RELATIONSHIP BETWEEN CUBE AND CYLINDER STRENGTHS FOR HIGH STRENGTH CONCRETE

by

Kiv Sodana

Dissertation

Submitted to the Civil Engineering Program
in Partial Fulfillment of The Requirements
for the Degree Bachelor of Engineering (Hons)
(Civil Engineering)

Supervisor
ASSOC. PROF. Dr. Nasir Shafiq

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Ksodana

KIV SODANA

ABSTRACT

One of the most important properties of concrete is its compressive strength. The strength of concrete can be affected by size, shape of specimens and many more factors. This project aims to experimentally develop mathematical relationships between standard cube and standard cylinder strengths, smaller cube and standard cube strengths, and smaller cube and standard cylinder strengths for high strength concrete. A total of 144 cubes_{150mm}, 72 cubes_{100mm} and 72 $\text{cylinders}_{150\Phi x300mm}$ were made from 12 mixes which comprised of 6 different design mix compositions. All specimens from the same batch were identically cast, cured and tested. The concrete strength of each mix was designed to have cubic strength of 50 MPa and higher at 28 days. Expressions relating the compressive strengths of standard cylinder, standard cube and smaller cube are presented. These expressions might be used to combine with other researchers' results to obtain useful interrelationships between the strengths of any two types of specimens.

ACKNOWLEDGEMENT

This dissertation could not have been written without Associate Professor Dr. Nasir Shafiq who not only served as my supervisor but also supported and encouraged me throughout my research. Together with my best effort, his continuous helps and supports have brought me to the completion of this dissertation at ease. I am very grateful to him for everything he has done.

I am also thankful to my university, Universiti Teknologi PETRONAS for the provision of the facilities to conduct my laboratory works as well as for its financial support toward this research.

Very special thank to my best friend, Jose Maria Esono Micha, and all my friends and juniors who assisted me during the mixing processes. Without them none of the mix would be cast and subsequently this research would never reach its successful implementation and completion.

April 17, 2008

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Concrete is a material that literally forms the basis of our modern society. Concrete is a composite material composed of coarse granular material (the aggregate or filler) embedded in a hard matrix of material (the cement or binder) that fills the space between the aggregate particles and glues them together *(Neville 2002).*

The most sought-after property of a concrete is probably strength, despite the fact that in many cases other characteristics, such as durability, may be equally or even more important. Concrete strength is an elusive property which all factors are known to affect the strength potential *(Popovics 1998).*

Even if the properties and inherent variability in the concrete-making materials, proportions, air content, mixing, temperature, and others are absolutely constant, there still can be a wide dispersion in the numerical value of the measured strength depending on how and how well the measurement is made, The number will depend on size, shape, and method of fabrication of the specimen; its age; its treatment prior to testing; its physical condition, particularly moisture distribution and content at the time of test; and the extent of correctness of the testing procedure *(Popovics 1998).*

There are generally no unique relationships between values for mechanical properties measured in different ways. If, for instance, we measure the compressive strength of concrete using two specimen shapes, cylinders and cubes, the ratio (cylinder strength/cube strength) will not have a constant value, but will vary depending on the type of concrete. Same goes to the case that if we measure the compressive strength of two different specimen size, says 100 mm cube and 150 mm cube, the ratio of 100mm-cubic strength/150mm-cubic strength is not constant *(Hewson, N. R. 2003)*.

Therefore, to minimize the confusion and to ease those who deal with different code of designs in which the design strengths are referred to different shape and size of concrete, the relationship of those concrete compressive strength are being researched.

1.2 PROBLEM STATEMENT

The relationship exists between standard cube (150 x 150 x 150) and cylinder (150 ϕ x 300) based on traditional concrete possessing medium strength (30 – 40 MPa) and made of typical constituents (cement, sand, gravel and water).

Since last two decades high strength and high performance concrete containing various additives (fly ash, micro silica, and superplasticizer) is becoming very popular and the relationship between cubes and cylinders is still not yet studied for such concrete.

In addition to the above problem, when the concrete strength gets higher, many research establishment and testing laboratories do not have the capabilities to break the standard cubes or cylinders. As the result, they reported concrete strength based on smaller specimens, for example 100mm cube or 100Φx200mm cylinder. The relationship between those smaller specimens and the standard ones is still not yet established as well.

1.3 OBJECTIVES AND SCOPE OF STUDY

The main objective of this project is to find the relationship between standard cube and cylinder strengths of high strength concretes. The secondary objective is to find the relationship of smaller cube (100mm cube) with those standard strengths for high strength concrete. In other word, this project aims to find the relationships of high strength concrete in various shapes and sizes.

Due to time constraint and suitability to be a final year project of undergraduate study, the project is scoped down in which it is aimed:

1. To determine the relationship between standard cube and cylinder strengths and 100mm cube and standard strengths for the following concrete:
   i. Concrete made of 100% composite cement and possessing 28 days strength of 50 – 60 MPa.
   ii. Concrete containing cement replacement materials such as PFA and possesses concrete grade between 50 – 60 MPa.

2. To develop mathematical models for the relationships based on the experiment results.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

Concrete is a type of construction materials which comprises of cement (normally Portland cement), coarse aggregates such as gravel limestone or granite, fine aggregates such as sand or manufactured sand and water. Sometime also there is some cement replacement materials added such as pulvarized fuel ash, micro silica etc. Concrete solidifies and hardens after mixing and placement due to a chemical process known as hydration. The water reacts with the cement, which bonds the other components together, eventually creating a stone-like material.

Strength of concrete is commonly considered as its most valuable property, although in many practical cases, other characteristics such as durability, permeability may in fact be more important. Concrete has relatively high compressive strength, but significantly low tensile strength (about 10% of the compressive strength). As a result, concrete always fails from tensile stresses — even when loaded in compression.

Concrete strength is affected by many factors, such as water/cement ratio, gel/space ratio, porosity, shape, size and etc. In general, the change of a structural property when the shape of a structure changes is known as a shape effect related to this property. In other words, if geometrically different specimens do not behave similarly, this is called a shape effect. Shape effects occur in concrete in any loading conditions. On the other hand if the change of a structural property occurs when the size of a structure changes it is known as a size effect.

Due to the differences in the shape, size, aspect ratio, and the associated end restraint provided by the machine platen, cube and cylinder strengths or smaller cube and bigger cube strengths obtained from the same batch of concrete differ. The size and shape of compressive strength test specimens of concrete varies from one country to another. There are basically two shape of test specimens, cube and cylinder, that are used in the determination of the compressive strength of concrete.

2.2 STANDARD CUBE AND CYLINDER STRENGTHS

Cube standard is the standard used in the United Kingdom, Germany, and many other European countries. Some code such as British Standard base their design rules on cube strength concrete. Cube strength is determined by crushing 150 x 150 x 150 mm samples *(Tokyay and Ozdemir, 1997).*

Cylinder standard is the standard used in the United States, Canada, France, Australia, etc. Some codes such as American AASHTO standard and EUROPEAN standard use the cylinder strength of concrete as their basic design rules. Cylinder strength is determined by crushing 150 mm diameter by 300 mm long samples *(Tokyay and Ozdemir, 1997).*

These two standard strengths are not the same even with an identical casting and curing. One of the reasons that cause these differences can be due to the friction between the platens and the cube specimen ends creates much more confinement in the specimen than in the case with cylindrical specimens. This leads to higher strength values when measured on cubes rather than cylinders *(Soroka and Baum, 1994).*

Generally cylinder test strength is between 5% and 25% less than cube test strength for a given concrete mix. The ratio between cube strengths and cylinder strengths is commonly assumed to be 1.25 for normal strength concrete *(Mansur, 2002).*

However a vast amount of research has showed that the conversion factor of cylinder strength and cube strength does not remain constant for all grades of concrete. The relationship between cube strength and cylinder strength varies depending on concrete strength and its properties. Many researchers have noted that the factor decreases as the concrete strength increases. The factor is ranging from about 1.3 for low-strength concretes to about 1.04 for higher strength concretes *(Hewson, 2003)*. As an approximate guide the comparison given in Figure 1 can be taken.

