to the fact that recent studies proved that flexural stresses are the main culprit in producing failures on pavements (Wright and Garwood, 1952). Comparing this test with the tensile strength test, it is more preferable due to its incredible convenience in addition to its advantage of high suitability for site conditions.

According to BS EN 12390-5:2009, to carry out the procedures, the test begins with the cleaning of the equipment bearing exteriors followed by the cleaning of the concrete surfaces to eliminate any moveable grit as well as those unwanted substances. Extra wiping has to be carried out if the samples are kept inside liquid for moisture removal. The sample needs to be positioned in a manner which is ideally centred. Besides, the placement has to ensure that the longitudinal axis of concrete tested is situated at 90 degrees to the longitudinal axis of the rollers at the top and bottom part. For the recording part, it is similar to other concrete strength tests, which is to take the load reading at the maximum that is showed when specimen failure is being detected.

2.4 Non-destructive Test

In order to get the compressive strength of concrete tested as well as its additional properties, a method known as the non-destructive test is conducted instead of the ordinary destructive concrete test (Mishra, 2018). For this particular method, it gives an instant outcome of the compressive strength and characteristic of the structure tested. Normally, samples cast at the same time are tested for various types of strength such as tensile, compressive and flexural strengths as a means of analyzing the standard of concrete in construction or any buildings. Nowadays, most of the industrial processes such as mechanized creation process in the factory and the operating examination process adopt various non-destructive tests in order to achieve optimum monitoring of these progressions while limiting the expenses incurred for their respective products (Asnt, 2017).

It is argued that there are no straightforward measurements for obtaining the properties of concrete strength. This is mainly because, in the process of finding the concrete strength, it requires destructive stresses. Despite this, there are plenty of methods for concrete testing created that will not destroy the concrete specimen. The convenience of these non-destructive means of obtaining some of the physical characteristics of the concrete which are connected to strength opens up more possibility to devise these methods. Several important properties are being identified for the testing process. These aspects are the competence for rebound in the rebound hammer test, the ability of concrete to convey ultrasonic pulses, hardness and the degree to which the concrete can resists projectile penetrations.

There are several methods of non-destructive testing of concrete that are designed to identify its compressive strength. Among the various non-destructive tests, they are mainly classified as penetration method, pull-out test method, rebound hammer tests, dynamic test methods and radioactive means of testing.

2.4.1 Penetration Method

Penetration test is a special method that is ideal when a certain situation requires the identification of the value of the concrete relative strength in structures. However, this particular test fails to give any relevant concrete compressive strength that is absolute. This is mainly due to the instruments' nature that is limiting the experimental process (Mishra, 2018). This method is then named the penetration resistance of hardened concrete after it is being standardized in some standard in the ASTM.

For most of the testing scenarios**,** the theory of this particular test revolves around the fundamental principle that compressive strength of concrete has a major influence on how penetration works on the concrete sample. The strength affects the degree of penetration of a probe that is widely known as the Windsor Probe which is incurred into the surface of the specimen tested (Quality Engineering and Construction, 2014). Nevertheless, the existing factors of proportions as well as the characteristics of the aggregate used for the concrete are resulting in a considerable interference in this correlation. Thus, according to BS 1881, it is necessary to prepare a separate relationship for the testing of every concrete.

Windsor probe gives an experimental outcome that is based on the quality of concrete as it is principally regarded as a hardness tester in the determination of in-situ concrete strength (Swamy and Ali, 1984). By utilizing the means of mathematically devised empirical formulas derived from a curve which is plotted from various test results, the expected value of in-situ compressive strength can be computed. It is noticed that errors could surface in the process of doing estimation if the dependency on a single curve or the actual site situation that is not synchronized with the assumed conditions is being focused (Quality Engineering and Construction, 2014). Therefore, an individual relationship that can link penetration resistance and strength of concrete together has to be formed in order to produce a more significant and consistent approximation.

This particular method composed of features similar to a driver with actuated gunpowder and a toughened composite rod probe made of alloy (Gharpedia, 2018). Moreover, the equipment comprises of loaded cartridges, a gauge used for monitoring the depth and many more. The driver has the function to fire an alloy rod probe on the concrete, and the penetration deepness is affected by how big is the concrete strength. Normally, the strength of the concrete tested is obtained and estimated by averaging three sets of value acquired from the fired probes.

While carrying out the test, a depth gauge that is calibrated precisely is used to measure the probe length that is been exposed. However, it is highly recommendable that the coefficient of variation should be defined according to the penetration depth because the compressive strength of concrete is directly linked to the parameter of depth due to penetration (Tay and Tam, 1996). The probe is able to be fitted neatly and tightly into the hole of the driver alongside with a washer that is made of rubber. The test is carried out rather different when the concrete structure is reinforced with steel. A significant decrease in the probe penetration distance is identified when the steel reinforcement is situated in the region of impact. For that case, a seemingly larger strength value can be acquired from the lowered penetration depth provided that the steel bars within the structure are measured from the probe at a distance not more than 100 mm (Tay and Tam, 1996). Figure 2.3 demonstrates the illustration of the Windsor Probe penetration test.

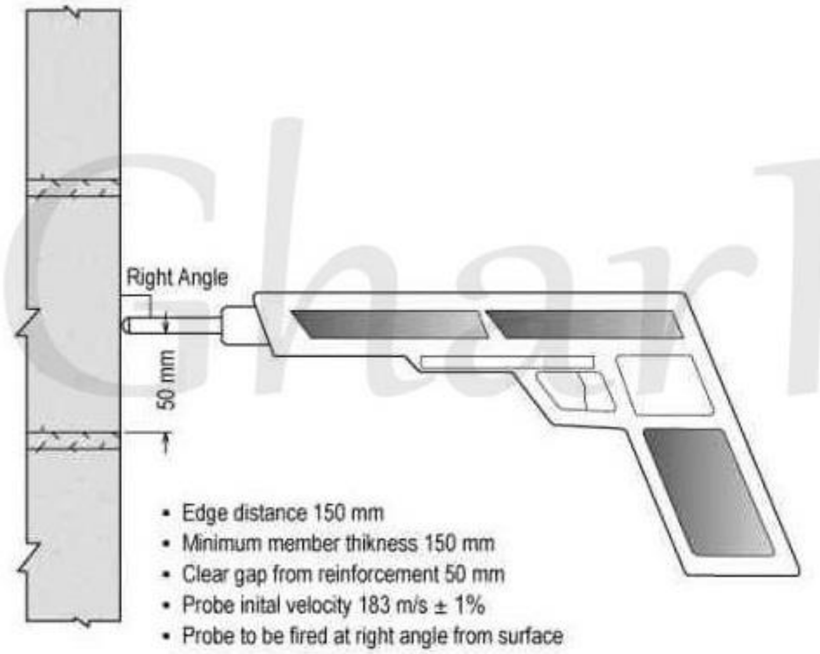

Figure 2.3: Illustration of a Windsor Probe Penetration Test (Gharpedia, 2018)

2.4.2 Pull-Out Test

For this test, the distinct failure is inevitable in the in-situ concrete though, on the other hand, generates the important static strength characteristics (Gharpedia, 2018). For the purpose of conducting the test, the tool is design to be convenient and user-friendly to function. However, some expertise is needed for conducting this test. Generally, to start the test, the instrument needs to undergo some fixing process, which is crucial as this is prior to generating sufficient pull out forces for the pulling out course and that particular force is very much interrelated to the strength of concrete. This relationship is accomplished by getting the value of the measurement of pull out force needed to pull the entrenched probe or embedded disc. There are two ways for the steel probe and disc to be utilized. The first way is by casting the probe into the freshly produced concrete. The other way is to fix it in the solidified concrete specimen, which is against a spherical counter force positioned on the surface of the specimen (Gharpedia, 2018). Moreover, the pull-out method of testing is proved to be potentially capable of acquiring the safe removal period for forms. Besides, for post-tensioning process of prestressed tendons seen in construction, it also demonstrates the ability to obtain the earliest period which this process may be carried out without any harm or being interfered (Bishr et al., 1995). The two types of concrete pull-out tests that are going to be discussed are Punch-out (LOK) test and Cut and Pull Out (CAPO) test.

The first type of pull out test, known as LOK test, recently established an exceptional connection linking two important parameters which are the force due to pulling out and regular concrete strength. This successful accomplishment provided a lot of interests as well as attention in the concrete casting sector (Zhu, Gibbs and Bartos, 2001). The destruction of the concrete is kept to its minimum due to the advantage that the structure of the test is not limited by a lot of restrictions. It is utilized for gaining relevant information regarding the standard of the cover of concrete and its homogeny in the concrete strength evaluation test. In this process, the magnitude of the force exerted during pull out is identified for each of the respective days. A drawing provides a brief illustration of the inserts of the method of testing and the display of the pull-out is provided in Figure 2.4.

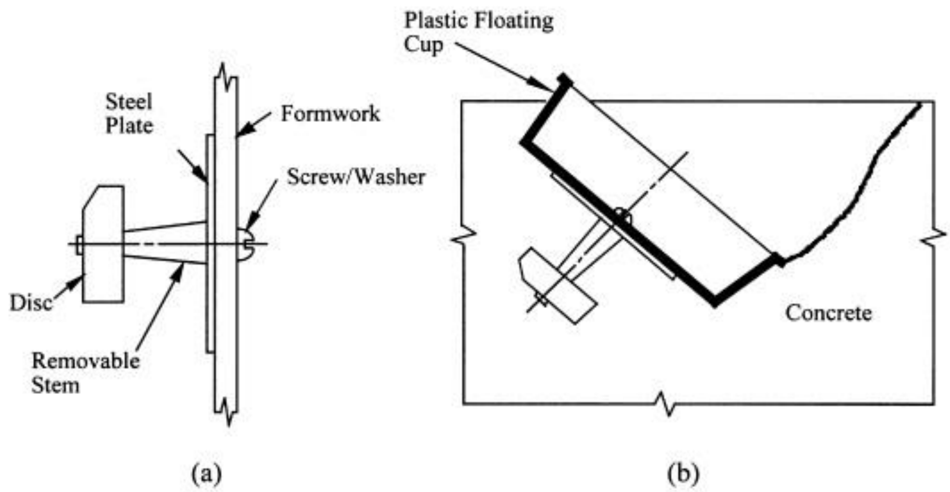

Figure 2.4: LOK test inserts and pull-out arrangement used: (a) formwork type and (b) floating type (Long, Henderson and Montgomery, 2001)

CAPO test is a type of test that is extremely similar to LOK test which is suitable for the testing as well as evaluation of concrete. For this test, in order to make a groove available for into which a compacted circular band that is made of steel is able to be expanded to give a comparable test pattern, it is necessary to perform under-reaming as well as drilling works to satisfy the required conditions, as shown in Figure below (Bungey and Soutsos, 2001). Although the way of exerting load is of a jack that is alike, but the operation is time-consuming. Nevertheless, the limitation does not stop the possibility for like relationships that are related to the strength of concrete to be applied for the respective concrete test analysis. Figure 2.5 shows the arrangement of CAPO test in detail.

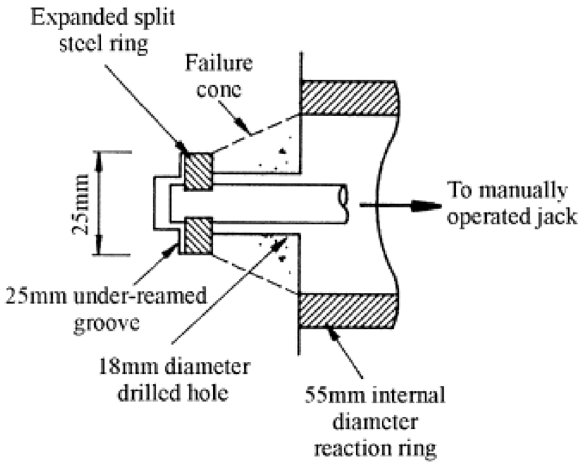

Figure 2.5: CAPO test arrangement (Bungey and Soutsos, 2001)

2.4.3 Rebound Hammer Test

The rebound hammer is a tool or a piece of gadget designed and created for the purpose of evaluating the relative concrete strength according to the level of hardness at or close to the bare surface of the concrete specimen. The configuration of the hammer is based on a mass that is monitored by spring that will slip on a housed plunger (Mishra, 2018). This type of hammer is widely recognized as Schmidt's Hammer or Swiss Hammer because its invention came from an engineer named Ernst Schmidt who was originated from Swiss.

A detailed illustration is provided in the ASTM C805 and BS 1881: Part 202 for the test. It is categorized as a type of test for concrete hardness. Its derivation originates from the fundamental aspect that the recoil of an expandable mass relies on the surface hardness in opposition to which that particular mass impose (Qasrawi, 2000). The amount of energy that is taken up by the concrete is affected by the strength of the concrete. In spite of its obvious plainness, some existing setbacks relating to impact and the connected transmission of stress-wave continue to pose challenges for the test.

To start the studying of the concrete sample, it begins with the delicate and distinct approach of selecting and setting up the surface of the concrete. When the appropriate surface is picked, its preparation is going to include the use of an abrasive rock. This involvement is to ensure the smooth testing surface of the concrete (Aydin and Saribiyik, 2010). After that, a force with a fixed energy quantity is exerted by pressing the hammer onto the surface of the concrete. One thing to take note is that the plunger should be permitted to hit at right angle to the concrete surface to be tested. This is mainly because the inclination position has a significant influence on the outcome. The number of rebound is then recorded following the impact of the hammer on the concrete. A minimum of 10 readings should be collected from every single area that is experimented (TS 3260, cited in Aydin and Saribiyik, 2010).

Researches show that there is zero exclusive connection established between hardness and compressive strength of concrete. However, continuous experiments conducted for a particular concrete sample is very likely to yield some specific data correlations for in-depth analysis (Basu & Aydin, cited in Shariati *et al.*, 2011). Nevertheless, this correlation is unable to separate itself from different types of consideration which significantly interfere with it. These aspects, for example, the saturation level, warmth, position and concrete surface preparation, and the kind of finishing for the concrete surface tested continue to play their role in affecting the surface of the concrete specimen. This particular end result is also influenced by the variety of hammer type used, leaning of the hammer, mix fraction and the aggregate used. Some of the areas that need to be steered clear of are scaling, honeycombing, rough uneven surface, or high level of porosity (Qasrawi, 2000). Other than that, the concrete used should possess similar maturity level, wetness conditions and scale of carbonation that is exactly the same. Something to note down is that surfaces that consist of carbonation can give larger values of rebound. Figure 2.6 illustrates the different working principles for the test.

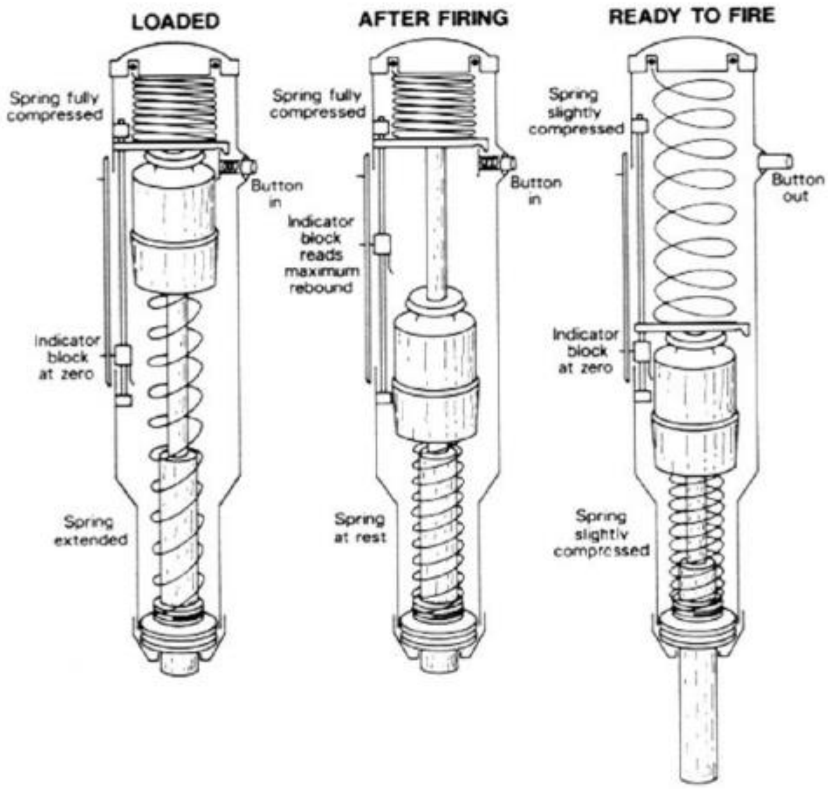

Figure 2.6: Working principles of rebound hammer test (Basu and Aydin, 2004)

2.4.4 Radiographic Testing

Radiographic test method of the building strengthening in the essentials of the reinforced structure of concrete is conducted by utilizing equipment which consists of gamma radiation or supplies of beams of X-ray. Nowadays, the most favourable radioactive emission supplies for radiographic testing of reinforced concrete (RC) are isotopes of type Co-60 of elevated activity, and also the carbon isotopes of C-137 (Popovics, 2003). Moreover, X-ray instrument of voltage higher than 200 kV and also the betatrones and microtones giving energy which contains radiation ranging between 6 and 30 MeV both plays a vital role in the radiographic assessment of concrete (Runkiewicz, 2009). While carrying out tests of civil building structures, moveable and variable sources are applied. These sources comprise of defectoscopes with gamma elements, equipment of X-ray and betatrones that give energy and so on.

By referring to the fundamentals of acquiring test results, it is concluded that the ability to distinguish cavities as well as steel bars within the concrete tested is adequate for the purpose of building construction activities, provided that the related factors are properly considered. The parameters used for this test termed in this particular means allow an evaluation of the steel bars, hollow space and honeycombing inside the concrete with a precision percentage ranging within 2 to 5% (Runkiewicz, 2009). Figure 2.7 illustrates the test method of the position of the reinforcement within the RC beam structure using radiograph.