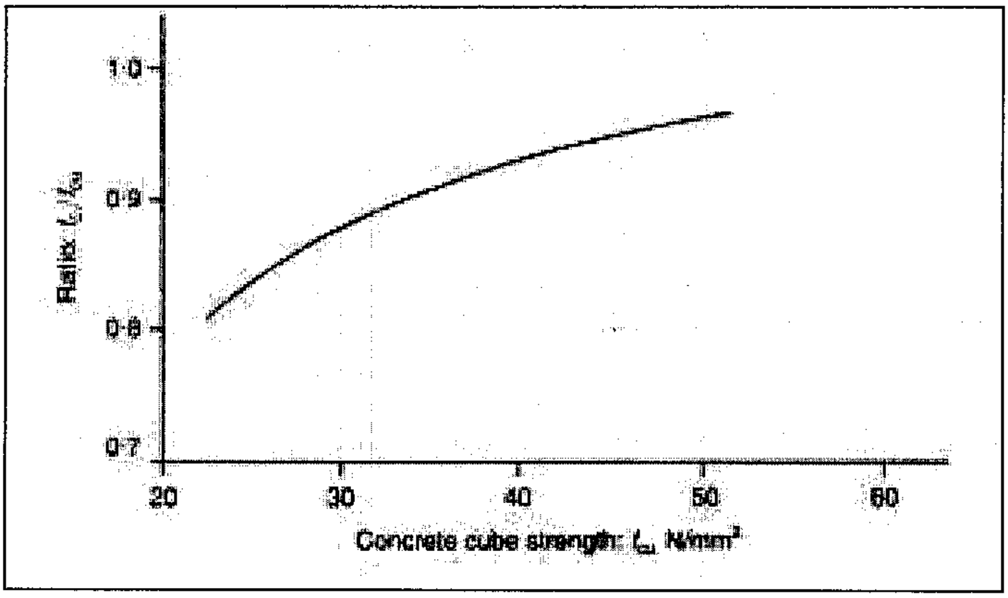

Figure 2.1: Cube vs. Cube-Cylinder Strengths Ratio ***(Hewson, 2003)***

The above figure has shown that the shape of specimen is less influent to those high-strength concretes. However the guidelines for converting cylinder to cube strength or vice versa for the whole range of concrete grades currently in use still remains a point of contention. The investigations of relationship between cube strength and cylinder strength especially for high strength concrete are still necessarily conducted around the globe.

2.3 HIGH STRENGTH CONCRETE

High strength concrete is a type of high performance concrete. Although it is often considered a relatively new material its development has been gradual over many years. As the development has continued, the definition of high-strength concrete has changed. In the 1950s, concrete with a compressive strength of 5000 psi (34

MPa) was considered high strength. In the 1960s, concrete with 6000 and 7500 psi (41 and 52 MPa) compressive strengths were used commercially. In the early 1970s, 9000 psi (62 MPa) concrete was being produced. More recently, compressive strengths approaching 20,000 psi (138 MPa) have been used in cast-in-place buildings. *(ACI Committee 363, 1997)*

For many years, concrete with compressive strength in excess of 6000 psi (41 MPa) was available at only a few locations. However, in recent years, the applications of high-strength concrete have increased, and high-strength concrete has now been used in many parts of the world. The growth has been possible as a result of recent developments in material technology and a demand for higher-strength concrete *(NRMCA)*.

Based on National Ready Mixed Concrete Association (NRMCA), high strength concrete is necessarily used in some applications as follows:

- To put the concrete into service at much earlier age, for example opening the pavement at 3-days.
- To build high-rise building by reducing column sizes and increasing available space.
- To build the superstructures of long-span bridges and to enhance the durability of bridge decks.
- To satisfy the specific needs of special applications such as durability, modulus of elasticity and flexural strength. Some of these applications include dams, grandstand roofs, marine foundations, parking garage, and heavy duty industrial floors.

Furthermore *NRMCA* stated that some basic concepts that need to be understood for high strength concrete when designing its mixture are:

- Aggregates should be strong and durable. They need not necessarily be hard and of high strength but need to be compatible, in terms of stiffness and strength, with the cement paste.

- High strength concrete mixtures will have high cement content that increases the heat of hydration and possibly high shrinkage leading to the potential of cracking. So to reduce the heat induced in the concrete, most mixtures contain one or more cement replacement materials such as pulvarized fuel ash, ground granulated blast furnace slag, silica fume, and natural pozzolanic materials.
- High strength concrete mixtures generally need to have a low water cement ratio. These low water cement ratios are only attainable with quite large doses of high range of water reducing admixtures such as superplasticizers.

2.4 MATERIALS USED

As mention earlier in section 2.3, in high strength concrete mixtures some additive materials such as cement replacement materials are used to reduce the heat induced in the concrete and water reducing admixtures are used to achieve a low water cement ratio in the mixture. Particularly in the project, pulvarized fuel ash is used as cement replacement material and superplasticizer is used as water reducing admixture.

2.4.1 Pulvarized Fuel Ash

Pulvarized fuel ash (PFA) is a waste product produced when pulvarized coal is burned in power station furnaces. Most of the ash is fine enough to be carried away with the flue gases and to prevent atmospheric pollution this "fly ash" is removed from the gases by electrostatic precipitators *(Neville, 2002)*.

The precipitated material is a fine powder which can have pozzolanic properties, i.e. when mixed into concrete it can react chemically with the calcium hydroxide that is produced during the hydration of Portland cement. The products of this reaction are cementitious, and in certain circumstances PFA can be used to replace part of the Portland cement in concrete mixes *(Neville, 2002)*.

Not all PFAs are suitable for use in concrete, mainly because the quality can vary as a result of fluctuations in the demand for electricity. The most consistent PFAs come from base-load stations which run continuously under constant operating conditions, and it is from these sources that PFA is usually processed and graded for use in concrete. So because of the variability of the PFA produced even from a single plant quality control is particularly important.

Substitution for PFA for Portland cement is not a straightforward replacement; there are certain points that we have to bear in mind when designing PFA mixes:

- PFA reacts more slowly than Portland cement, and at early ages it contributes less strength; the potential strength after three months is likely to be greater than OPC provided that the concrete is maintained in a moist environment. This may adversely effect the time at which the forms can be stripped, particularly at low temperatures. One way of dealing with this problem is by further reducing the water cement ratio, though the use of even more superplasticizer. Clearly, if high early strength is needed, it may be necessary to reduce the PFA content.
- The density of PFA is about three-quarters that of Portland cement. So at the substitution level used (15-30%), PFA will have very little effect on the maximum temperature development in mass concrete pours.
- The existing test data are rather ambiguous with regard to the free-thaw durability of high strength concrete made with cement replacement material. This is true for both air-entrained and non-air-entrained mixes. Therefore, until more data are available, designers should be cautious when using high strength concrete in an environment in which the concrete will be subjected to many freeze-thaw cycles in a saturated state.

2.4.2 Superplasticizer (Water Reducing Admixture)

Superplasticizer is linear polymer containing sulfonic acid groups attached to the polymer backbone at regular intervals *(Verbeck, 1968)*. Most of its commercial formulations belong to one of four families:

- Sulfonated melamine-formaldehyde condensates (SMF)
- Sulfonated naphthalene-formaldehyde condensates (SNF)

- Modified lignosulfonates (MLS)
- Polycarboxylate derivatives

The sulfonic acid groups are responsible for neutralizing the surface charges on the cement particles and causing dispersion, thus releasing the water tied up in the cement particle agglomerations and thereafter reducing the viscosity of the paste and concrete *(Mindess and Young 1981).*

As reflect to its function mentioned above, superplasticizer is mainly used in the purpose is to produce flowing concrete with very high slump to be used in heavily reinforced structures and in placements where adequate consolidation by vibration cannot be readily achieved. The other major application is to produce high-strength concrete at low water cement ratio *(Ramachandran and Malhotra 1984).*

As we know strength of concrete is inversely proportional to the amount of water added or water cement ratio. So in order to produce high strength concrete, less water should be used. This would make the concrete mixture very unworkable therefore the use of superplasticizer is necessary to improve its workability.

The ability of superplasticizers to increase the slump of concrete depends on such factors as the type, dosage, and time of addition of superplasticizer; water cement ratio; and the nature or amount of cement. It has been found that for most types of cement, superplasticizer improves the workability of concrete. The capability of superplasticizers to reduce water requirements 12-25% without affecting the workability leads to production of high-strength concrete and lower permeability.

However, one problem associated with using a high range of water reducer in concrete is slump loss. In a study of the behavior of fresh concrete containing conventional water reducers and high range water reducer, *Whiting and Dziedzic (1989)* found that slump loss with time is very rapid. Anyhow, slump loss of flowing concrete was found to be less severe, especially for newly developed admixtures.

The slump loss problem can be overcome by adding the admixture to the concrete just before the concrete is placed. However, there are disadvantages to such a procedure. The dosage control, for example, might not be adequate, and it requires ancillary equipment such as truck-mounted admixture tanks and dispensers. Adding admixtures at the batch plant, beside dosage control improvement, reduces wear of truck mixers and reduces the tendency to add water onsite *(Wallace 1985)*.

CHAPTER 3
METHODOLOGY

To ensure the accomplishment of the objectives set in this project, the following processes are planned as the methodology in conducting this research:

3.1 LITERATURE REVIEWS

Literature review is one of the important aspects of the project, as it is the first step of the project work. In order to successfully complete this project, a strong fundamental knowledge on several aspects of concrete properties such as concrete strength, the factors affect its strength, methods of concrete strength testing and etc. should be acquired. Journals, publications, and books regarding the relevant fields are planned to study and review from time to time to enhance the knowledge and understanding of the topics.

3.2 CONSULTATION

Consultation sessions with the supervising lecturer are frequently arranged to update the supervisor with the activities done in the project and to seek for the solutions of the problems faced throughout the works done. This is an important approach to achieve the success in the project as the advice from an experienced lecturer is a great help in avoiding unnecessary mistakes and ensuring that the student's work is on the right track. The consultation sessions were arranged quite often in the early stages of the project as there were many doubts on the project before it got started. But when it came to the later stages, the consultation sessions were not as often as before anymore as the project is just going well as planned. However meeting with the supervising lecturer was still made once in a while to update the lecturer with the project progress.

3.3 LABORATORY WORK

Laboratory work is the most major activity in this project as this project is somehow is a lab-work based project. The needed data to fulfill the objectives is not available in any sources like books, internet, journal etc but data is required to be produced through the lab work experiments. The flow of lab work experiment is shown in the following diagram:

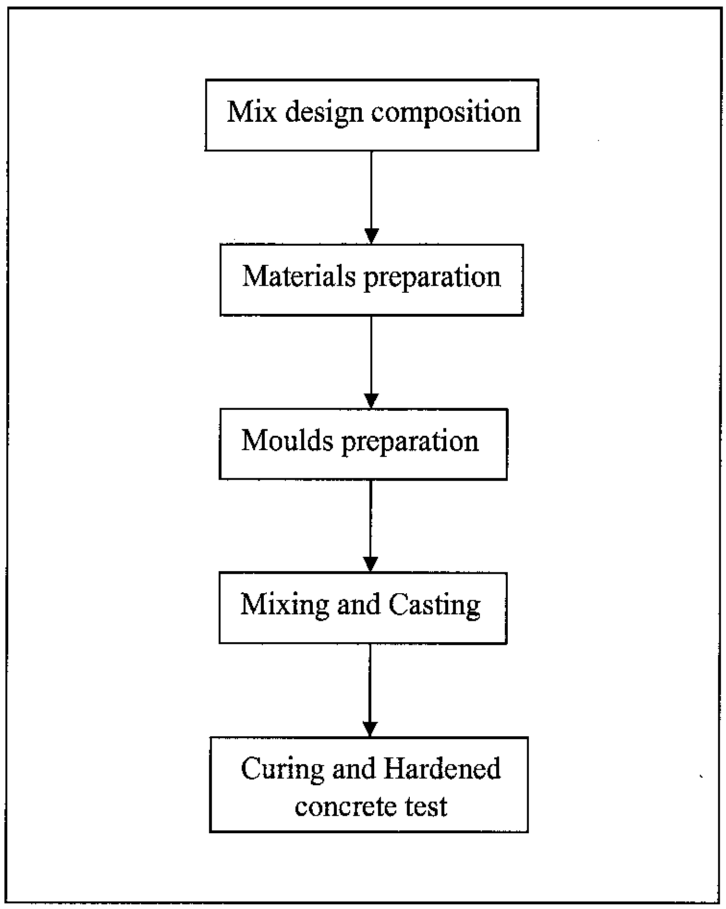

Figure 3.1: Flow Chart of Lab Work Activities

3.3.1 Mix Design Composition

There are several trial mixes have been done by a master student whose research is still an on-going research. Since the design strengths and design mix composition done by that master student are met the requirement in my project, so to simplify the work and to get the work done faster, the master student's design mix proportion are directly used in this project. The following table shows the design mixes which are supposed to be done:

Table 3.1: Mix Design Compositions

Mix no.	CPC	PFA	Coarse Aggregate	Fine Aggregate	W/C	Water	SP
1	360	0	1152	720	0.4	144	3.6
2	380	0	1140	684	0.4	152	3.8
3	288	72	1152	720	0.4	144	7.2
4	288	72	1260	720	0.4	144	7.2
5	288	72	1260	792	0.4	144	7.2
6	280	70	1225	700	0.4	140	7
Note: All units are in kg/m^3 except for w/c is dimensionless							

The above mix design proportions are aimed to produce the harden concrete with cubic strength of 50 MPa and 60 MPa at 28 days strength.

Six mixes consisting of twelve 150mm cubes and twelve 150Φx300mm cylinders each mix were planned to complete in first semester (final year project 1). Another six mixes of same design mix proportion consisting of twelve 100mm cubes and twelve 150mm cubes each mix were planned to complete in second semester (final year project 2). In total there are together twelve mixes are required to be successfully done in this entire project.

3.3.2 Materials Preparation

The materials used in this project are composite cement which the composition of cement is based on Malaysian Standard, crushed gravel as coarse aggregates, river sand as fine aggregates, Pulvarized Fuel Ash (PFA) as cement replacement material, superplasticizer as water reducing admixture and tapped water.

Cement, PFA and superplasticizer are ordered from the suppliers by the laboratory technicians and they are directly used in the mixing without any prior preparation as they are properly stored in the laboratory. They are not just properly stored but they are newly bought as well so their quality is good enough for the project.

However gravel and sand are just dumped outside of the laboratory so they are exposed to dust, dirt, rain and so on. Therefore, few days or a week prior to the casting day gravel and sand (aggregates) are needed to be cleaned by washing out all dust and dirt. Then they are dried by storing at the appropriate corners of the laboratory.

3.3.3 Moulds Preparation

This project is all about the investigation of the concrete strengths regarding its shapes used in different standards and different size of specimens. There is not any beam, column or slab involved in this project.

Therefore the complex formworks are not required in this project. Samples are required to cast in the standards cube, standard cylinder and smaller cube. In every mix of the first six mixes, 12 150mm cube moulds and 12 cylinder moulds with 150mm in diameter and 300mm in length are used. Whereas in the last six mixes, every mix consists of 12 150mm cube moulds and 12 100mm cube moulds are used.

As the fact of the project nature mentioned earlier, it is very simple to prepare the moulds for casting as all those moulds are available in our university laboratory. Things that need to be done are just fixing the moulds to make sure that they are firmly closed, cleaning the inner faces of moulds and applying the grease or used oil on the faces that in contact with concrete to avoid the bonding between the moulds and the concrete.

3.3.4 Mixing and Casting

The concrete was mixed using a tilting drum mixer. According to *"Manual of Laboratory" of Concrete Technology course,* the mixings are carried out as recommended by BS 1881: Part 125: 1986 with the procedures as follow:

- The mixer is initially wetted to prevent absorption.
- Both coarse and fine aggregates are poured into the mixer and mixed for 25 seconds.
- Half of the water is added and mixed for 1 minute.
- The mix is left for 8 minutes to let the water to be absorbed by the aggregates.
- Cement and PFA (if any) are added and mixed for another 1 minute.
- Another half of the water with superplasticizer are added and mixed for 1 minute again.
- The mixing machine is stopped and the hand mixing is performed to ensure homogeneity.

After mixing is completed, the fresh concrete is brought to the laboratory and placed into the readily prepared moulds. There is not any fresh concrete test necessary to perform because this project focuses only on the harden strength of concrete. Furthermore the mix proportions are given by the master student who had already done the fresh concrete tests when the mixes were on trial.

Fresh concrete is placed into the moulds in three layers and vibrated using the manual vibrator for about 10 seconds for each layer. After the top layer has been tamped, the surface of the concrete is struck off level with top off the mould with a trowel. Once the concrete placing is complete, the moulds filled with fresh concrete are covered with polythene sheet to prevent evaporation and they are left for 24 hours *(Concrete Technology Course "Manual of Laboratory")*,.