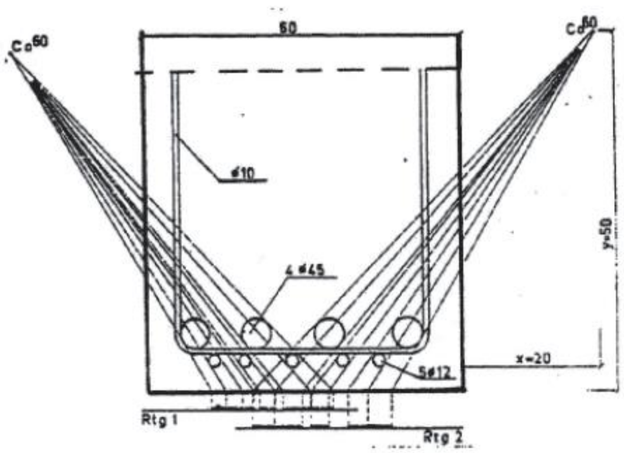

Figure 2.7: Assessment of bottom reinforcement in the beam inside the middle of the span with the use of radiographic method (Runkiewicz, 2009)

2.4.5 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity (UPV) method, a method that is used to determine the value of the pulse velocity to find out the compressive strength of concrete stipulated in every single standard is derived from the similar fundamental. Past researches proved that this method is qualified to be used to evaluate the excellence of construction by running inspection on the distribution of concrete strength (Bungey, 1980). Pulsations of longitudinal and stress waves with elastic properties are produced using an electro-acoustical electronic transducer that is put in contact with the concrete specimen surface in a direct manner. As the pulsations traversed across the whole concrete, they are delivered and changed into electric-containing energy by another transducer. Determination of the strength of concrete is then achieved by processing the data collected.

For this particular method, three types of probable arrangements are explained and illustrated for the electronic transducers. For the first type, they are placed directly opposed to one another. This type is known as the direct transmission UPV method. The next type of UPV method is the diagonal transmission. This method positions the transducers in a crossways form to one another. The third arrangement that can be used for this testing is known as the indirect transmission, whereby the transducing equipment is bind to the same concrete surface and parted by an identified length between each other. In terms of sensitivity, the arrangement with the greatest sensitivity is the direct transmission method, while indirect way of conduction method is the one with the least sensitivity (Komlos et al., 1996). The wave transmitting velocity, v is determined by using the distance, l from one transducer to another and the time travelled, t of the wave which will be obtained by electronic means as $v = l/t$.

2.5 Elastic Wave

An elastic wave in its theoretical state is referred as the transmission of a type of motorized interruption across a given medium, producing a circumstance which drives the material particles to fluctuate in the fixed range from the equilibrium location (Walley and Field, 2001). However, the actual situation may vary from this hypothetical case. The way in which the frequency changes significantly affect the wave and causes reduction in its properties in terms of length travelled.

In the past century, physicists like Cauchy and Poisson managed to discover the existence of two main types of elastic wave, which are widely known as the P-wave or longitudinal wave, and the S-wave or the transverse wave oscillating in a medium with isotropic characteristics, while another type of wave known as the surface wave was also being realised by Lord Rayleigh (Pao, 1983). Investigations regarding these waves and the theory of elasticity revolving around them were carried out actively since then until today.

When the topic of elastic wave energy is discussed, it is always noted that the energy originates from it is able to undergo diffusion over substantial travel distance which is aided by the movement of the wave itself. When the motion induced is distributed across several particles one by one from the first unit and unlike those that are caused by continuous massive motion of whole substance, the impact on the energy distribution can be inevitable (Achenbach, 2012). Therefore, the properties of medium utilized for wave transmission is crucial while wave propagates.

2.5.1 Elastic Wave Properties

There are several properties of elastic wave that can be studied and assessed in order to define and classify it. These informational data are extremely useful for engineering applications, particularly in field involving infrastructure and building construction. The engineering and science organizations have done plenty of research to create the efficient ways of utilizing elastic wave for structural evaluation, which is now called the NDT method (Meo, Polimeno and Zumpano, 2008). Nowadays, these methods are utilized to conduct investigation on the changes that occur on the wave properties such as the wave velocity, frequency and amplitude.

2.5.1.1 Wave Velocity

The first important wave property that can be used for evaluation and application purposes is the velocity of the elastic wave. In the engineering era, waves are normally propagated through a particular material and the pattern of wave is then studied. The velocities of elastic waves are very convenient to be used for prediction of certain parameters as well as comparison of any effects incurred on a material.

For velocity of P-wave, researchers have put plenty of effort to illustrate the fact that its velocity can be influenced by factors such as the pressure and saturation of solution while applying this elastic wave by conducting experiments using means involving ultrasonic (Gardner, Gardner and Gregory, 1974). Connections that link P-wave velocities in rocks with the existing stresses and containment of solution are being established with various on-site conditions being taken into consideration.

In the crack detection application using elastic waves, it is observed that the existence of these cracks causes a significant reduction in the elastic moduli of the substance, making the prediction of the decrease of wave velocities to be reasonably valid (Guéguen and Schubnel, 2003). Examinations have produced findings that the crack porosity impacts the density of the material which in turns affects the elastic wave velocity as well. The wave velocity formula is listed down below:

$$V = \sqrt{\frac{M}{\rho}} \tag{2.2}$$

where:

V = wave velocity, m/s

M = elastic modulus, GPa

ρ = density, kg/m^3

In addition, elastic wave velocities are being assessed for its depending factors such as the saturation degree of gaseous substance. Certain issued findings that originate from the sonic frequency group are able to give estimations for the condition when the frequency is at zero value, which implies that the predictions from the results are in good terms with Gassmann's model (Gassman, cited in Cadoret, Marion and Zinszner, 1995). Nevertheless, the complications arise when evaluating the correlations between saturation of water and the velocity itself in the ultrasonic frequency and heavy focuses have to be put on porosity and type of rock (Gregory, cited in Cadoret, Marion and Zinszner, 1995).

2.5.1.2 Wave Amplitude

The amplitude of a wave is a wave characteristic that displays the transmission of energy and also the quantity stored within that particular wave, means that larger value of amplitude indicates that the wave contains greater amount of energy (Physics Classroom, 2018). In cases that include longitudinal P-wave, measurements of amplitude are normally done by taking the highest displacement value from the equilibrium spot while experimenters usually take the displacement value of whichever point at its greatest on the string from the string's resting position for situations of transverse S-wave (Encyclopedia Britannica, 1998).

2.5.1.3 Wave Frequency

Wave frequency can be regarded as the total amount of completed sequence given a value of time period. In the general equation of the wave frequency formulation, both parameters of period and frequency are reciprocals to each of the factors, which further provides the relationship that a large wave period given will induce smaller amount of wave cycles completed in that particular time frame, then the frequency becomes lower (Study, 2018). The frequency of a wave has a role to play which is as important as the role of wave velocity in most of the NDT tests.

2.5.2 Types of Elastic Wave

There are a lot of elastic waves that are present in the engineering and physics world. It is classified into two main forms, which are the longitudinal wave and transverse wave. Besides, surface wave is also another type of wave that has a certain degree of significance, except for the fact that its movement varies from the longitudinal and transverse waves. These 3 waves are further discussed in the next few subsections.

2.5.2.1 Longitudinal Wave

Longitudinal wave is a type of wave that has the medium elements pulsates about their mean spot towards the path where the interruption in the material oscillates, and during the propagation the displacement generated from this phenomenon is side by side with the wave oscillation (QS Study, 2018). The common illustrations of this form of waves that are present in the physics discovery are sound waves, seismic P waves, ultrasounds etc.

To put in a different explanation, longitudinal wave, which is also known as P-wave moves across any medium by adopting the patterns of compression and rarefaction. When it reaches the state of compression, the wave acquires the characteristics of maximum pressure and density and vice versa while it undergoes rarefaction (Physics@TutorVista, 2018). It is relevant to note that this wave usually travels in gas medium only. For experimental and research uses, the parameters such as velocity, amplitude and frequency of the wave can be studied by examining the wave’s distinctiveness. The motion of longitudinal wave is represented in Figure 2.8.

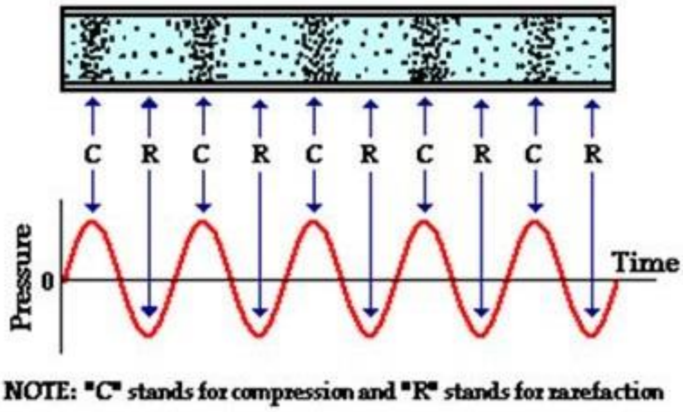

Figure 2.8: Graphical Motion of Longitudinal Wave (Physics Classroom, 2018)

2.5.2.2 Transverse Wave

Transverse wave has a displacement which is situated at right angle with the route of oscillation of that particular wave and this configuration can be simply observed for a wave that propagates on an elastic object such as a thread (Hyper Physics, 2018). However, gas and fluid mediums serve as a great restriction for transverse wave due to the absence of means available to allow the wave to move at upright position to the wave oscillation. This wave is also widely known shortly as T-wave.

From previous studies on transverse wave with the conditions of varying frequencies, it is discovered that situations that involve minimal frequencies favour the purpose of conducting elasticity imaging because the weakening of the wave is not significant in addition to the fact that velocity of wave oscillation is lowered as well (Muthupillai et al., 1996). Therefore, it is safe to say that the fundamentals for the mechanical transverse wave propagation are suitable for determining the wave pattern of any type of recurrent movement. In this modern era, this unique wave has been utilized as a mode called the surface transverse wave mode in audio instruments due to its great sensitivity to mass which is very useful for engineering function that involves compound and organic sensors (Radeva and Avramov, 2000).

2.5.2.3 Surface Wave

The surface wave is another well-known wave that is sometimes called the radio wave and it has the ability to move its body along the earth’s face, earning the propagation term of surface wave propagation (Quantum Study, 2018). Surface wave or ground wave oscillates and tour in the curve region that surrounds the earth and sometimes can twist itself round any substance's angle in the world.

Another variation of surface wave that is worth studying is the Rayleigh wave. It is commonly mistaken as the ordinary surface wave from the first peek when researchers failed to notice the distinctiveness that particles in Rayleigh wave form an oval-like motion that is in opposition to the path of oscillation (UC Berkeley, 2009). Experiments proved that the concavity of the surface travelled can be a significant factor to the speed of the surface waves that are travelling in planar surface or a rounded exterior (Moser, Jacobs and Qu, 1999).

Surface wave has given plenty of contribution to the studies of Earth interior imaging by acting as critical seismic information, providing researchers with the most precious constriction on the upper covering buildings that surpasses all the other seismic data (Ekström, Tromp and Larson, 1997). For Rayleigh wave, its investigations are being focused on the factor of the geology of the location and a model that consists of two layers are being formed to develop useful approximations for the wave condition (Murphy & Shah, cited in Jongmans and Demanet, 1993).

2.6 P-wave

P-wave which is essentially a form of elastic seismic wave is a unique wave with the capability to be distributed no matter by fluid or solid substances in this world and can be classified under the longitudinal wave category (Encyclopedia Britannica, 1998). This wave has its own simplicity as it has the pattern of vibration induced to the medium that is very alike to the behaviour of sound waves. P wave is the fastest wave known to physicists due to its amazing speed and makes it always the first to land itself on earth's ground exterior (Encyclopedia Britannica, 1998).

Figure 2.9 shows a brief comparison between P-wave and S-wave as both of them are in the seismic wave group. It is useful to study the occurrence of earthquake using this evaluation.

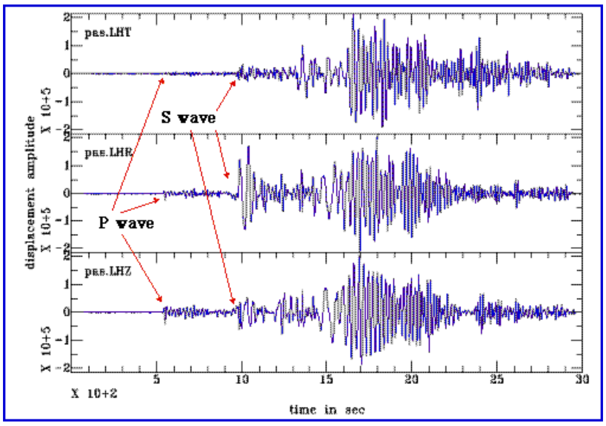

Figure 2.9: Comparison of P-wave and S-wave (Indiana, 2018)

In the world of engineering and science, the non-invasive eletrocardiology manages to advance further with a series of new findings thanks to the involvement of the application of scattering P-waves. It is predicted that the electrocardiographic (ECG) marker will be utilized in an extensive manner due to these vast enhancements of P-wave evaluation, mostly in the medical situations especially in the process of hazard consideration for atrial fibrillation (AF) (Dilaveris and Gialafos, 2001). When studying the use of collision of these waves, the occurrence of Feshback resonance that happens once the relative energy of the incident particle unit is very close to deterioration with a quasibound form is extremely important for the wave assessment purpose (Regal et al., 2003). This resonance is advantageous because the utilization of the magnetic field has made the harmonisation of wave energy to be possible.

2.6.1 Measurement of P-wave

The ways in which measurements of elastic waves are being done are classified into two main types. They are known as the direct transmission and indirect transmission method. An alternative method of conducting measurements on the elastic waves called the diagonal transmission method is being used as well. For direct transmission method, the transducers are being placed in positions that are opposite to each other while the sensors are positioned at the same surface but divided apart by a certain calculated distance for indirect transmission method (Song and

Saraswathy, 2007). For diagonal transmission, the marked locations for transducers are in a diagonal manner.

In a slightly varying method of measuring elastic P-wave, the direct way of wave diffusion is being carried out by self-infliction using force hammer in which the wave is generated through hammering impact and the use of accelerometer is mandatory for the other side of the structural material to receive the incident wave (McCann and Forde, 2001). The other transmission methods along with the direct way are illustrated in the diagrams below. The two means are semi-direct and indirect transmission method. These methods are used broadly in the NDT method of assessment of concrete structures. These modes are shown in Figure 2.10.

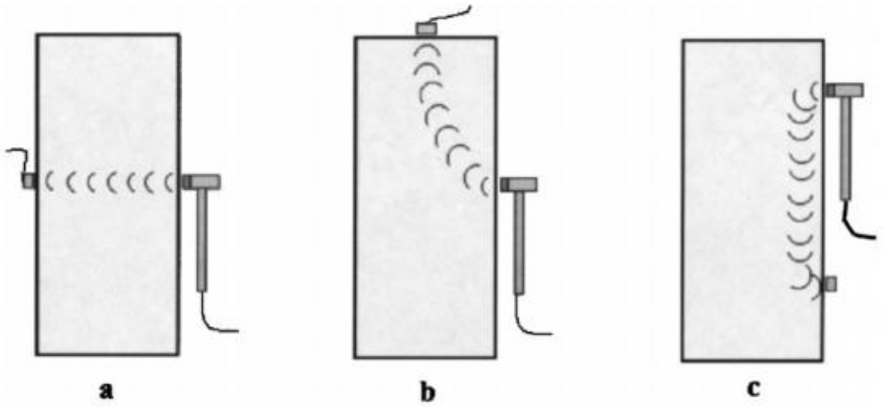

Figure 2.10: Transmission modes for sonic/ultrasonic wave tests: (a) direct; (b) semi-direct; (c) indirect (McCann and Forde, 2001)

2.6.2 Attenuation of P-wave

Generally, it is natural that the wave undergoes pressure deterioration when the travel distance increases. The energy contained within the wave is lower than its initial level due to dissipation that leads to constant loss of energy. The longer the distance travelled, the higher the degree of energy dissipation and the greater is the attenuation of the elastic P-wave.

Since concrete is considered as a type of porous media, the investigations done to assess the possibility of P-wave attenuation in this form of medium are relevant and the recent discoveries show that it is originated from wave-induced liquid movement at levels of macroscopic, mesocopic and even up to microscopic extent (Pride *et al.*, cited in Carcione and Picotti, 2006). Based on the related experiments, sufficient evidences have made the conclusion that the most credible means that leads to P-wave attenuation is mesoscopic loss, particularly at seismic frequencies due to the properties of microstructures as well as the pores of the medium (Carcione and Picotti, 2006).

A preceding experiment that was conducted on the wave attenuation in the shore water showed some interesting results. It is discovered that the waves that experience motions at the sea bottom undergo energy loss which is much larger than that from the consequence of percolation due to the existence of frictions (Tubman and Suhayda, 1977). This significant observation further implies that wave that travels at moderate water depth in seaside that is filled with mud experiences greater energy dissipation compared to the waves that move in sandy shores. The results from this experiment are further analysed for contribution to the engineering field.