3.3.5 Curing and Harden Concrete Test

After casting for 24 hours, the concrete specimens are removed from the moulds. On top of every specimen, the mark of indicating the date of casting is written. Then the specimens are stored in the curing tank at a temperature of 20+5 °C until they are to be tested. The ages of concrete for tests are 3 days, 7 days, 28 days and 90 days and three specimens are tested every preferred age.

Compressive strength test is the only harden concrete test is performed in the project as the strength is one of the most important properties of concrete. Compressive strength is taken as the maximum compressive load concrete can carry per unit area. The Compression Testing Machine which is capable to compress up to 2000kN is used in this test.

To perform this test, firstly the specimens are removed from curing tank and wiped off the surface water. Then the specimens are placed on the center of the lower platen and it is ensured that the load will be applied to two opposite cast faces. Next the load is applied continuously and increasingly at a constant rate of 5.3 kN/s for cylinders, 6.8 kN/s for 150mm cubes and 3.0 kN/s for 100mm cubes until no greater load can be sustained. Lastly the maximum load and stress that concrete can sustain is recorded *(Concrete Technology Course, "Manual of Laboratory").*

3.4 HAZARD ANALYSIS AND SAFETY

This project is all about finding the mathematical relationship between non-standard cube, standard cube and standard cylinder strengths for high strength concrete. It is a research based on the experimental results obtained from the laboratory works. All the laboratory works, ranged from aggregates preparation, moulds preparation, mixing till testing, are all conducted in Concrete Laboratory which is located at Civil Engineering Department building of Universiti Teknologi PETRONAS.

There are many possible hazards that can be occurred in the laboratory. Those hazards can be classified into two main categories which are hazards due to the laboratory environment and hazards due to equipments handling

3.4.1 Hazards Due To The Laboratory Environment

The possible hazards under this category and the actions that should be taken to prevent respective hazard are briefly summarized in table 3.2 below:

Table 3.2: Summary of Hazards Due To Laboratory Environment and Recommended Actions

Hazards	Recommended Actions
1. Excessive noise: it is occurred when many activities are conducted concurrently.	▪ Wear earplug or earmuffs.
2. Dust: the lab is generally dusty no matter how often the working area is swept. This is because most of the works are dealing with small particles materials such as cement, PFA, Fly ash, sand and etc.	▪ Wear mask to protect the breathing. ▪ Wear safety goggles to protect the eyes.
3. Vibration: during casting process, fresh concrete is placed into the mould in three layers and well vibration is needed for each layer.	▪ Wear gloves and use thick cotton or sponge when handle the vibration machine to reduce the direct vibration from machine to the body.
4. Accidents: such as slip, fall or misstep can be caused by poor housekeeping.	▪ Clean up working area upon completion of work. ▪ Clean and restore all equipments to its original location.
5. Fire and explosion: certain equipments in the lab are dealing with flammable gas. There is tiny possibility that gas can be exploded if it is not properly stored or handled.	▪ Ensure that all equipment, gasses, and power utilities are properly off or shutdown upon completion of work. ▪ Access to exit and emergency equipment and controls should NEVER be blocked

3.4.2 Hazards Due To Equipments Handling

Similar to the first hazardous category, the possible hazards and the recommended actions are listed in table 3.3 below:

Table 3.3: Summary of Hazards Due To Equipments Handling and Recommended Actions

Hazards	Recommended Actions
1. Heavy materials drop: when loading the samples in place with unsafe acts, the heavy concrete or steel can be dropped. This can cause injured to user's hands or feet.	▪ Wear proper protective gloves and shoes. ▪ Close the cover and lock it well.
2. Flying chips: sometime while mixing or testing the concrete, chips of concrete can be flown to hit parts of the user's body.	▪ Wear proper lab coat or safety jacket or apron. ▪ Close the cover safety guard properly.
3. Awkward position: improper position when handling heavy materials such as lifting, carrying, pushing or pulling can cause backache or back injury.	▪ Follow the six basic steps for proper lifting. ▪ Share the tasks with few people. ▪ Use suitable carriers such as carts or hand truck to move the materials.

CHAPTER 4
RESULT AND DISCUSSION

As mentioned in section 1.3, objectives and scope of work, this project aims to find the relationships of high strength concrete in various shapes and sizes. In other to investigate the concrete strengths, concrete must be cast and tested. So the mix designs are prepared and the laboratory works are the main activity in this whole project.

Although it was planned to do 12 mixes of six different mix proportions for the entire project, in actual work more than 12 mixes were done. Throughout this project 14 mixes were done. Two extra mixes were required because the results obtained were not accurate enough to be used in the research. Therefore the repetition was needed for those mixes that were disqualified.

In mix number 2 of 150mm cube and 150x300mm cylinder, it was found that the strength of the cylinder was not right as it gave the 28 days strength less than 7 days strength and the 7 days strength was even less than 3 days (see appendix C). However the cubic strength was just fine, the strength gained as expected. Hence the mix of cylinder was advised to repeat.

For mix number 3 of 150mm cube and 150x300mm cylinder, when the specimens were removed from the moulds it was found that there are too many voids in both cube and cylinder specimens. With voids the concrete cannot give the correct strength as it is supposed to be. So the results from the void samples are intolerable (see appendix C). Thus the whole 3rd mix was required to repeat.

The raw data obtained from the qualified 12 mixes can be found in appendix D. The totals of 288 specimens were successfully tested in this research. It should be noted that the results of identical specimens must not be different more than 15%. The results with'*' are those exceed this limit and are excluded when finding the average.

Each strength value was tested on three identical specimens and was calculated by averaging the strength of at least two of those three specimens which are not different more than 15%. The summary of the average strengths obtained from those qualified 12 mixes of 3 days, 7 days, 28 days and 90 days strengths are shown in table below:

Table 4.1: Summary of Average Strengths

		Part 1		Part 2	
Mix	Age (Days)	150 cube (MPa)	150x300 cylinder (MPa)	150 cube (MPa)	100 cube (MPa)
1	3	26.49	23.95	37.04	41.25
	7	42.19	32.89	40.95	43.10
	28	67.35	42.86	54.98	59.01
	90	78.04	53.38	56.97	60.96
2	3	34.24	28.72	31.48	33.61
	7	40.02	35.09	38.06	41.20
	28	54.22	36.02	46.38	39.65
	90	63.66	42.77	52.64	58.92
3	3	37.80	29.66	29.26	33.10
	7	46.24	29.39	36.25	38.22
	28	56.85	32.22	52.24	51.45
	90	72.81	58.12	57.61	66.15
4	3	45.35	26.44	27.03	29.59
	7	46.26	34.42	33.25	39.60
	28	50.18	35.54	45.67	50.06
	90	64.44	41.23	50.40	57.96
5	3	40.47	39.67	34.01	37.29
	7	48.61	47.66	40.85	46.04
	28	57.24	43.86	48.09	47.05
	90	70.56	51.28	59.54	63.60
6	3	34.54	30.78	25.97	30.66
	7	45.14	39.88	33.94	39.13
	28	60.19	42.42	45.11	37.61
	90days	60.69	46.78	52.34	59.25

Regardless the differences in mix and age of concrete strengths, the results in table 4.1 above are combined as sets of data according to their shape and size only. Various graphs are plotted based on those data as shown in the followings:

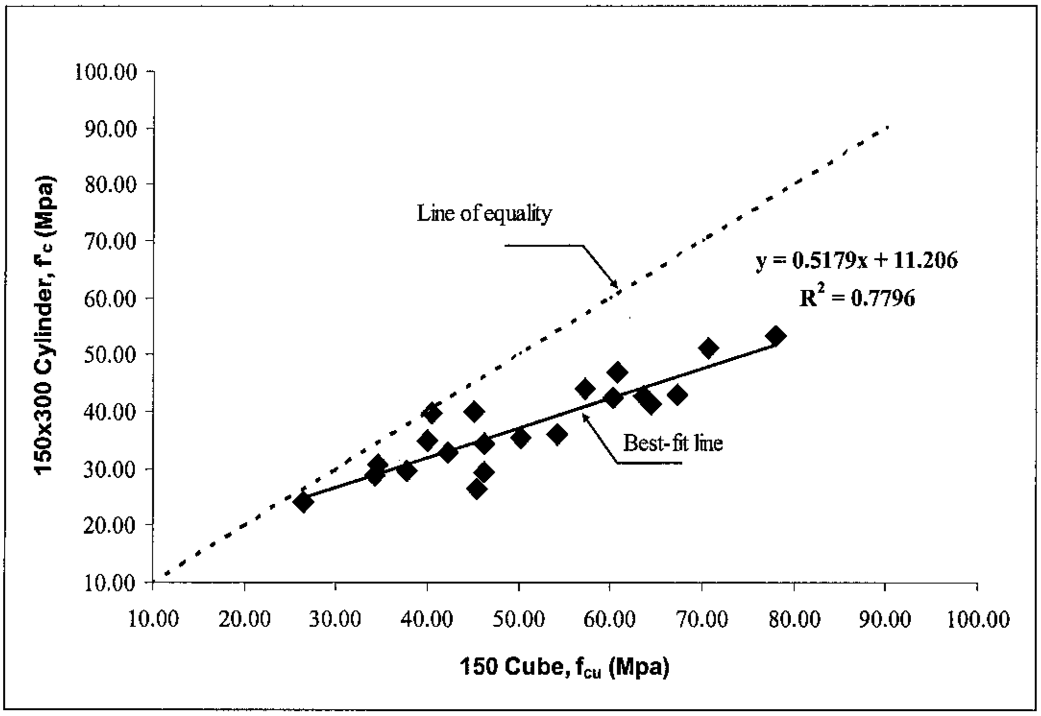

Figure 4.1: 150x 300mm Cylinder vs. 150mm Cube Strengths

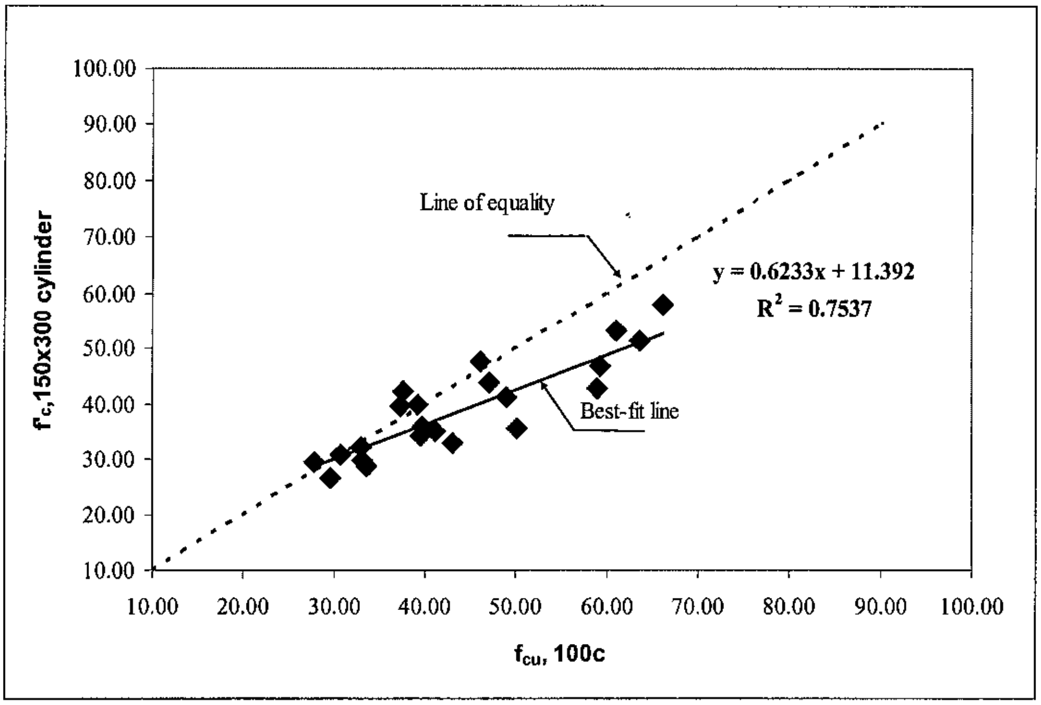

Figure 4.2: 150x300mm Cylinder vs. 100mm Cube Strengths

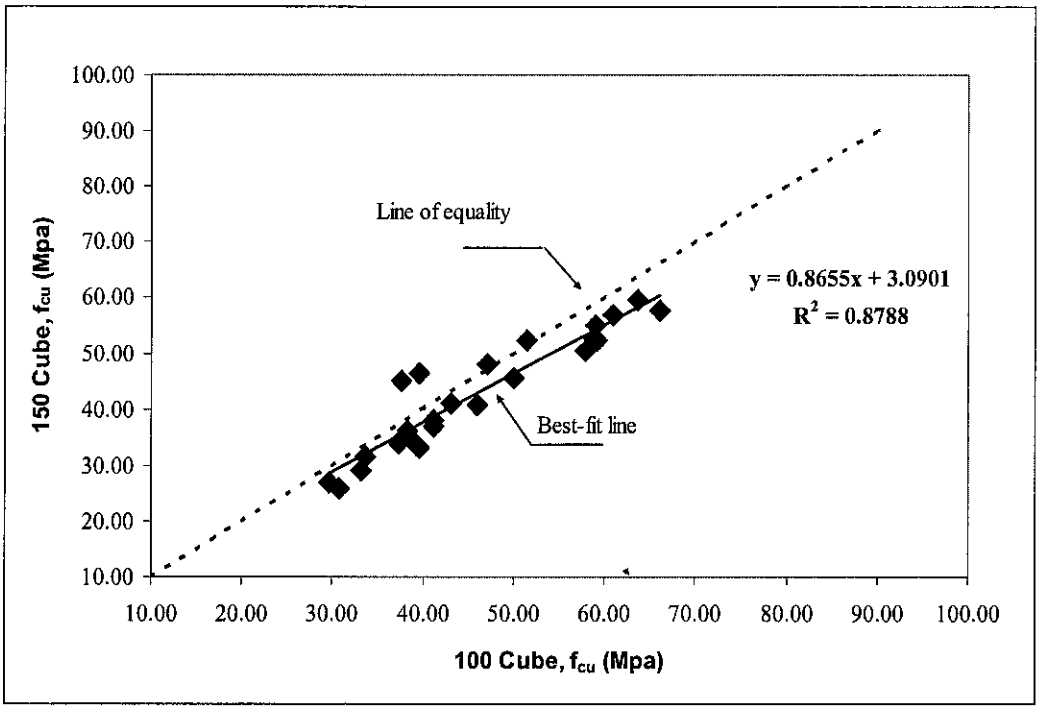

Figure 4.3: 150mm Cube vs. 100mm Cube Strengths

The linear regression analysis was carried out to analyze the three graphs above. The least-squares regression lines (minimum correlation coefficient 0.70) were yielded. The relationship between concrete strengths of different shape and size can be presented by the following equations:

- For 150x300mm cylinder and 150mm cube:
  $(f_c')_{150x300} = 0.5179\ (f_{cu})_{150} + 11.206$ (1)
  Correlation coefficient = 0.7796

- For 150x300mm cylinder and 100mm cube:
  $(f_c')_{150x300} = 0.6233\ (f_{cu})_{100} + 11.392$ (2)
  Correlation coefficient = 0.7537

- For 150mm cube and 100mm cube:
  $(f_{cu})_{150} = 0.8655(f_{cu})_{100} + 3.0901$ (3)
  Correlation coefficient = 0.8788

Where f_{cu} and f_c' are cube and cylinder strength in MPa respectively; and the subscripts denote the size of the specimens in mm.

The above relationships are obtained based on all strengths of concrete regardless their age. It can be considered as general relationships for respective strengths regarding only shape and size of specimen. Practically, not all strengths of every age are critical or equally important. Normally the strength at 28 days is the most important compared to the rest of the ages of concrete and it is normally used in design. To counter check whether or not the above general relationships give the most conservative results, it is necessary to find the relationships of those strength at respective age.