2.6.3 Analysis of P-wave

To conduct analysis on the elastic P-wave, several parameters regarding the properties of the wave need to be determined. By using concrete as the medium of study, the ultrasonic pulse velocity and the elastic modulus of the concrete are both important values for analysis. The equation for ultrasonic pulse velocity of the wave is shown below (Bogas, Gomas and Gomas, 2013):

$$UPV = \sqrt{\frac{E_d}{\rho}\left(\frac{(1-v_d)}{(1+v_d)(1-2v_d)}\right)} \tag{2.3}$$

Where:
E_d = dynamic modulus of elasticity, GPa
v_d = dynamic Poisson’s ratio
ρ = density, kg/m^3

For this particular analysis, relationships are being established in order to link the three properties mentioned above with the wave velocity and the compressive strength of concrete. Another indirect parameter which is the elastic modulus, E_c is required for this objective and the equation is listed below, where f_c = compressive strength of concrete (Bogas, Gomas and Gomas, 2013).

$$E_c \approx 22\left(\frac{f_c}{10}\right)^{0.3}\left(\frac{\rho}{2200}\right)^2 \tag{2.4}$$

Where:
E_c = elastic modulus, GPa
f_c = compressive strength of concrete, N/mm^2
ρ = density, kg/m^3

In general, when elastic waves travelled into the medium, they are affected by a lot of factors apart from those listed in the previous paragraph. While low frequency plays a significant role in affecting the wave motion, the degrees of saturation of medium, as well as the possible existence of ground water table, have slight impact on P-wave behaviour but for mediums that involve compressibility factor, the effects on the wave pattern and its velocity are very essential (Degrande et al., 1998). Besides, the void ratio is related to the compressibility as well and strengthens its significance when using concrete as a medium. All these factors need to be taken into consideration while analyzing the P-wave motion.

In a nutshell, there are various aspects and limitations that need to be evaluated while conducting investigations on elastic P-waves. The velocity of P-wave is a suitable wave characteristic for analysis purpose due to its vulnerability to those factors and the velocity data is a very useful means to evaluate the wave.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The third chapter gives an in-depth illustration that demonstrates the detailed parts of the report. They include the materials chosen for the tests, laboratory equipment and apparatus used in the civil engineering laboratory as well as the experimental procedures of conducting cube tests and NDT elastic wave tests to determine the compressive strength of the concrete. The significant materials needed for this research are Ordinary Portland Cement (OPC), coarse aggregates, fine aggregates and water. Additional descriptions are given regarding the dimensions and concrete design mix proportions adopted and samples with varying fine aggregate/coarse aggregate ratio are going to be used for experimental assessment.

3.2 Materials Used

To form a normal weight concrete, the materials required for its composition are OPC, coarse aggregates, fine aggregates and water.

3.2.1 Ordinary Portland Cement

In the formation of concrete, the utilization of cement is mandatory and extremely important to create the composition. It can be referred as a type of water-based substance that is manufactured using fresh ingredients that originates from sources of calcium, silicon, iron plus aluminium which are limestone, clayey soil plus sandy soil (Engineering Intro, 2012). When the cement paste undergoes hydration, cement serves as a binding agent that binds the elements of water and aggregates together.

For the experimental objective purpose, the use of Type 1 Ordinary Portland Cement for the production of concrete mix is ideal to form normal weight concretes. Besides, the utilization of this particular type of OPC in most of the constructions in our country makes the choice to be more suitable for the experiment. Figure 3.1

gives a demonstration about OPC sample while **Table 3.1** illustrates the specification of the chemical composition of Type 1 OPC obtained from the experiment.

Figure 3.1: Ordinary Portland Cement (OPC)

Table 3.1: Specification of Ordinary Portland Cement American Standard ASTM C 150 – Type 1 (Tiger Cement, 2018)

Chemical Composition	**Limits as per ASTM C 150 – Type 1 (%)**	**Tiger Cement Test Results (%)**
Loss on Ignition (LOI)	3.00 Max	0.93
Insoluble Residue (I.R)	0.75 Max	0.26
Silicon Oxide (SiO_2)	20.00 Max	20.59
Aluminium Oxide (Al_2O_3)	6.00 Max	4.96
Iron Oxide (Fe_2O_3)	6.00 Max	3.77
Calcium Oxide (CaO)	-	63.35
Magnesium Oxide (MgO)	6.00 Max	2.94
Sulphur Trioxide (SO_3)	3.00 Max	1.96
Alkali Eq.	0.60	0.53
C_3S	-	53.8
C_2S	-	20.19
C_3A	8.00 Max	6.4
C_4AF	-	12.04
Chloride (Cl)	-	0.01

3.2.2 Coarse Aggregate

Coarse aggregate is a type of rock that has the size that exceeds the dimension of 4.75 mm (The Concrete Portal, n.d.). This type of aggregate typically composes of crushed stones, pebbly stones like gravel, and furnace slags. In order to distinguish as well as separate coarse aggregates with fine aggregates, sieve analysis is essential to be carried out for a sample of mixed aggregates.

When sieving was being conducted, the sample of aggregates was positioned onto various sieves with sizes of 4.75 mm, 10 mm as well as 20 mm. This process was carried out to separate the aggregates into two size ranges which were 4.75 to 10 mm and 10 to 20 mm portions. After the separation was completed, the aggregate specimens were cleaned to eliminate unwanted substances situated on the surfaces such as dust and then placed into containers for storage. The storing process was carried out deliberately because it was significant to avoid the possibility of letting the aggregates come into contact with additional moisture as this could lead to a reduction of concrete strength after casting.

Figures 3.2 and 3.3 illustrate the aggregates that were sieved into size ranges of 4.75 to 10 mm and 10 to 20 mm.

Figure 3.2: Coarse aggregates of 4.75 to 10 mm size range

Figure 3.3: Coarse aggregates of 10 to 20 mm size range

3.2.3 Fine Aggregate

In the categorization of fine sized aggregate, the aggregates that are having sizes of 4.75 mm or lesser are placed in this group and most of them consist of natural sandy substances. Generally, the standard size range for fine aggregate is from 75 µm to 4.75 mm (ASTM, 2007). While sieving was carried out as usual, the sand sample was placed onto the sieves of with sizes of 600 µm and 4.75 mm. The samples were washed thoroughly so that unwanted impurities such as dust particles can get rid of effectively. Then, they have dried again before being kept inside other separate containers. Figure 3.4 shows the samples of fine aggregate sand placed inside a tray.

Figure 3.4: Fine aggregate sand of size 4.75 mm or below

3.2.4 Water

Water acts as a mixing liquid agent that is mandatory for the formation of concrete composition and the process as well. By referring to standard requirements, the water chosen for the purpose of conducting concrete mixing has to be drinkable which means it is free from any possible contaminant while for water that is not fit for consumption, it is compulsory to conduct testing before it is utilized for the concreting objective (ASTM, 2012). For this particular experiment, the water used was acquired from sources that originated from the municipal water supply.

3.3 Trial Mixture Design

Concrete trial mix is a preliminary step of casting concrete that is essential so that the process of selecting the most favourable mixing proportion that has the best chance of forming the concrete with compressive strength of grade closest to C25. It is an important stage to ensure that the concrete specimens have a low possibility to undergo failure during the actual experiment.

3.3.1 Mixing Proportion

A series of trials were performed with the varying amount of cement, aggregate or water content for each of the mix proportion, thus yielding different mix proportions. For this experimental purpose, the aspect that was taken into consideration while using the mix proportion is the target compressive strength. The strength that was required to achieve was in the range of 20 N/mm^2 to 35 N/mm^2. To accomplish this, 3 sets of trial mix proportions with their own unique amounts of cement, water and aggregate were devised for the objective. Table 3.2 illustrates the various contents of trial mix proportions with the intention to attain the desired compressive strength and Figure 3.5 shows the concrete cube cast using trial mix proportion with water-cement ratio of 0.51.

Table 3.2: Trial mix proportions for Normal Weight Concrete

Normal Weight Concrete			
Aggregate type	Crushed	Crushed	Crushed
w/c ratio	0.60	0.55	0.51
Cement (kg/m^3)	350	382	412
Water (kg/m^3)	210	210	210
Sand 4.5 mm (kg/m^3)	699	699	699
Aggregate 10 mm (kg/m^3)	571	571	571
Aggregate 20 mm (kg/m^3)	571	571	571

Figure 3.5: Concrete cube with water-cement ratio of 0.51

3.3.2 Mixing Procedure

In the mixing process, several steps and precautions have to be carried out properly so that the concrete cast yield the most dependable outcomes with the greatest efficiency. The important steps have to be done according to the properties required and the type of concrete cast. This process was carried out for both trial mix and the actual experimental concrete mix.

At first, the cement, coarse aggregates and fine aggregates needed for the mixing process were made sure so that they were always in an air-dry state. This is significant to ensure that the possibility of formation of slumps was zero. To extract the aggregates with the desired sizes, the aggregates were being sieved accordingly. After this, all the materials were weighed in order to get the required amount of materials based on the adopted design mix proportion. The fine aggregates were then placed into an oven to be oven dried at 100 °C for 24 hours. After that, the materials were placed into a concrete mixer for thorough mixing. The course of mixing the ingredients followed the order of placing the aggregate with the largest size to finer sizes, then ended with OPC. After allowing the mixture to undergo blending and mixing inside the concrete mixer for about 3 minutes, it was left there to rest and then water that had the required weight was emptied into the mixer with the mixture. After that, the concrete mixer was permitted to rotate for about 2 to 3 minutes and the mixing was then completed. Figure 3.6 demonstrates the concrete in a concrete cube mould used in the civil engineering laboratory.

Figure 3.6: Concrete in a concrete cube mould

3.3.3 Concrete Curing

As soon as the mixing process was done, the concrete mixture was placed into the respective mould and they were moved to a certain area to undergo hardening for 24 hours. The samples were stored as soon as possible so that the amount of moisture loss to the environment was controlled and minimized. For the actual experiment, several concrete moulds were prepared for casting.

After that, the concrete sample was demoulded. For the concrete to be usable for further testing, several steps had to be conducted. The demoulded specimens need to undergo moist curing which means that the concretes were stored inside water storage tank in order to maintain the presence of free water on the exterior of the specimens for the entire curing period of 28 days (ASTM, 2007). During curing, the elements of cement experienced chemical reaction with water and the process of binding of aggregates were started, causing heat to be emitted from the concrete. By the time the concrete was cured for 28 days, the specimens were removed from the water tank as they had achieved optimum maturity. Figure 3.7 shows the concrete curing process in water storage tank.

Figure 3.7: Concrete curing process in water storage tank

3.4 Testing of Concrete Samples

In this research, there are plenty of tests that are required to be conducted in the entire experimental procedures. These tests are compulsory to be carried out because the steps guaranteed better end results and minimize the occurrence of failure and errors while obtaining the compressive strength of concrete. Table 3.3 illustrates the type of main tests and the number of cube samples required for the whole experiment.

Table 3.3: Testing Methods and Number of Concrete Samples Required

Testing Methods		**No. of Samples Required**				
		Fine Aggregate/Coarse Aggregate Ratio for Concrete Cube Samples				
		1:1.60	1:1.64	1:1.68	1:1.72	1:1.76
Compression test (control)	**1 day**	3	3	3	3	3
	7 days	3	3	3	3	3
	28 days	3	3	3	3	3
NDT elastic wave method	**1 day**	3	3	3	3	3
	7 days					
	28 days					
Total		12	12	12	12	12

3.4.1 Slump Test

Slump test is an essential assessment that is mandatory to ensure that the workability of the concrete is within the desired range. The test allows researchers to determine the degree of workability of concrete samples by measuring the height of the slump produced by the concrete mix before concrete is being cast. It is done for concretes for both trial mixing and actual experimental mixing.

The test was started by filling the concrete mixture into the mould that is with a cone shape and the mixture is placed inside into 3 layers. For each of the concrete layers, they were required to be compacted evenly for 25 times with the use of tamping rod. After that, small portions of concrete in excess were eliminated from the top of the mould by utilizing trowel. After the removal of unwanted concrete, the mould was allowed to face the base plate while releasing the concrete from the mould at the same time by turning it downwards instantaneously. The separation vertical distance between the height of the mould and the released concrete was measured and the slump value was acquired. Figure 3.8 below illustrates the slump test for concrete.

Figure 3.8: Slump Test for Concrete (Daily Civil, 2018)

3.4.2 Compression Test

The compression test for concrete cube samples is one of the evaluation methods for the compressive strength of concrete which is devised and based on the standard procedures in ASTM C109. The process of obtaining the strength value involves the analysis of the strength development phases. It requires 3 sets of samples for 3 different maturity periods which are 1 day, 7 days and 28 days. Concrete samples with 100 mm x 100 mm x 100 mm size were used for this experimental test.

To execute this test, the concrete cubes that were initially in the curing tank were removed. This step was necessary to make sure that the concrete samples are in saturated surface dry (SSD) conditions. For each of the set of samples, 3 concrete cube specimens were tested for 1 days, 7 days and 28 days respectively to determine their compressive strengths so that the average value between the 3 results can be acquired. The concrete cubes were tested by positioning them onto the compression machine and the machine was operated to enable the samples to receive compression force. The compression process was done in a uniform manner until structural failure occurs and the pressure value displayed on the compression machine was the maximum load capacity. Figure 3.9 shows the compression machine used to assess the concrete cubes.

Figure 3.9: Compression Machine for Cube Test

3.5 Elastic Wave Method

This method is an NDT test that utilizes electronic instruments such as data logger and piezoelectric transducers which involves the use of software for data analysis in the correlation phase. For this test, it is carried out for 1 day, 7 days and 28 days like the compression test except that it does not require as many specimens. Figure 3.10 shows a more advanced version of data logger that is connected to a laptop.

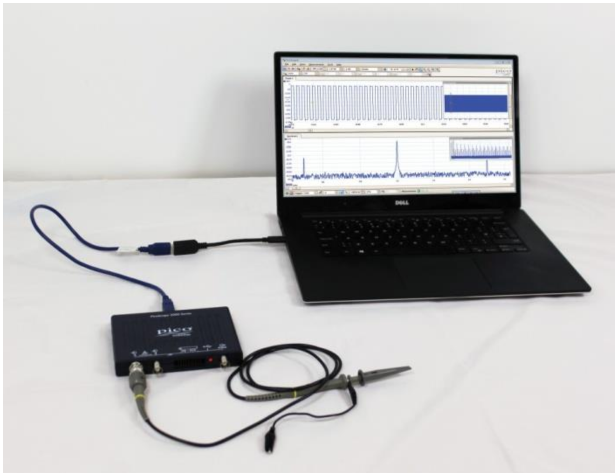

Figure 3.10: Data logger connected to a laptop (Picotech, 2018)

At first, the piezoelectric transducers were connected to a portable computer with installed software called Labview Signal Express and a data logger that has cables attached to the computer to conduct wave analysis. When the cable attachments were done, the piezoelectric transducers were dropped with coupling agent wax and attach to the surface of the specimens as shown in Figure 3.11. After that, the steel ball was used to hammer the specimens. The impact on the specimens is known as impact echo, causing the production of elastic waves moving through or within the specimens. Then, the analysis of elastic waves was started to observe the formation of the wave.

For this elastic wave test, the assessment of elastic wave generated within the concrete cube samples is most suited to be done with the adoption of direct transmission method as it is one of the most acceptable ways of arranging the piezoelectric sensors due to the fact that the wave travels in a path that is normal to the face of sensors (Abo-Qudais, 2005). While for indirect wave transmission, the positions of the piezoelectric receiver and transmitter are placed on at least two specimen surfaces for measurement of time and distance propagated.

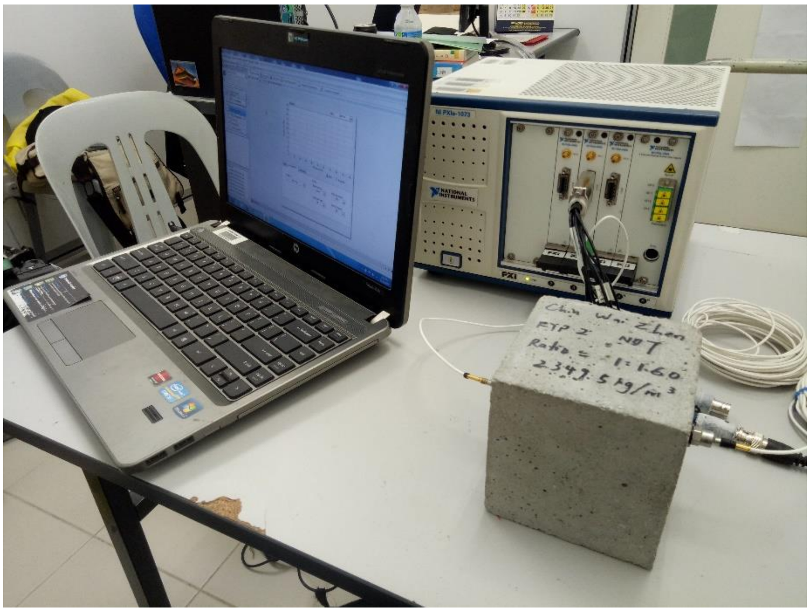

Figure 3.11: Experimental set up of data logger and piezoelectric transducer

3.5.1 Measurement of Elastic Wave Velocity

To compute the velocity of the P-wave generated for this test, the formula used follows the standards of ASTM C 597. When the transmitted wave traverses across the regions within the specimen, it is changed into electrical energy and this conversion is achieved with the use of a second transducer positioned at a travel path length, where the wave propagates from the first transmitting transducer (ASTM, 2002). By the application of electronic functions embedded in the system, the wave transmission time is computed for velocity determination using the formula below.

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (3.1)$$

where:
$E =$ dynamic modulus of elasticity, GPa
$\mu =$ dynamic Poisson's ratio
$\rho =$ density of concrete samples, kg/m^3

3.6 Summary

For the entire experiment, it involved two main tests which are the compression test and the elastic wave test that features 60 cube samples with the dimension of 100 mm x 100 mm x 100 mm and the control factor utilized is the fine aggregate/coarse aggregate ratio, where 12 samples are required for each of the ratio values. Among these samples, 9 of them were tested using compression test to obtain the compressive strength while the remaining one was used for the P-wave assessment using elastic wave method with the aid of data logger and Labview Signal Express software and both tests are carried out for 1 day, 7 days and 28 days. The correlation of compressive strength was done by comparing the values and conduct analysis with the elastic wave parameters.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The following chapter illustrates and describes the results and answers extracted from a series of tests, which includes the ordinary material tests and non-destructive tests. For laboratory material test, it consists of concrete compression test and slump test while for non-destructive test, the test that was carried out is the impact-echo test using the national instrument.

4.2 Laboratory Material Test

The tests that are necessary to be conducted in the laboratory are slump test and compression test as stated above. These tests are designed with different proportions for each of the concrete cubes to study the compressive strength, as well as the workability of the specimens. The mixing proportions are displayed in table 4.1.

Table 4.1: Different mixing proportions for concrete cubes.

Fine to coarse ratio	1:1.60	1:1.64	1:1.68	1:1.72	1:1.76
Mass of cement (kg/m^3)	350	350	350	350	350
Mass of water (kg/m^3)	210	210	210	210	210
Mass of fine aggregate (kg/m^3)	707.66	696.81	686.50	676.38	666.63
Mass of coarse aggregate 4.75-10mm (kg/m^3)	566.17	571.60	576.75	581.81	586.68
Mass of coarse aggregate 10-20mm (kg/m^3)	566.17	571.60	576.75	581.81	586.68

Prior to conducting any analysis to the results obtained, each set of samples is defined accordingly based on their respective fine aggregate to coarse aggregate ratio. The characterizations are shown in Table 4.2 below.

Table 4.2: Naming of samples based on fine aggregate to coarse aggregate ratio

Sample	Fine aggregate to coarse aggregate ratio
S1	1:1.60
S2	1:1.64
S3	1:1.68
S4	1:1.72
S5	1:1.76

4.2.1 Slump Test

Slump test is one of the common tests that are carried out to determine if the workability of the concrete mixture is adequate for casting or not. The drop of slumps indicates the workability of the fresh concrete. This is to ensure that the concrete casting can be carried out smoothly with minimal problems when the specimens start to harden. Problems that may occur due to low workability are excessive voids and honeycomb effects due to segregation while a concrete that has higher workability that the optimum range may be unable to achieve the minimum strength. For this study, the 5 different mixing proportions managed to pass the slump test by achieving the minimum slump requirement of 10 t0 30 mm. This means that the concretes have sufficient workability.

4.2.2 Compression Test

Compression test is another essential test that needs to be carried out for the concrete samples using the compression machine in the laboratory. The dry density and the compressive strength for different fine aggregate to coarse aggregate ratios of concretes for day 1, day 7 and day 28 are shown in Tables 4.3, 4.4 and 4.5.

Table 4.3: Compressive strength for different samples for day 1.

Sample	Oven dry density (kg/m³)			Compressive strength (MPa)			Average dry density (kg/m³)	Average compressive strength (MPa)
	1	2	3	1	2	3		
S1	2112	2302.5	2234.5	4.54	5.28	4.87	2216.33	4.90
S2	2228	2260	2231.5	5.11	5.45	4.72	2239.83	5.09
S3	2156	2123.5	2169.5	5.95	5.69	6.48	2149.67	6.04
S4	2170	2157.5	2127.5	6.73	7.14	7.61	2151.67	7.16
S5	2224.5	2164	2104.5	7.37	8.15	7.92	2164.33	7.81

Table 4.4: Compressive strength for different samples for day 7.

Sample	Oven dry density (kg/m³)			Compressive strength (MPa)			Average dry density (kg/m³)	Average compressive strength (MPa)
	1	2	3	1	2	3		
S1	2135	2307.5	2258.5	19.71	24.00	23.24	2233.67	22.32
S2	2246	2273.5	2259.5	22.86	23.13	21.49	2259.67	22.49
S3	2174.5	2143.5	2188.5	21.86	20.34	19.21	2168.83	20.47
S4	2164	2174.5	2151.5	20.95	22.19	29.15	2163.33	24.10
S5	2245.5	2183	2122	19.52	27.57	26.57	2183.50	24.55

Table 4.5: Compressive strength for different samples for day 28.

Sample	Oven dry density (kg/m³)			Compressive strength (MPa)			Average dry density (kg/m³)	Average compressive strength (MPa)
	1	2	3	1	2	3		
S1	2283	2228	2185.5	27.33	37.07	30.80	2232.17	31.73
S2	2232	2257	2253	31.39	29.47	28.66	2247.33	29.84
S3	2276.5	2275.5	2140.5	35.62	24.15	38.36	2230.83	32.71
S4	2286	2191.5	2306.5	38.14	36.86	31.31	2261.33	35.44
S5	2193.5	2266.5	2288	35.62	34.41	29.36	2249.33	33.13

Based on the results obtained in the tables above, it is clearly seen that the compressive strength increases as the fine aggregate to coarse aggregate ratio increases. For day 1 specimens, the compressive strength increases a little with the variable from 4.90 to 7.81 MPa. The strength values for day 7 concrete do not see an increase when it comes to S3 with 1:1.68 fine aggregate to coarse aggregate ratio. This occurrence is explained by the strong possibility that the specimens were not mixed evenly during the casting process, which leads to poor hardening that reduces the strengths. The strengths range from 22.32 to 24.55 MPa. For day 28 concrete samples, it is observed that the compressive strengths for S4 and S5 are higher than the other 3 concrete samples despite that the samples do not illustrate a clear increase in the strengths. They range from 29.84 to 35.44 MPa.

Besides that, all ratios of concretes demonstrate significant increases in compressive strength throughout time. This is because concrete undergoes maturity as time goes by from day 1 until day 28. To give a better illustration, the concrete specimens for S1 increases from 4.90 MPa to 22.32 MPa and finally 31.73 MPa for day 1, day 7 and day 28 respectively. On the other hand, the concrete specimens for S5 show a steady rise from 7.81 MPa to 24.55, then to 33.13 MPa for day 1, day 7 and day 28 respectively. Figure 4.1 demonstrates a concrete sample that has undergone compression test and experienced failure.

Figure 4.1: Concrete cube sample after undergoing compression test

4.3 Non-destructive Impact Echo Test

For this particular test, 3 types of parameter are extracted and analysed. These parameters are amplitude, velocity and frequency which are obtained from the raw data graphs generated in software upon testing the concrete samples. Each of these wave characteristics is then computed together and studied in detail based on the variable properties of the concrete samples. A steel ball with a diameter of 15 mm is used to carry out the impact echo test.

4.3.1 Wave Amplitude

As the elastic wave is formed and propagates throughout a medium, its energy level decreases gradually due to the dissipation of energy that occurs due to travelling in a medium. As a result, the longer the distance of travel of the wave, the higher is the energy loss experienced by that particular wave. The energy level is indicated as the amplitude of the wave in the analysis.

To observe and study the elastic wave, a software known as the Labview Signal Express 2011 is being used to record the data regarding the wave with the help of sensors. The software displays a graph of amplitude over time which the amplitude values can be extracted from it. Each of the cube specimens is being hit for 10 times for a total of 10 iterations so that 10 amplitude values are acquired.

Taking the concrete cube with fine aggregate to coarse aggregate ratio of 1:1.68 which is S3 as an example, the behavioural changes of the elastic wave can be seen clearly. The amplitude of P-wave undergoes a noticeable increase from day 1 to day 7 and finally day 28. For day 1, the average value of the amplitude of P-wave is 0.007286 m for sensor 0 and 0.002632 m for sensor 1. Moving on to day 7, the average amplitudes are significantly higher, which is 0.008873 m for sensor 0 and 0.002958 m for sensor 1. For day 28, the amplitudes are the highest among the 3 days, which are 0.013488 m and 0.009423 m for sensor 0 and sensor 1 respectively. For the rest of the concrete samples with different fine aggregate to coarse aggregate ratios, the changes are observed to be very similar as well. To make a rough conclusion, it is fairly certain that the P-wave amplitude increases over maturity time. The P-wave behavioural changes for day 1, day 7 and day 28 are illustrated visibly in the acceleration vs time graphs in Figures 4.2, 4.3 and 4.4.

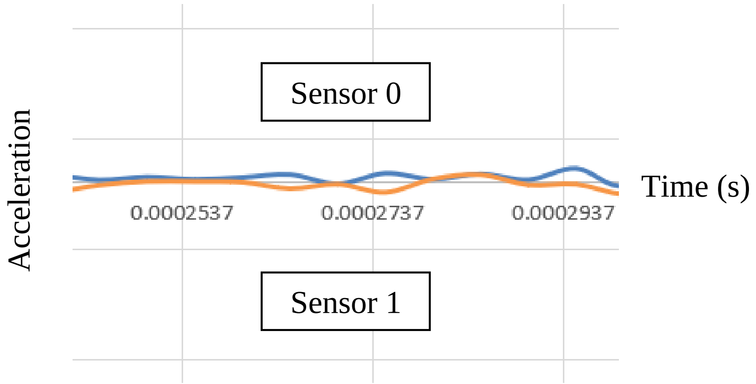

Figure 4.2: Acceleration vs time for day 1 maturity (S3)

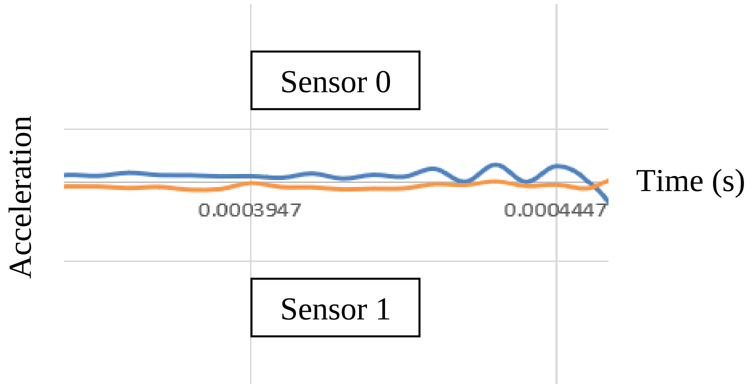

Figure 4.3: Acceleration vs time for day 7 maturity (S3)

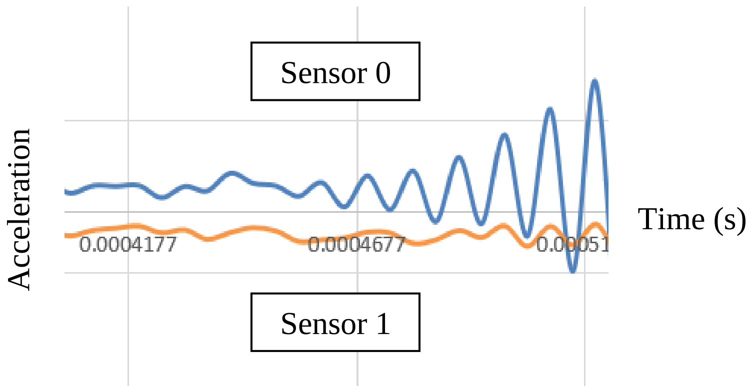

Figure 4.4: Acceleration vs time for day 28 maturity (S3)

4.3.2 Wave Frequency

Frequency of any type of wave can be defined as the number of waves that propagate through a known distance in a particular time period. The fundamental unit that is used for this parameter is Hertz (Hz). In layman's term, one unit of Hz means one wave per unit second.

During the NDT test, the Labview Signal Express software records the frequencies of the elastic wave in the spectrum graph, or sometimes known as the power spectrum. This graph is in the form of amplitude vs frequency, which displays the distribution of energy levels according to different wave periods. The frequency where the amplitude is at its peak level is known as the dominant frequency which contains the largest energy level while fundamental frequency has the lowest energy level. To study this, the spectrum graphs for day 1, day 7 and day 28 are compared in detail and results for cube specimen S3 with fine aggregate to coarse aggregate ratio of 1:1.68 is used. For this comparison, a steel ball with a diameter of 15 mm is used as usual. Figure 4.5 displays the spectrum graphs for each of the days.

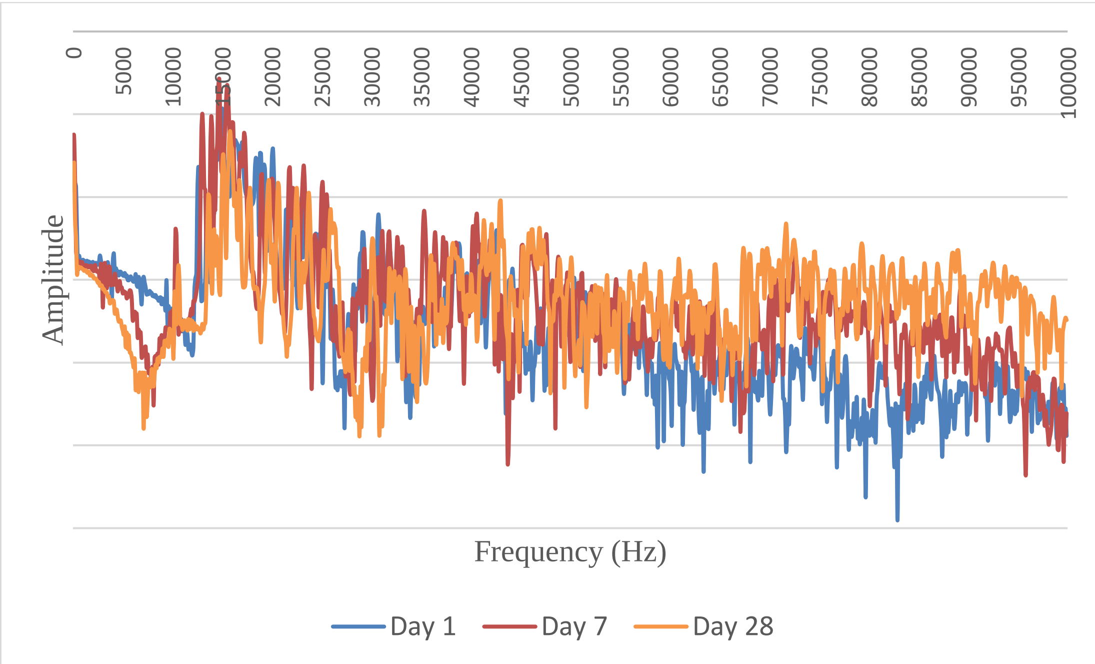

Figure 4.5: Comparison of spectrum graphs for day 1, day 7 and day 28 (S3)

From this figure alone, the difference between the 3 graphs is simply noticeable. It is observed that the dominant frequency range for this particular specimen is between 10000 to 20000 Hz whereas the fundamental frequency range falls in the region of 70000 to 85000 Hz. The average dominant frequency of this sample is the highest at day 28 which is 15613.33 Hz while lowest when it is in the maturity of day 7 which is 14676.67 Hz. This comparison also demonstrates that the wave that propagates in day 28 sample carries a significantly higher average energy level for every frequency compared to day 1 and day 7. Besides, day 28 sample also has a lower fundamental frequency than day 1 and day 7 sample.

4.3.3 Wave Velocity

The velocity of the wave is the parameter that indicates how fast the wave moves along a medium. P-wave is the fastest wave among other types of wave and comparing to those waves, it has the lowest amount of energy. To compute the velocity of P-wave, the location of P-wave point is determined from the acceleration vs time graph generated from software. Once the P-wave point is located for both sensor 0 and sensor 1, the travel time is obtained. Then, the distance travelled by the wave is acquired by averaging the widths of the concrete specimen. By dividing distance travelled (d) by time taken for the wave to travel to its destination (t), v = d/t, the velocity is then computed.

It is discovered that the velocities of the P-wave follow a significant trend throughout the whole NDT test. The velocities increase with the maturity time of the concrete for most cases. However, due to some mixing problems during concrete casting, it is not the case for a minority of concrete specimens. The results for every specimen are tabulated in tables below. Table 4.6 shows the distance travelled by the wave for each of the cube specimens while Table 4.7 shows the velocity of P-wave for day 1, day 7 and day 28, as well as the average velocity of P-wave for each fine aggregate to coarse aggregate ratios.

Table 4.6: Average distance travelled for different concrete cubes

Sample	**Average distance travelled, d (mm)**				
	S1	**S2**	**S3**	**S4**	**S5**
1	97.0	100.0	100.0	98.0	99.0
2	96.5	101.0	99.0	98.0	99.0
3	98.5	100.5	101.0	99.0	97.5

Table 4.7: Velocity of P-wave for day 1, day 7, day 28 and corresponding average

Sample	**Velocity for day 1 concrete cubes (m/s)**				
	S1	**S2**	**S3**	**S4**	**S5**
1	2852.9412	2857.1429	3076.9231	4083.3333	3535.7143
2	2643.8356	2623.3766	3193.5484	3563.6364	3960.0000
3	2462.5000	3465.5172	3884.6154	3473.6842	4333.3333
Sample	**Velocity for day 7 concrete cubes (m/s)**				
	S1	**S2**	**S3**	**S4**	**S5**
1	4619.0476	4444.4444	4395.3191	4900.0000	5657.1829
2	4386.3636	3482.7586	3666.6667	6322.5806	5076.9231
3	3716.9811	5153.8462	4590.9091	5823.5294	6724.1379
Sample	**Velocity for day 28 concrete cubes (m/s)**				
	S1	**S2**	**S3**	**S4**	**S5**
1	5542.8571	6060.6061	5263.1579	6758.6207	6387.0968
2	7148.1481	6733.3333	5823.5294	6322.5806	7333.3333
3	5324.3243	4902.4390	7481.4815	7615.3846	8863.6364
Sample	**Average velocity for day 1, day 7 and day 28 cubes (m/s)**				
	S1	**S2**	**S3**	**S4**	**S5**
Day 1	2653.0923	2982.0122	3385.0290	3706.8846	3943.0159
Day 7	4240.7974	4360.3497	4217.6316	5682.0367	5819.4013
Day 28	6005.1098	5898.7928	6189.3896	6898.8620	7528.0222

4.4 Data Correlation and Discussion

The relationships between compressive strength of concrete and P-wave properties are certain to be inevitable. Parameters such as amplitude, velocity and frequency are put together with their corresponding compressive strength data to undergo correlations. Different approaches are used to evaluate and assess the correlation processes depending on the factors and standards regarding the specimens.