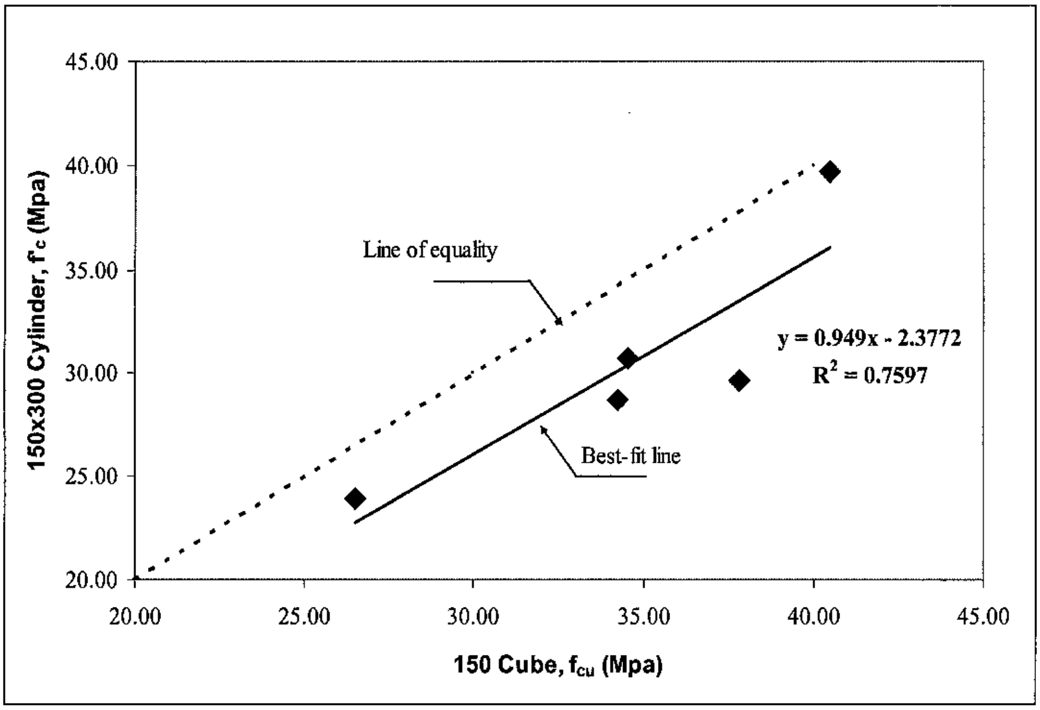

Figure 4.4: 150x300mm Cylinder vs. 150mm Cube 3days Strengths

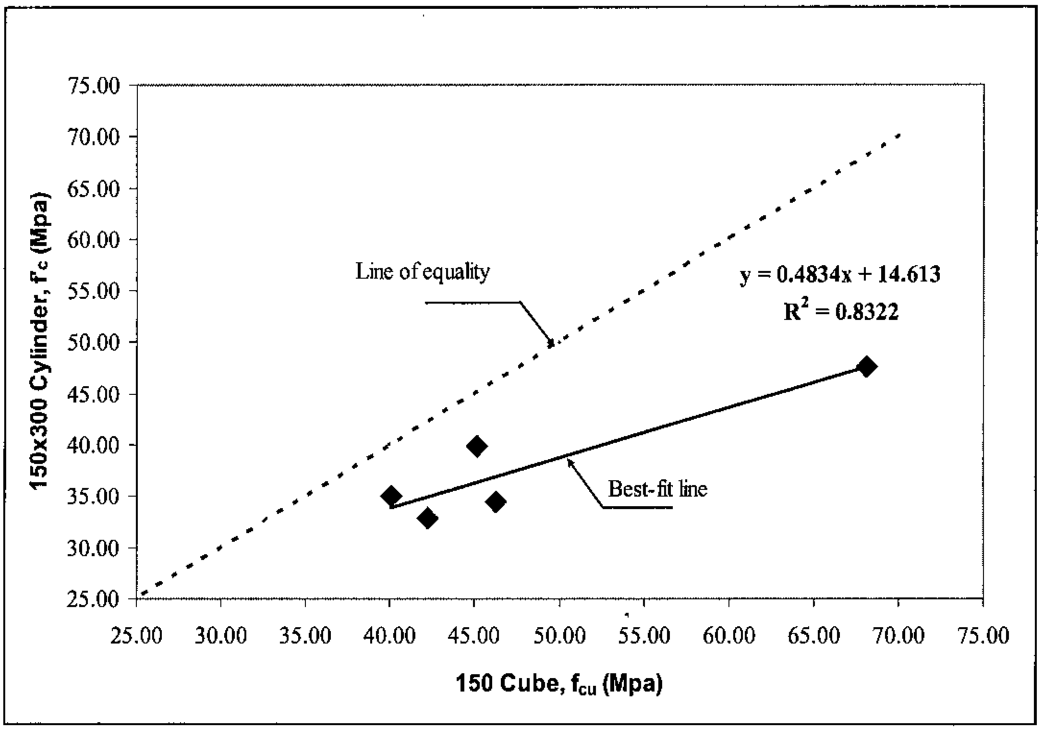

Figure 4.5: 150x300mm Cylinder vs. 150mm Cube 7days Strengths

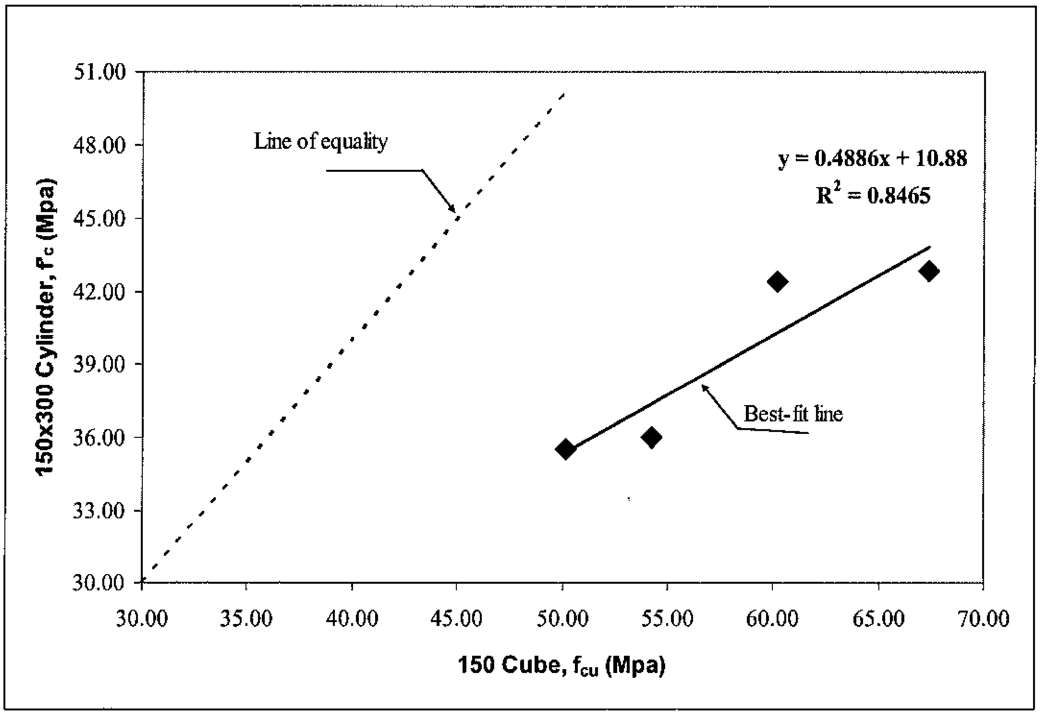

Figure 4.6: 150x300mm Cylinder vs. 150mm Cube 28days Strengths

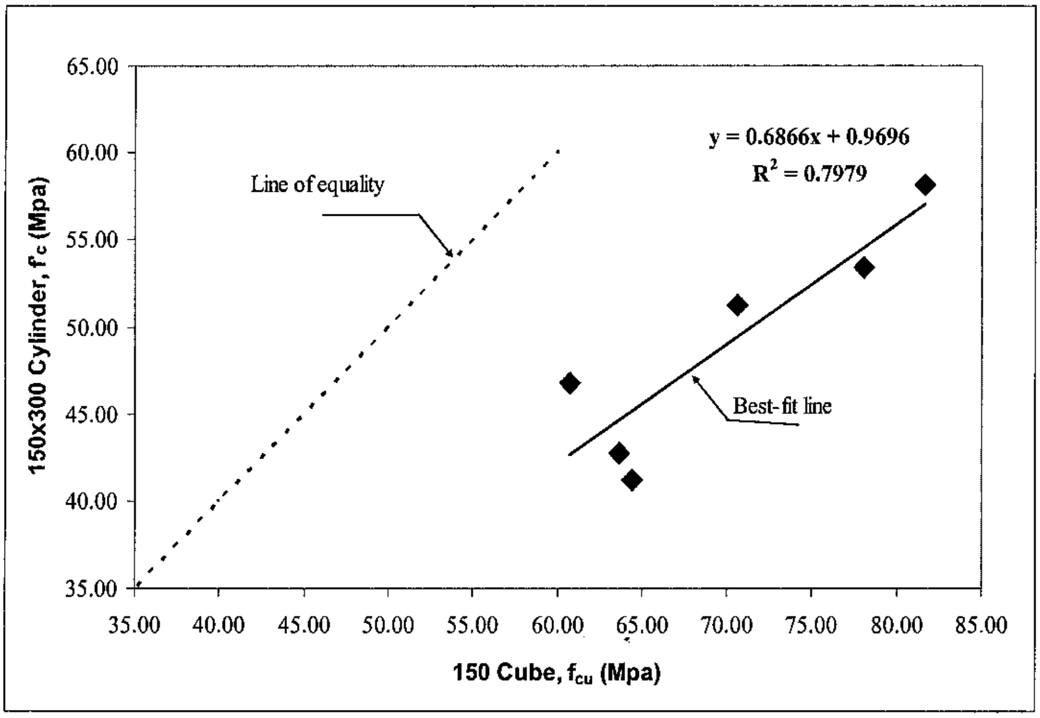