4.4.1 Correlation with P-wave Amplitude

For this case, the amplitudes that are extracted from P-wave data are placed in comparison with compressive strengths for all 5 sets of concrete cubes with different fine aggregate to coarse aggregate ratios, and each of these sets of specimens consists of 3 specimens each for day 1, day 7 and day 28. The graphs that are formulated are P-wave amplitude versus compressive strength. These methods that are incorporated into the correlation is correlation regardless of factors, correlation by comparing different sensors, and correlation by comparing different maturity days.

4.4.1.1 Correlation Regardless of Factors

Using this method of assessing both wave and compressive strength data, the idea is to insert every single average value of amplitudes into one single chart according to their respective compressive strengths without separating them into different charts. This is an effective way to observe if all these amplitude values are following a single pattern or not, which is a good way to study every single data together. For this case, a single graph of P-wave amplitude versus compressive strength is plotted as shown in Figure 4.6.

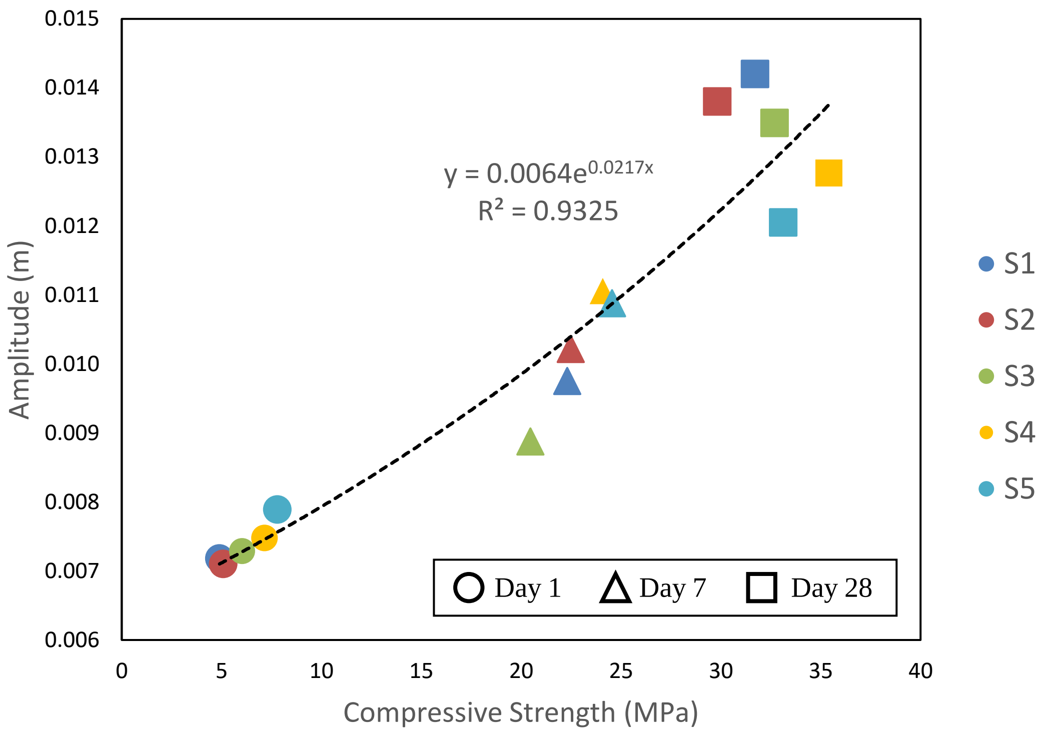

Figure 4.6: Correlation between Amplitude and Compressive Strength for All Data Points in One Graph

By observing Figure 4.6, the pattern of the changes of these data is obvious. In other words, the amplitudes of P-wave follow an incremental trend line with the compressive strength data. The trend line shows a smooth incremental curve from day 1 to day 7 and then day 28. This also means that the energy level of P-wave increases as the compressive strength of specimen increases regardless of any factors. To explain this in terms of wave analysis, the energy level of P-wave increases because the rate of energy dissipation is getting lower when compressive strength increases. The trend line above can be represented by an exponential function of $y = 0.0064e^{0.0217x}$. Besides, it has a high coefficient of correlation, R^2 of 0.9325. As R^2 is much higher than the minimum acceptable value of 0.8, this correlation is said to be suitable for this particular function and trend line.

When analysing Figure 4.6, it is noted that the are 3 noticeable data saturation regions in the graph, which are observed to be day 1, day 7 and day 28 data. To discuss this phenomenon, one of the reasons is because the differences in fine aggregate to coarse aggregate ratio between the 5 sets of data is small, which only has a minor difference of 0.4. This causes the differences in amplitude for the data in each of the respective days to be insignificant, especially for day 1 results. By comparing day 1, day 7 and day 28 results in a different angle, the curing and hardening period for day 28 is higher than day 7 while day 7 samples had undergone longer curing when it is being compared with day 1 samples. This proves that the curing and hardening period are the significant factors that affect the wave amplitude.

In terms of science, this occurrence is unavoidable because as concrete undergoes maturity throughout time, it experiences hardening and curing that causes a chemical reaction that binds water with cement and aggregate. As time goes by, the hydration process causes the formation of calcium-silicate-hydrate (C-S-H). These crystals of C-S-H fills up the empty spaces within the concrete when hydration is completed, which leads to reduction of voids. As concretes in day 28 have undergone a longer curing period, more void spaces have been occupied compared to day 1 and day 7 samples. As the wave travels throughout the concrete, energy is lost due to penetration of air in void spaces. This explains why the amplitude of concrete samples in day 28 is considerably higher than day 7 and a similar case is seen for comparison between day 1 and day 7 specimens.

Despite the observable trend in the graph, it is reminded that this correlation between wave amplitude and compressive strength may not have a high accuracy. This is due to the fact that concrete is a type of heterogeneous compound. Depending on the mixing process, the concrete formed is usually having a distribution of aggregates that is not uniform. The uneven binding of the particles of cement and aggregate significantly influences the energy level of the elastic wave generated due to formation of voids that can easily distort the amplitude readings.

4.4.1.2 Correlation by Comparing Different Sensors

During the test, 2 sensors are used to obtain the P-wave data since the method of placement of sensors is the direct transmission method. For this correlation, the P-wave amplitude versus compressive strength graph for sensor 0 is compared with sensor 1, and then their average too. This is to observe the difference and available at any changes that are significant between the 2 different sensors. A total of 3 graphs are formulated for the amplitude data of sensor 0, sensor 1 and the average of these sensors as shown in Figures 4.7, 4.8 and 4.9.

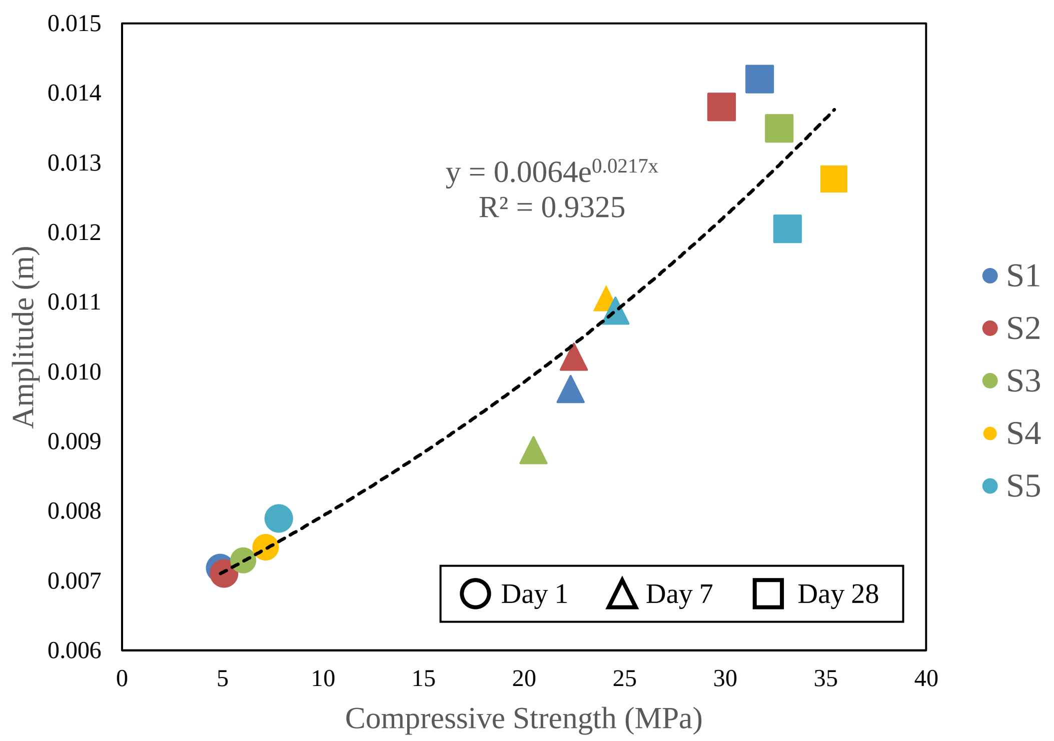

Figure 4.7: Correlation between Amplitude and Compressive Strength for Sensor 0

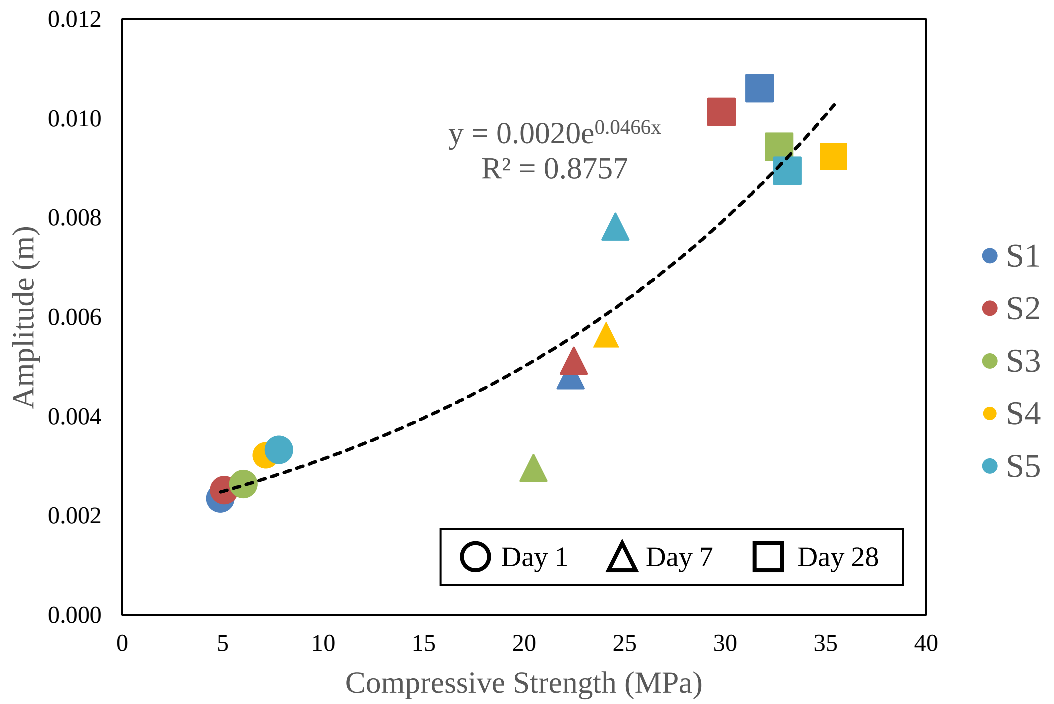

Figure 4.8: Correlation between Amplitude and Compressive Strength for Sensor 1

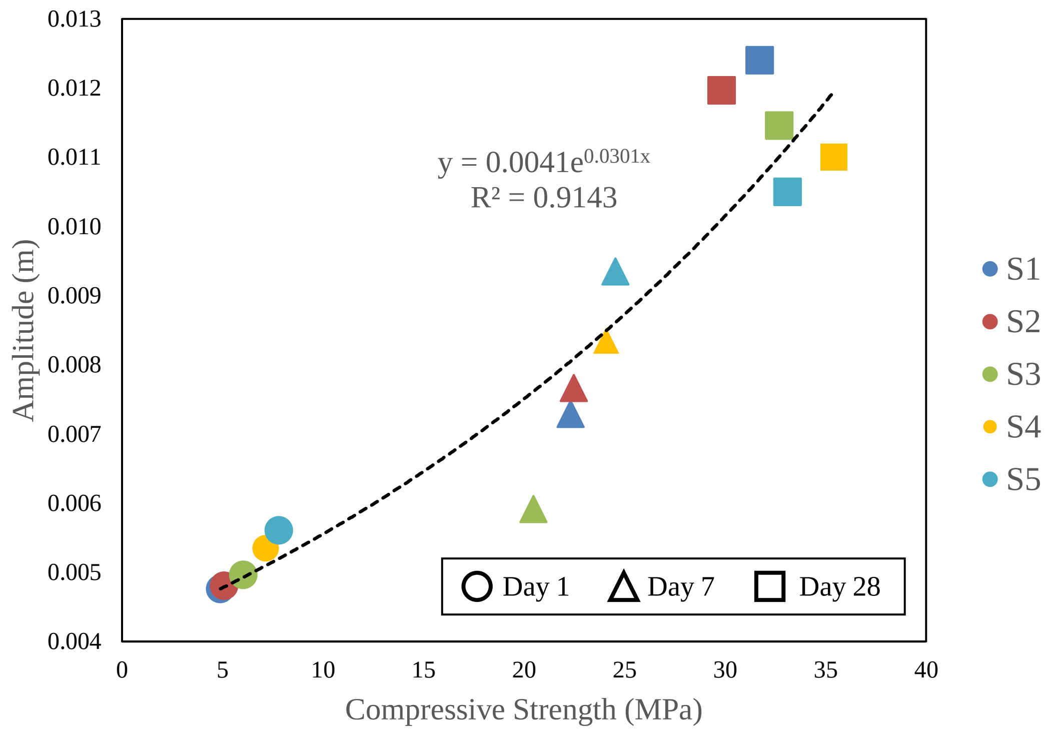

Figure 4.9: Correlation between Amplitude and Compressive Strength for the Average of Sensor 0 and Sensor 1

While assessing the patterns in these 3 figures, all the graphs show a similar trend which is an increasing curve. These graphs are very alike when compared with the first graph in section 4.4.1.1 as expected. The amplitude values increase along with their respective compressive strengths too. While all the trend lines are having exponential functions, their correlation accuracies are not the same. For sensor 0, the trend line has a function of $y = 0.0064e^{0.0217x}$ as stated in the section above with R^2 of 0.9325. For sensor 1, the exponential function is different, which is $y = 0.0020e^{0.0466x}$ with R^2 of 0.8757. When averaging the values from both sensors, a new graph with the trend line equation of $y = 0.0041e^{0.0301x}$ and a R^2 value of 0.9143 is generated.

Comparing the amplitudes of P-wave for sensor 0 and sensor 1, it is noticed that the differences are quite significant. The amplitudes that are recorded at sensor 0 is greater than those from sensor 1. This is due to the different locations of the sensors during the test. As sensor 0 is placed on the surface which the impact force is received while sensor 1 is positioned on the opposite surface of the specimen, the rate of dissipation of energy of the wave recorded by sensor 0 is lower than sensor 1. When wave travels along the medium, it undergoes energy loss which reduces the amplitude values. The longer the travel distance, the higher is the rate of energy loss. Since sensor 0 is nearer to the location of impact, the energy level of the generated wave is still high compared to when it reaches sensor 1 after travelling a certain distance, which produces greater amplitude readings.

To make a simple conclusion among the 3 graphs, it is safe to say that the graph for sensor 0 is the most suitable graph to be used for correlation. Apart from the obvious reason that it has the highest R^2 value, it is best suited because of the nature of concrete which is heterogeneous. As concrete has an uneven distribution of aggregates and sometimes contains voids within the structure, the method of placing sensor near to the force of impact has the possibility to reduce the unwanted energy loss. Besides that, even though the graph of the average of the 2 sensors appears to be more uniform, it still possesses a lower R^2 value than the graph for sensor 0. Thus, it is concluded that the first graph is more appropriate for correlation.

4.4.1.3 Correlation by Comparing Different Maturity Days

Maturity of concrete plays a significant role in the changes occur in the wave amplitude. When the results are separated according to their maturity days, there are possibilities that a certain pattern can be observed and studied in those graphs. Therefore, 3 graphs of P-wave amplitude versus compressive strength are plotted with different maturity days as shown in Figure 4.10, 4.11 and 4.12.