Figure 4.7: 150x300mm Cylinder vs. 150mm Cube 90days Strengths

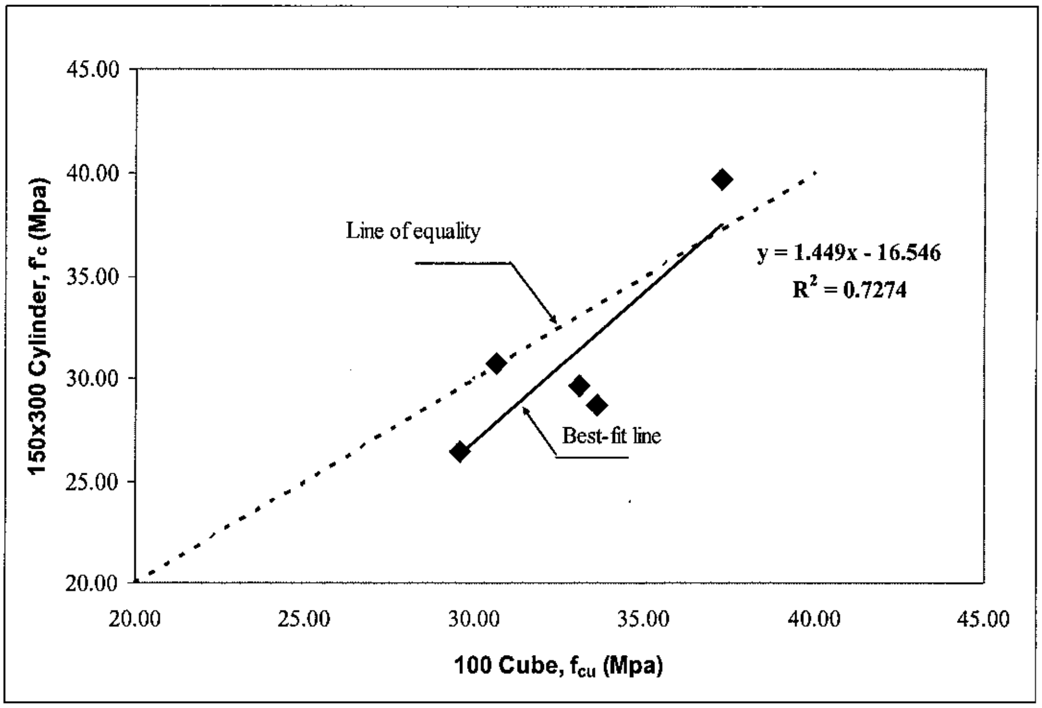

Figure 4.8: 150x300mm Cylinder vs. 100mm Cube 3days Strengths

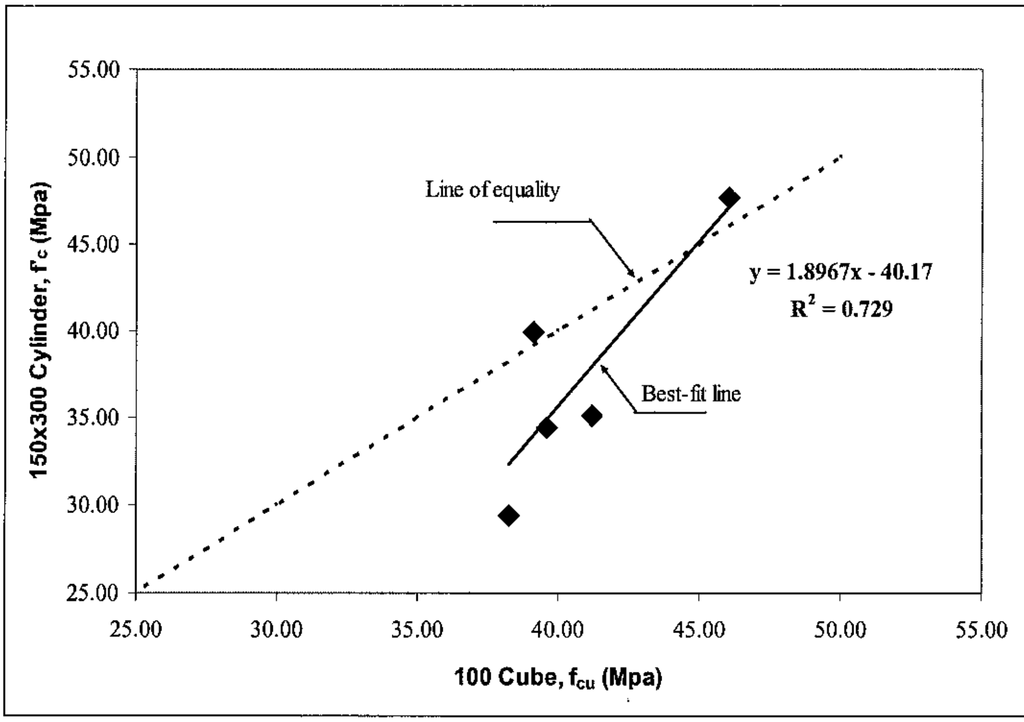

Figure 4.9: 150x300mm Cylinder vs. 100mm Cube 7days Strengths

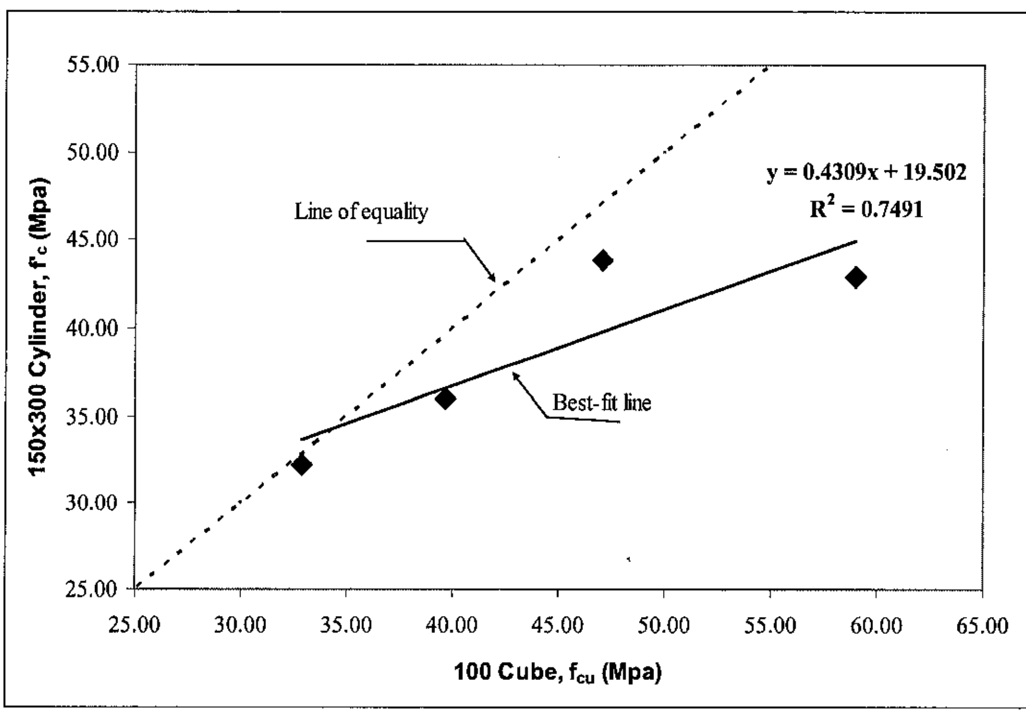