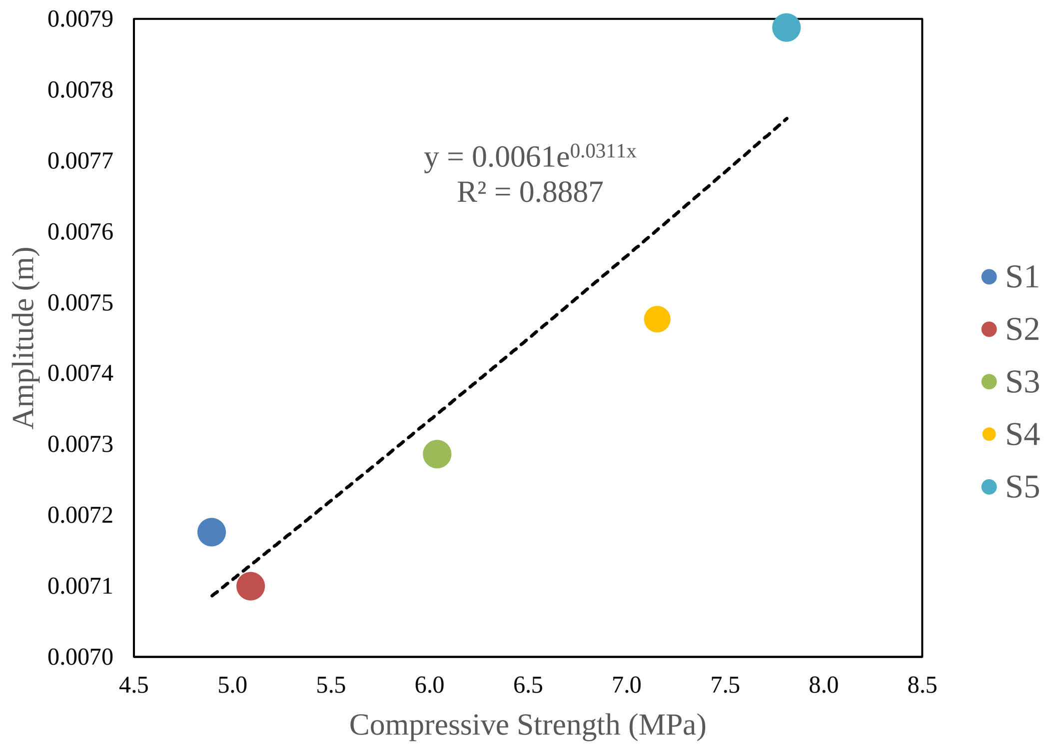

Figure 4.10: Correlation between Amplitude and Compressive Strength for Day 1

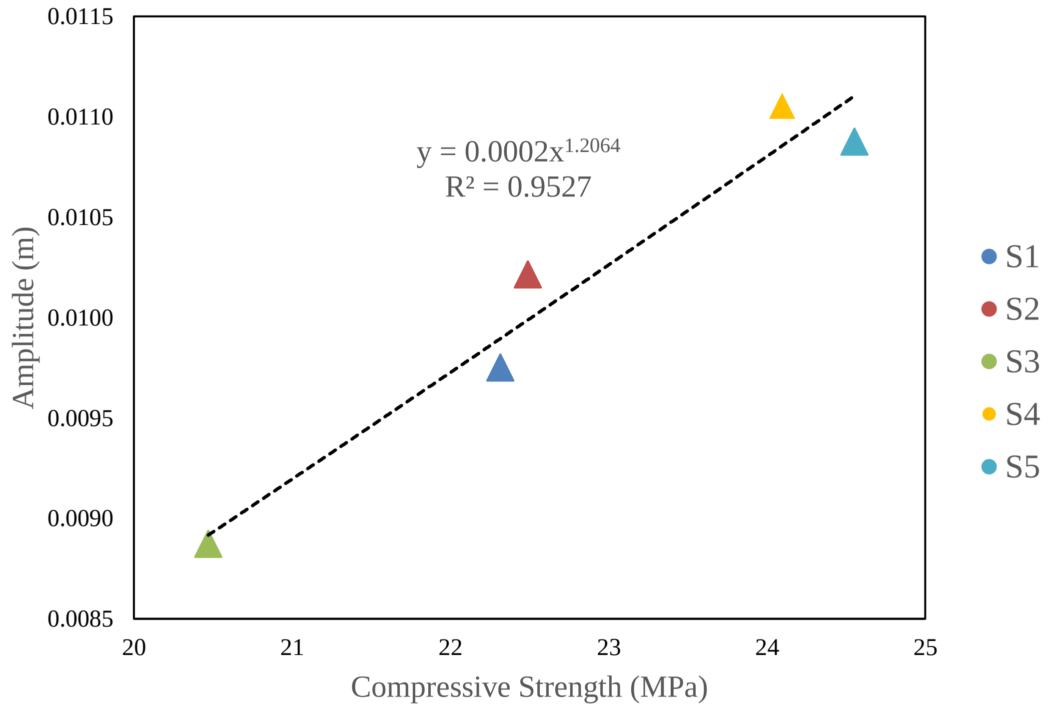

Figure 4.11: Correlation between Amplitude and Compressive Strength for Day 7

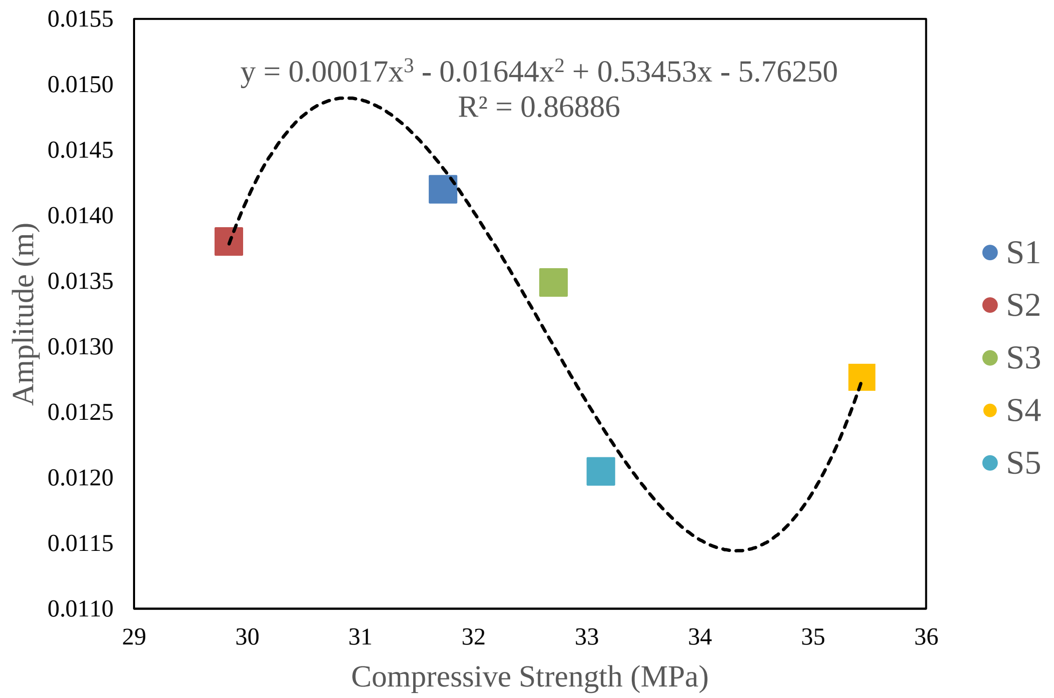

Figure 4.12: Correlation between Amplitude and Compressive Strength for Day 28

Based on the 3 figures, it is discovered that they are not showing the same type of trend lines as the previous correlations. This is clearly seen especially in the day 28 graph. While both day 1 and day 7 graphs demonstrate an increasing pattern with a curve, day 28 shows a rather interesting pattern that is not so reliable. It is noted that day 1 graph generates an exponential trend line with the equation of $y = 0.0061e^{0.0311x}$, while its R^2 value is 0.8887. For day 7, the graph produces a trend line with the power function of $y = 0.0002x^{1.2064}$ with R^2 of 0.9527. For day 28, the trend line produced shows an increase in its power up to power of 3 in the function which is $y = 0.00017x^3 – 0.01644x^2 + 0.53453x – 5.76250$ with a lower R^2, which is 0.86886.

In this correlation, the patterns produced by these graphs are not similar. Nevertheless, they show the same findings, that higher compressive strength yields a larger amplitude value. This is inevitable despite the unusual trend line illustrated by the graph for day 28. As described before, the voids in concretes that undergoes longer hardening and curing period are significantly less compared to those early age concretes, which yield waves that have higher amplitude readings.

To analyse the difference that presents in day 28 graph, the fundamentals of wave energy are brought up for discussion. Despite the fact that this particular graph displays a trend line that contradicts with the other 2, there is a hidden pattern that exists in the graph. It is noticed that the amplitude of P-wave decreases slightly along with the increase of fine aggregate to coarse aggregate ratio. This is because as the amount of coarse aggregate increases, the amount of void space increases too, making the wave that propagates in the concrete to be vulnerable to higher energy loss. As a result, the amplitude value decreases. This is hard to observe for specimens in day 1 and day 7 maturities because the specimens are still halfway along the process of hardening and curing. This means that the distribution of voids is very uneven and unable to display a pattern that is alike to day 28 samples.

To select the most suitable graph to be used for correlation, the graph for day 7 maturity seems to be the best choice since it has the highest R^2 value. Despite this, it is worth to take note that each of these graphs only has 5 data points which are barely the minimum points needed for graphs. The value of R^2 itself is not enough to prove that the correlation is a good analysis due to a smaller number of data points as lower data points decrease the accuracy of the trend line. Moreover, the difference in fine aggregate to coarse aggregate ratio between the 5 sets of the result is too small to show a significant pattern. In overall, choosing day 7 maturity graph is a good choice among these graphs but either of these graphs possesses lower accuracy as compared to the previous 2 correlations.

4.4.1.4 Summary

In a nutshell, the first correlation using sensor 0 is the most reliable and suitable method to analyse the P-wave velocity with concrete compressive strength. This is because it has a high R^2 that is more than 0.9. Apart from that, the correlation disregards any limitation and factors and puts every single data point into one graph, yielding a more uniform evaluation of data. This provides researchers with a better overall correlation that suits most cases because it does not limit to a certain type of study when it comes to P-wave velocity.

4.4.2 Correlation with P-wave Velocity

To obtain the P-wave velocity, the formula of v = d/t is applied, where d is the propagated distance of the wave which is represented by the average specimen width, while t is the difference in arrival time. Graphs of P-wave velocity versus compressive strength are plotted for the analysis purpose. For this particular circumstance, there are 2 ways of conducting correlation, which are correlation regardless of factors and correlation by comparing different maturity days.

4.4.2.1 Correlation Regardless of Factors

As discussed before in a similar case for amplitude, this approach has the major advantage of assessing all wave velocity data together with their respective compressive strengths in a single graph, thus enabling researchers to perform an overall analysis in a convenient way. A graph of P-wave velocity versus concrete compressive strength is plotted as demonstrated in Figure 4.13.

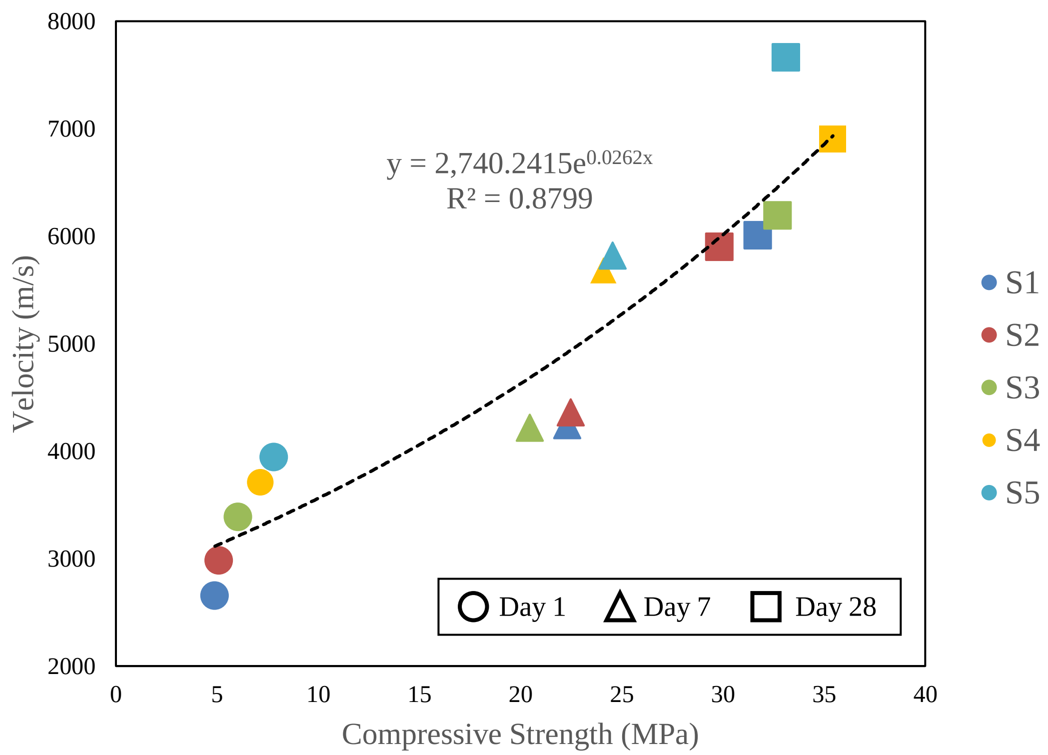

Figure 4.13: Correlation between Velocity and Compressive Strength for All Data Points in One Graph

According to this graph alone, all these data points are represented by a single trend line that fits a certain pattern. It shows a smooth increasing curve that demonstrates how the wave velocity increases as the compressive strength increases. Besides, the graph shows that the velocity of these data points increases from maturity of day 1 to day 7 and then day 28. For day 1 concrete specimens, the velocities range from 2653.0928 m/s to 3943.0159 m/s. For day 7, it has a range with greater velocities which is from 4217.6316 m/s to 5819.4146 m/s while day 28 concrete cubes demonstrate an increase in velocities, which fall in between 5898.7928 m/s to 7661.3555 m/s. In other words, the wave velocity undergoes a gradual increase along with the compressive strength of concrete. By observing this graph, it means that velocity is strongly related to compressive strength.

Analysing the data in terms of correlation factor, the trend line has an exponential function, which is governed by the equation of $y = 2740.2415e^{0.0262x}$. For the coefficient of correlation, the graph has a R^2 value of 0.8799 that passes that minimum requirement of 0.8. This means that this trend line is suitable for these data points. By just looking at the extracted data without plotting any graphs, the increasing trend of wave velocity with concrete strength is noticeable. The P-wave is able to travel at a faster speed as the concrete has higher compressive strength due to the changes that occur within the structure of the concrete that in turn leads to the increase in its strength.

To breakdown the analysis into pieces, the structural changes that happen within the concrete are a major discussion to explain the correlation. Besides maturity age, the porosity of the concrete is an important aspect that can be related to the relationship of this graph. It is noted that since concrete is considered a porous compound, the porosity has a greater tendency of affecting its material strength as it has a strong connection with the presence of air voids too (Lian *et al.*, 2011). As concrete ages, it hydrates even further and forms a matrix skeleton that links the aggregates together, which in turn reduces the internal pores of the concrete. As a result, this reduction in porosity raises the compressive strength of concrete. At the same time, the area that is required for P-wave to propagate is reduced, leading to a significant drop in the arrival time and increases the wave velocity.

To summarise this particular correlation, this graph supplies adequate information to show that it is suitable to be used for correlation. Apart from its high R^2 value, the relationship between P-wave velocity and compressive strength of concrete is strongly linked together too, making P-wave velocity a great selection when doing analysis with concrete strength.

4.4.2.2 Correlation by Comparing Maturity Days

By separating the data points based on their respective maturity days, the scope of study is being focused more on the fine aggregate to coarse aggregate ratio. Aiming to achieve this purpose, a total of 3 graphs of P-wave velocity versus compressive strength are generated, each with their separate data points according to their maturity days. These graphs are shown in Figures 4.14, 4.15 and 4.16.

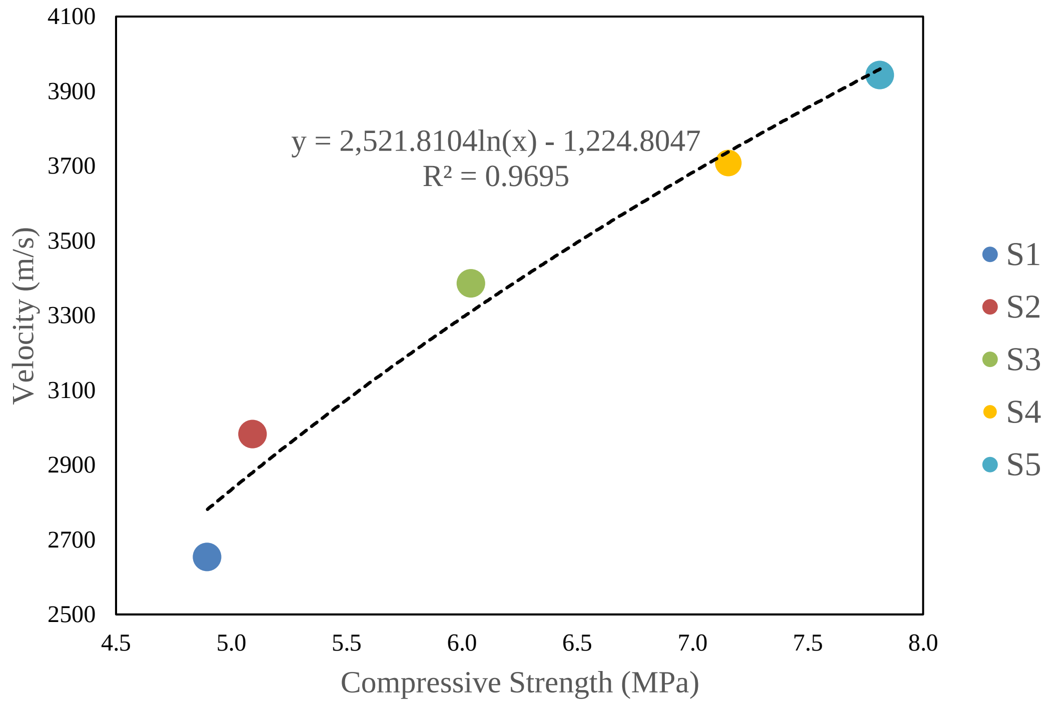

Figure 4.14: Correlation between Velocity and Compressive Strength for Day 1

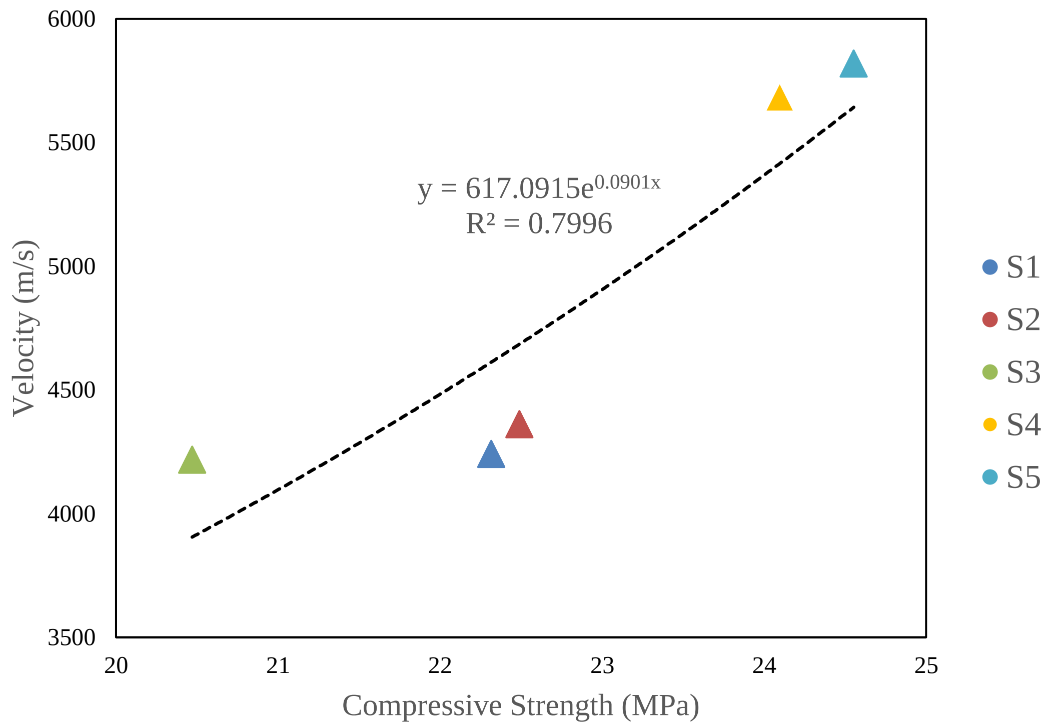

Figure 4.15: Correlation between Velocity and Compressive Strength for Day 7

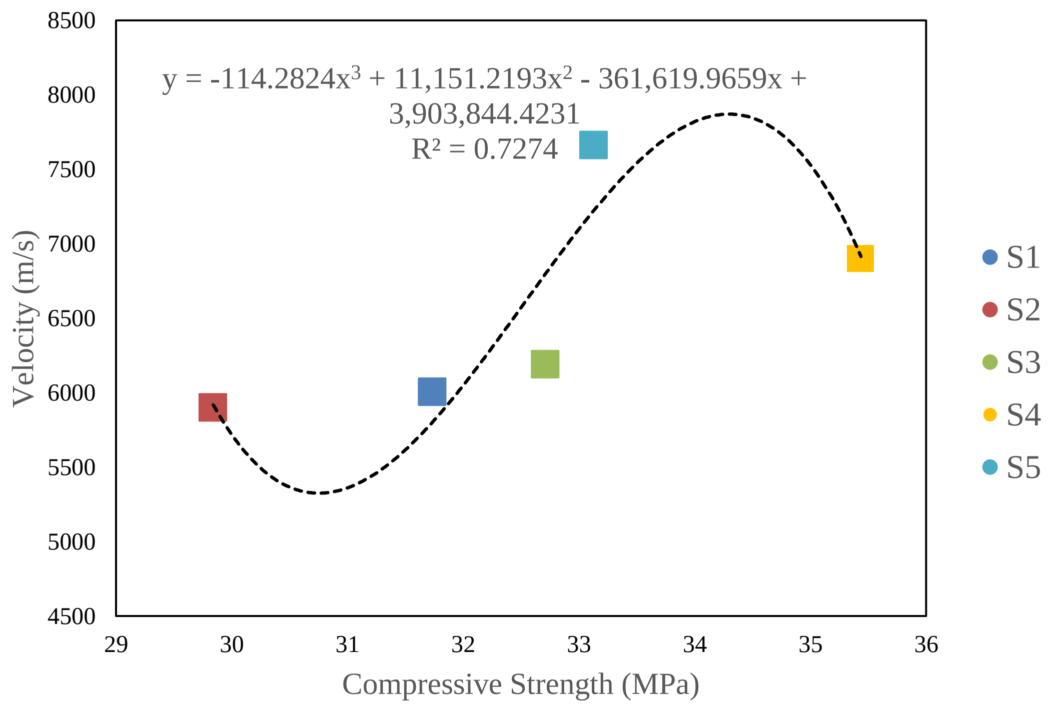

Figure 4.16: Correlation between Velocity and Compressive Strength for Day 28

From these figures, it is obvious that the first 2 graphs for day 1 and day 7 are showing a similar type of trend line while the last graph which is day 28 displays an unusual pattern. In terms of correlation of coefficient, day 28 graph does not achieve the acceptable requirement of 0.8. For specimens at day 1 maturity, they yield a trend line with the logarithmic function of $y = 2521.8104\ln(x) - 1224.8047$ with R^2 of 0.9695. For day 7 samples, they produce a graph with the trend line equation of $y = 617.0915e^{0.0901x}$ and R^2 value of 0.7996, which is 0.8 after rounding off. However, the graph for day 28 maturity shows a weaker correlation with a function of $y = -114.2824x^3 + 11151.2193x^2 - 361619.9659x + 3903844.4231$ while giving a R^2 of only 0.7274. The result is due to few of the total 5 concrete cubes that experienced some problems which affect the maturity processes.

Despite the fact that these graphs are not showing similar patterns, they share the same findings as the previous correlation graph. They show that the P-wave velocity is higher as compressive strength is increased. This can be seen in the major differences in the average wave velocities between day 1, day 7 and day 28 maturities. The variation in the fine aggregate to coarse aggregate ratios affects the compressive strength of concrete but it does not show a significant increase or decrease along with the ratio. This is because of the heterogeneity of concrete which makes the distribution of aggregates to always be uneven. Thus, the changes in fine aggregate to coarse aggregate ratios are sometimes difficult to influence the compressive strength of concrete in a steady manner. More in-depth evaluation and investigation is carried out in order to explain the unusual differences

When looking at the graph with day 28 maturity specimens, there are 2 specimens that are worth investigating, which are the specimens with fine aggregate to coarse aggregate ratio of 1:1.72 and 1;1.76, or referred as the S4 and S5 samples respectively. While both of them have higher compressive strengths than the remaining 3 specimens, it is discovered that the S4 concrete has a higher compressive strength than the S5 concrete. This is because of the obvious uneven distribution of aggregates of those specimens resulted by poor mixing process, causing some inaccuracies to exist during the compression tests. Thus, it gives a slightly higher average strength for the S4 cube while unexpectedly yields a lower average strength for the S5 cube.

Summarising the correlation steps, the graph with day 1 maturity cube samples is chosen as the graph for correlation. As usual, this is due to the fact that it has the highest coefficient of correlation. However, this alone is unable to prove that this graph has high accuracy to be used for future analysis. The main reason is because it has only 5 data points, which also means that it has a low accuracy. Furthermore, as stated in the previous correlations, the difference in the fine aggregate to coarse aggregate ratios is too small to demonstrate a great difference when the analysis is limited to a specific maturity period. In short, day 1 maturity graph is still the best choice but the obvious limitations cause all these graphs to have low accuracy regardless of their coefficient of correlation values.

4.4.2.3 Summary

To decide which one is the best choice for correlation, the 2 methods are studied in detail for several times. In the end, it is decided that the correlation regardless of factors is the most suitable graph for the aim of this research. Besides having a fairly high R^2 that is more than the acceptable value of 0.8, the fact that it does not associate itself with the limitations and factors enables the graph to increase its reliability and accuracy and has a more uniform data analysis.

4.4.3 Correlation with P-wave Frequency

To perform the analysis, the dominant frequency is extracted and used as the main parameter for plotting graphs. The P-wave dominant frequency is compared with the compressive strength of the concrete specimens. The 3 methods that are formulated for this set of results are the correlation regardless of factors, correlation by comparing different sensors and correlation by comparing different maturity days.

4.4.3.1 Correlation Regardless of Factors

By disregarding every limitations and factors, every single data point that is obtained from different fine aggregate to coarse aggregate ratios and different maturity days is placed into one single graph to conduct this correlation. A graph of P-wave dominant frequency versus compressive strength is generated, as illustrated in Figure 4.17.

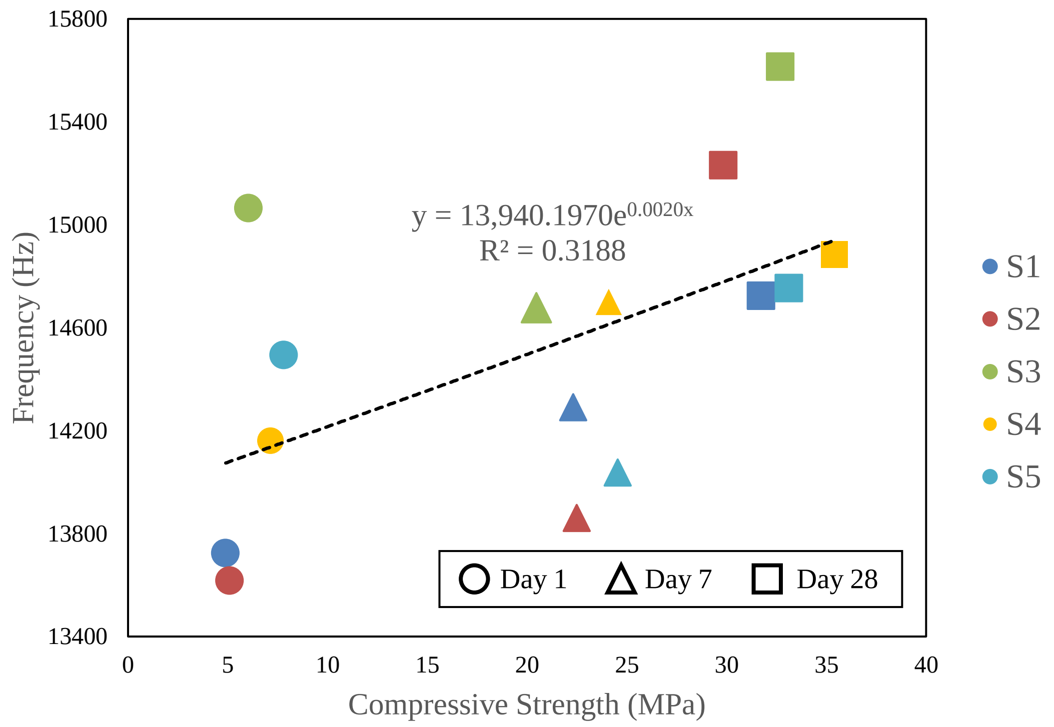

Figure 4.17: Correlation between Frequency and Compressive Strength for All Data Points in One Graph

According to the pattern of the graph, the trend line generated is a weak pattern and full of uncertainty. The coefficient of correlation of the line is very low, which is only 0.3188. Comparing to the acceptable value of 0.8, this value is far from reliable. There is no specific trend that can be identified from the data points in this graph, which also means the dominant frequency does not follow any pattern. It is unable to form a relationship with the concrete strength.

The graph consists of data points that are scattered unevenly, with no exact pattern. The dominant frequencies scattered in the range between 13616.67 Hz to 15613.33 Hz. The trend line function generated fails to represent the data points due to the nature of these points. Because of this, the strength of correlation is very weak, which leads to a very low value of R^2. The more scattered are the data points in the graph, the weaker is the correlation of the graph. Thus, this graph is unsuccessful in linking dominant frequency and compressive strength together.

4.4.3.2 Correlation by Comparing Different Sensors

For this case, the graph that is generated from the data at sensor 0 is compared with the graph from sensor 1 and lastly the average graph that is produced from these 2 sensors. Like the previous section, the graph of P-wave dominant frequency versus compressive strength is plotted. This is to enable any possible recognition of differences that exist between these sensors and study further to check if the different locations of sensors are capable of yielding noticeable differences. To achieve this, 3 graphs are formulated as shown in Figures 4.18, 4.19 and 4.20.

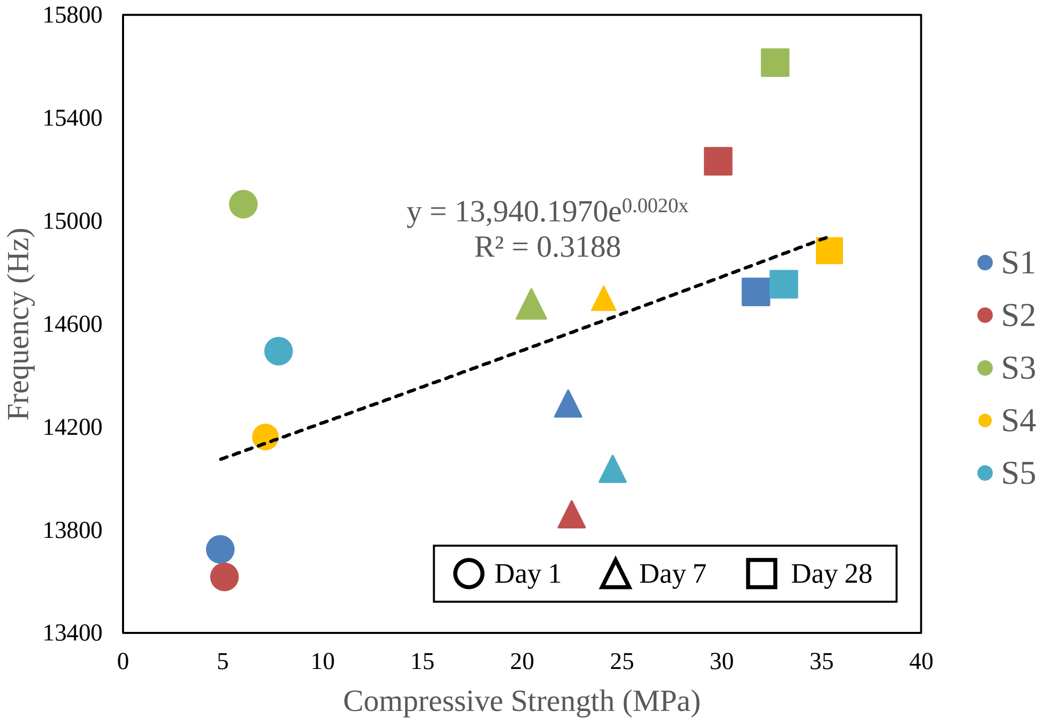

Figure 4.18: Correlation between Frequency and Compressive Strength for Sensor 0

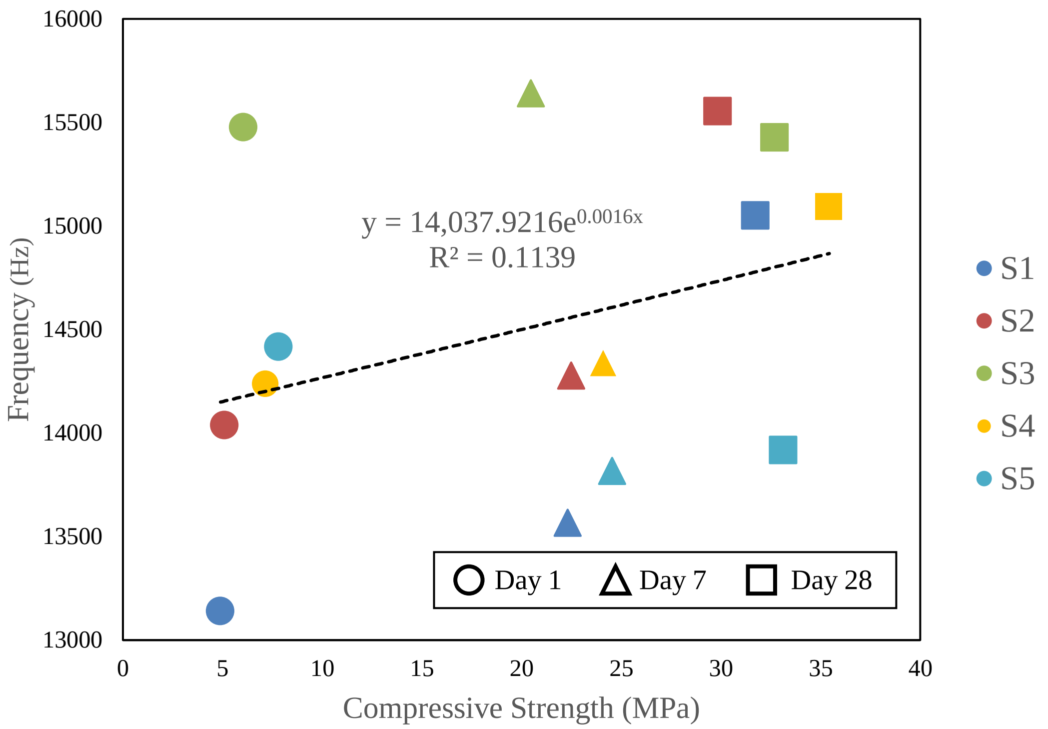

Figure 4.19: Correlation between Frequency and Compressive Strength for Sensor 1

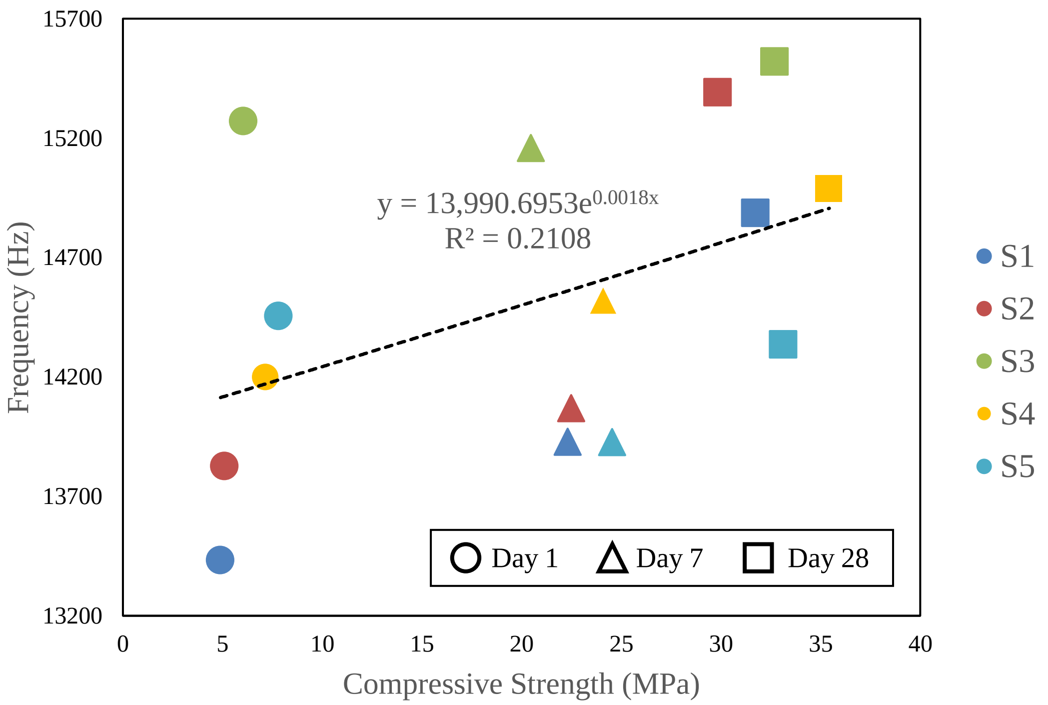

Figure 4.20: Correlation between Frequency and Compressive Strength for the Average of Sensor 0 and Sensor 1

It is obvious that all 3 graphs demonstrate unstable and weak correlations with trend lines that fail to represent their respective data points. The trend line for sensor 0 graph gives a R^2 value of 0.3188 while sensor 1 graph yields the weakest correlation among the other graphs, which has R^2 of only 0.1139. The graph with the average data of the 2 sensors still provides an unacceptable value of R^2 which is 0.2108. All trend lines are unable to pass the acceptable value of 0.8 for correlation of coefficient to strengthen the relationship in each of these graphs. Different sensor locations do not indicate a better or worse correlation as both of them show a similar pattern of scattered data.

To conclude this, none of these graphs are chosen to conduct correlation or use as a reference for future research. This correlation is always weak no matter where are the locations of the input sensors. Thus, these graphs are insignificant to produce relationships for P-wave dominant frequency and compressive strength.

4.4.3.3 Correlation by Comparing Different Maturity Days

This method separates the results according to maturity periods which focuses more on how the fine aggregate to coarse aggregate ratio is able to relate to compressive strength changes. Like the past correlations in the previous sections, a total of 3 graphs are generated with P-wave dominant frequency as y-axis parameter and compressive strength as x-axis parameter for day 1, day 7 and day 28 maturity. These graphs are displayed in Figures 4.21, 4.22 and 4.23.

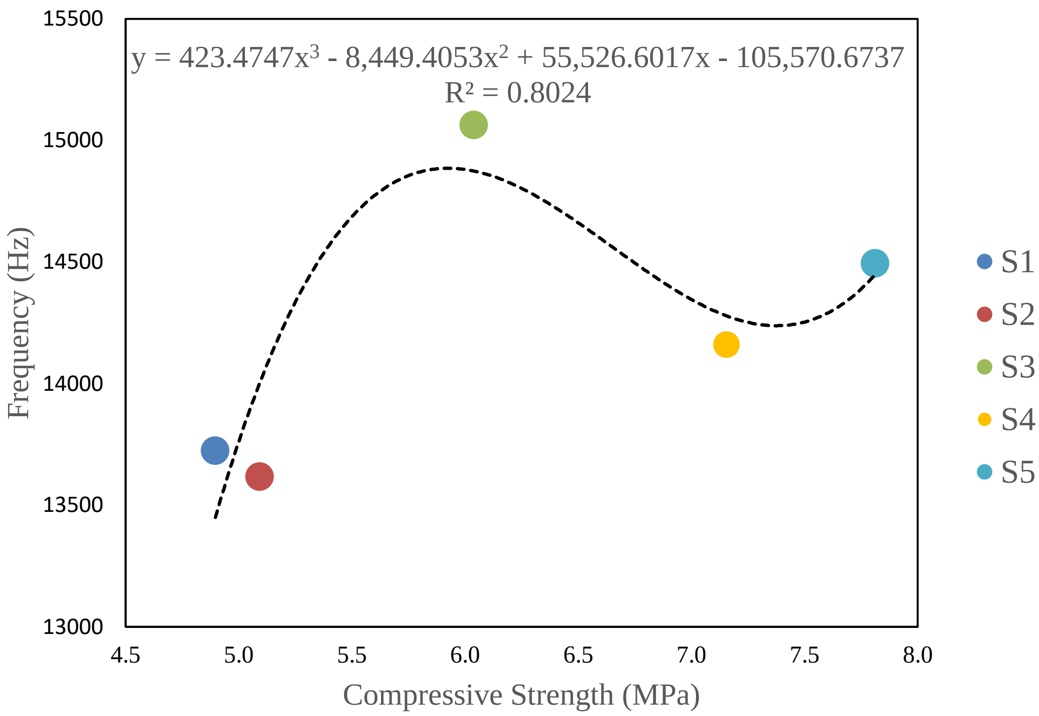

Figure 4.21: Correlation between Frequency and Compressive Strength for Day 1

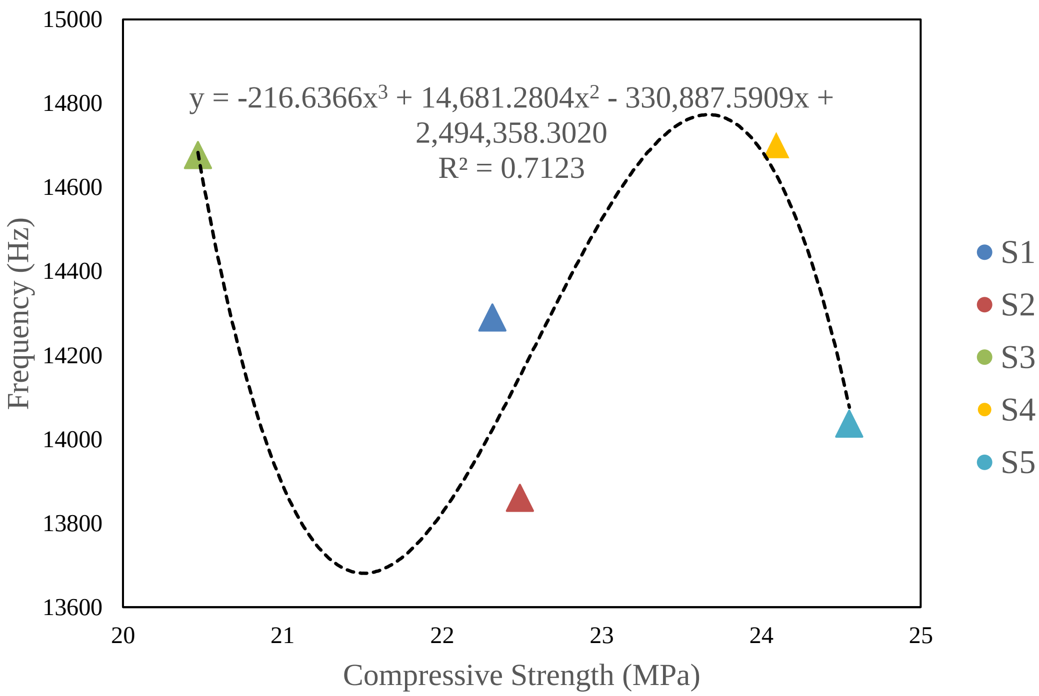

Figure 4.22: Correlation between Frequency and Compressive Strength for Day 7

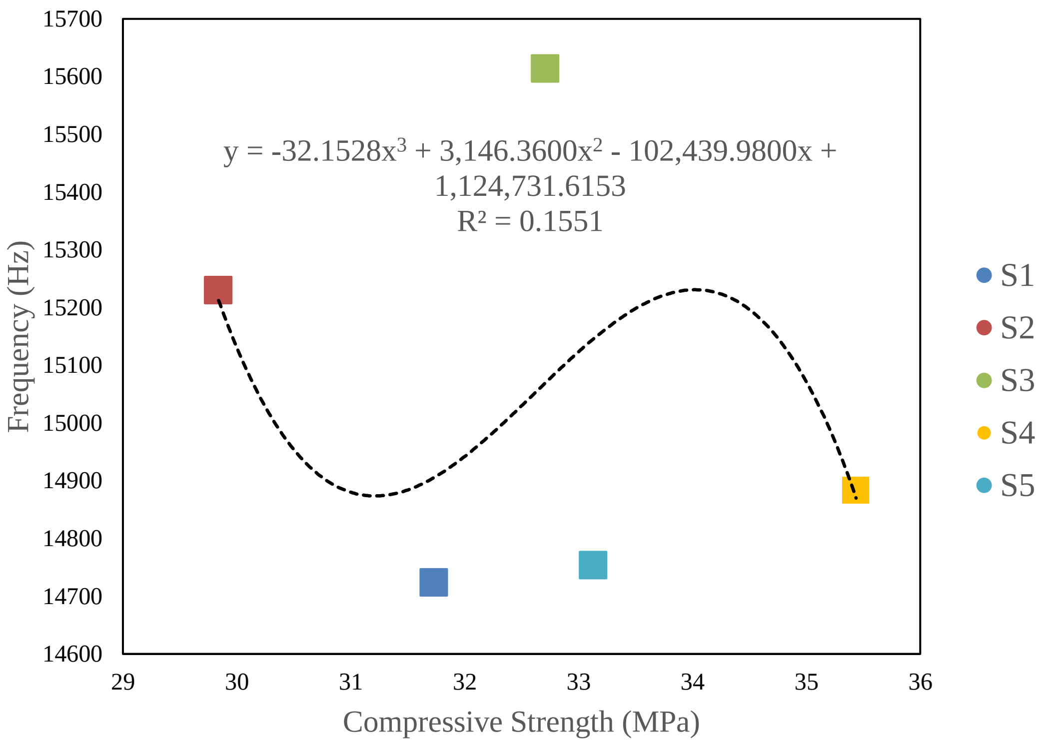

Figure 4.23: Correlation between Frequency and Compressive Strength for Day 28

Based on the patterns of these graphs, they demonstrate the same type of trend lines, which are the polynomial function line with power of 3. However, they still fail to provide a solid relationship for their data points. The graph for day 1 maturity gives a R^2 value that barely passes the minimum requirement, which is 0.8024 while day 7 maturity graph produces a trend line with R^2 of 0.7123, which is unacceptable as it falls below 0.8. For the graph of day 28 maturity, the trend line gives the weakest correlation coefficient, a R^2 of 0.1551. None of them are fairly strong to link the graph parameters together. All the 3 graphs are represented by polynomial functions with the power of 3, which makes them even unreliable to be used for prediction of compressive strengths. This is mainly because power of 3 literally means 3 possible x values, which indicates that there is a total of 3 different compressive strengths from a single y parameter. As a result, the situation reduces the accuracy of the graphs for correlation.

To select a graph to be used for correlation in future studies or a new set of data, the only graph that can be used is the graph for day 1 maturity. Despite being the only graph that passes the minimum R^2 requirement, it is still risky to use the graph in other experimental researches because like the other 2 graphs, it is represented by only 5 data points that are too little to increase its accuracy. This is judging from the fact that those data points are quite inconsistent and does not feel close enough to the trend line. This explains why the trend line has a R^2 that stays at the borderline instead of being much larger than 0.8. In order to use this type of graph for better analysis, more data points are needed for the same value of R^2. Therefore, the overall analysis for this correlation method is still not so dependable.

4.4.3.4 Summary

To summarize this, P-wave frequency is not suitable to be used as a parameter for correlation. It does not form a solid relationship with the compressive strength of concrete, thus demonstrating several weak correlations as observed from the 3 different methods of correlation. It is far too risky and unwise to use these trend lines produced from these approaches for future projects or references.

4.4.4 Counter Check Analysis

This analysis is a method that acts as a way to check if the correlation performed is valid or not. In other words, it measures the accuracy of the correlation conducted. The purpose of the counter check analysis is to confirm the validity of the correlation conducted by using another set of data as a comparison. When the new set of data is being inserted into the graph, the interpreted result is being compared with the existing data from the trend line. The smaller the difference between the two values, the more accurate is the correlation. Table 4.8 below shows two random data points extracted from a set of data produced from another final year student from last year that is used for this analysis. Since dominant frequency analysis is not reliable, it is not needed for this study.

Table 4.8: Data Points used for Counter Check Analysis

	Compressive strength (MPa)	**Wave amplitude (m)**	**Wave velocity (m/s)**
Data point 1	16.03	0.0073	-
Data point 2	6.43	-	3667.968

For wave amplitude correlation, the correlation adopts the first method which is the correlation regardless of factors. The trendline has a representative equation of $y = 0.0064e^{0.0217x}$. On the other hand, the wave velocity correlation analysis uses the same method which is the correlation that disregards any factors too and produces a trendline with the equation of $y = 2740.2415e^{0.0262x}$. By substituting the compressive strengths of both data points into the respective equations, two new amplitude and velocity values are acquired for comparison. Table 4.9 shows the values obtained and their respective percentage errors after comparing with the data from the previous final year student.

Table 4.9: Comparison between results from trendline and results from previous final year student and their respective percentage error

	P-wave Amplitude		
Data point 1	**Value from trendline (m)**	**Counter check value (m)**	**Percentage error (%)**
	0.0091	0.0073	24.66
	P-wave Velocity		
Data point 2	**Value from trendline (m/s)**	**Counter check value (m/s)**	**Percentage error (%)**
	3243.043	3667.968	11.58

Based on the comparisons, it is seen that both data points give values that are fairly acceptable. For P-wave amplitude, the difference between the trendline value and the counter check value yields a percentage error of 24.66% while the comparison for P-wave velocity produces a percentage error of 11.58%. These differences are not too large, which means that they are considered as tolerable. For this case, it is also discovered that P-wave velocity has a higher reliability and more accurate compared to P-wave amplitude due to its lower percentage error.

4.5 Summary

To correlate and evaluate the characteristics associated with the elastic P-wave, the important wave properties such as amplitude, velocity and frequency are involved in the analysis with the concrete compressive strength. Several graphs are produced, which are graphs of wave amplitude, velocity or frequency versus the concrete compressive strength and for each of these characteristics, there are 2 to 3 types of evaluation methods with their own specifications such as correlation regardless of factors, correlation by comparing sensors and correlation by comparing maturity days. From the final results, the chosen correlation graph for P-wave amplitude has the highest R^2 value of 0.9325 while the graph for P-wave velocity has a slightly lower R^2 of 0.8799 but it is more reliable than the amplitude graph due to its lower percentage value in the counter check analysis.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In the entire research for this report, correlations of P-wave amplitude, velocity and dominant frequency were conducted with concrete compressive strength and several results were produced. For amplitude and velocity, they displayed solid linkage to their respective compressive strength and yield strong relationships in overall. However, analysis for dominant frequency fails to form a reliable relationship as the graphs are unable to show a strong pattern for correlation. To select a wave characteristic as the best option, velocity is chosen due to its advantage of being more consistent and accurate after counter-checking its graph values with previous student's research. In comparison, velocity has a more accurate graph compared to amplitude. In real life application cases, velocity is still a better choice because of its accuracy to produce readings regardless of any site conditions compared to amplitude.

While looking at the consistency of P-wave velocity, it shows a range of R^2 values between 0.7274 and 0.9695 for the 2 selected methods used for correlation and the method that is chosen as the final graph of correlation has an R^2 value of 0.8799. These results prove that P-wave velocity has a strong connection with concrete compressive strength. By putting every single velocity data into one graph, the correlation becomes more reliable as they form a trendline that is represented by an equation with a high R^2 value. Furthermore, the graph clearly indicates that P-wave velocity increases when the compressive strength of concrete increases.

In a nutshell, correlation of P-wave velocity with concrete compressive strength has the highest dependability and more accurate to be applied in various NDT tools in construction sites.

5.2 Recommendation

In order to improve the results in this research, the accuracy of the data is the key to achieving this improvement. One of the effective ways to do this is by collecting more compressive strength data points for each of the analyses instead of just having the minimum amount of data points. To achieve this, more concrete specimens need to be produced. This is due to the fact that adding more information into a single analysis increases the accuracy of the whole evaluation process, which yields better results, especially while generating the correlation graphs. Besides that, a pendulum hammer can be a great alternative to ordinary metal balls while performing the impact test onto the concrete samples. This is because we can set the distance that the pendulum hammer needs to be released and standardize the force applied to the samples instead of manually applying the impacts. As a result, the wave information collected from the Labview Signal Express software are more consistent and have higher accuracy.

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