Figure 4.10: 150x300mm Cylinder vs. 100mm Cube 28days Strengths

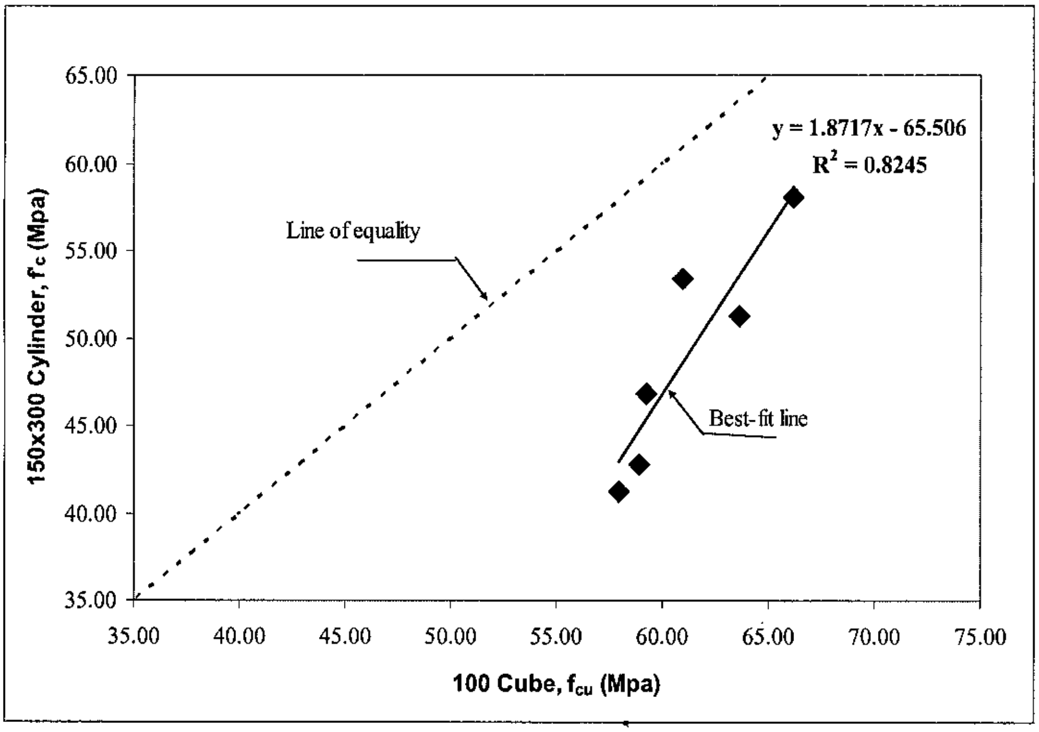

Figure 4.11: 150x300mm Cylinder vs. 100mm Cube 90days Strengths

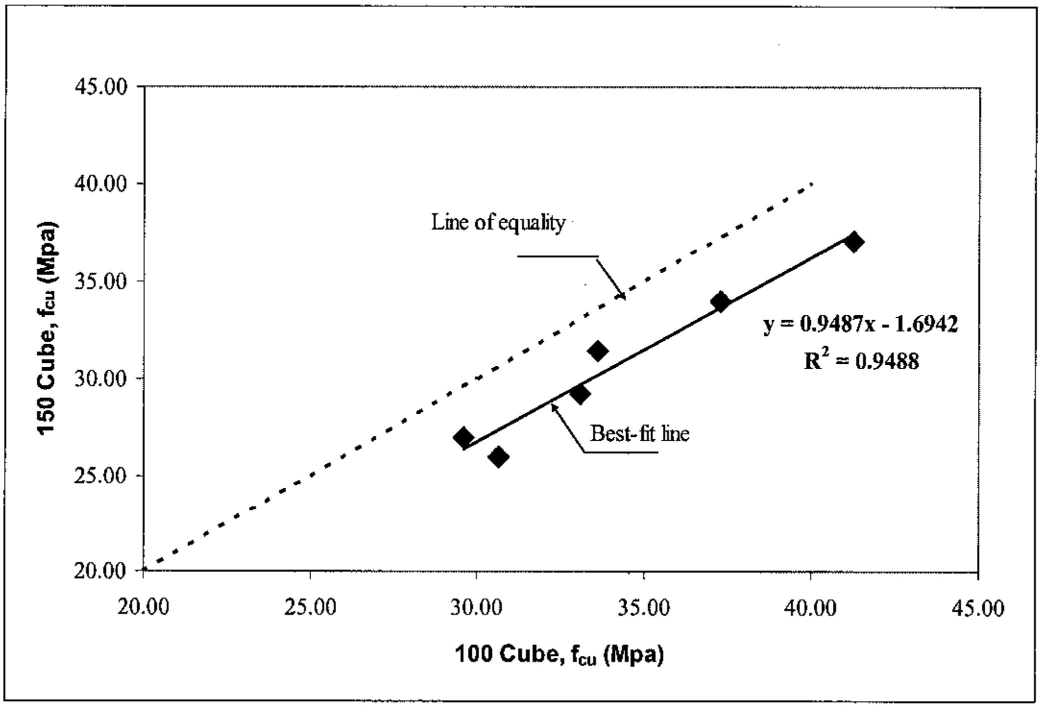

Figure 4.12: 150mm Cube vs. 100mm Cube 3days Strengths

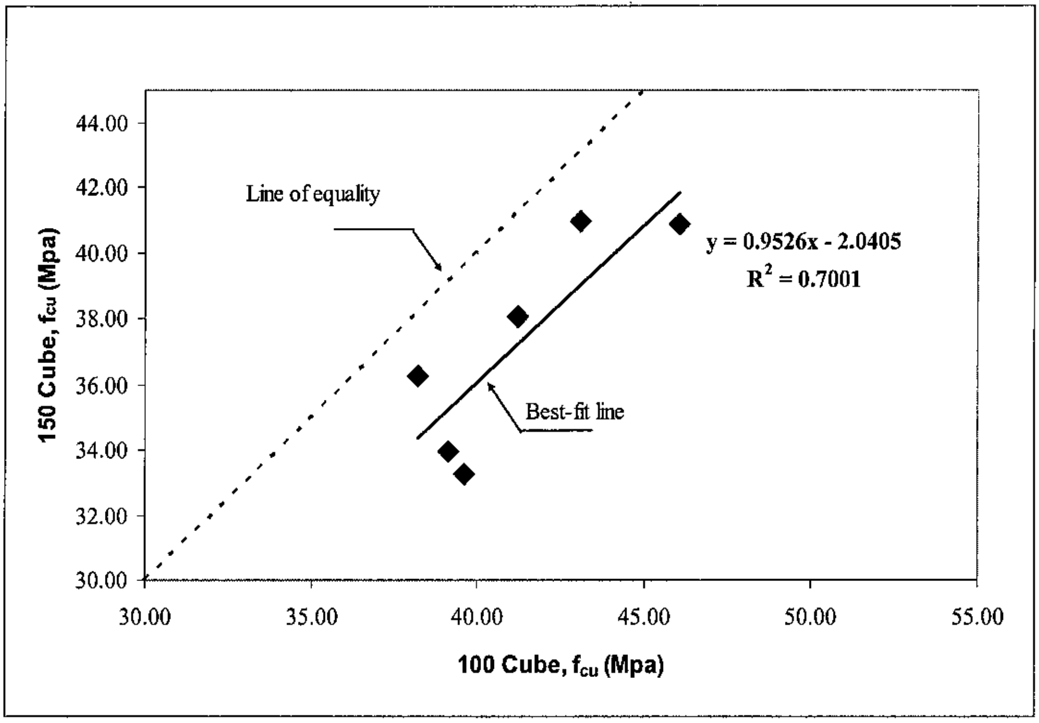

Figure 4.13: 150mm Cube vs. 100mm Cube 7days Strengths

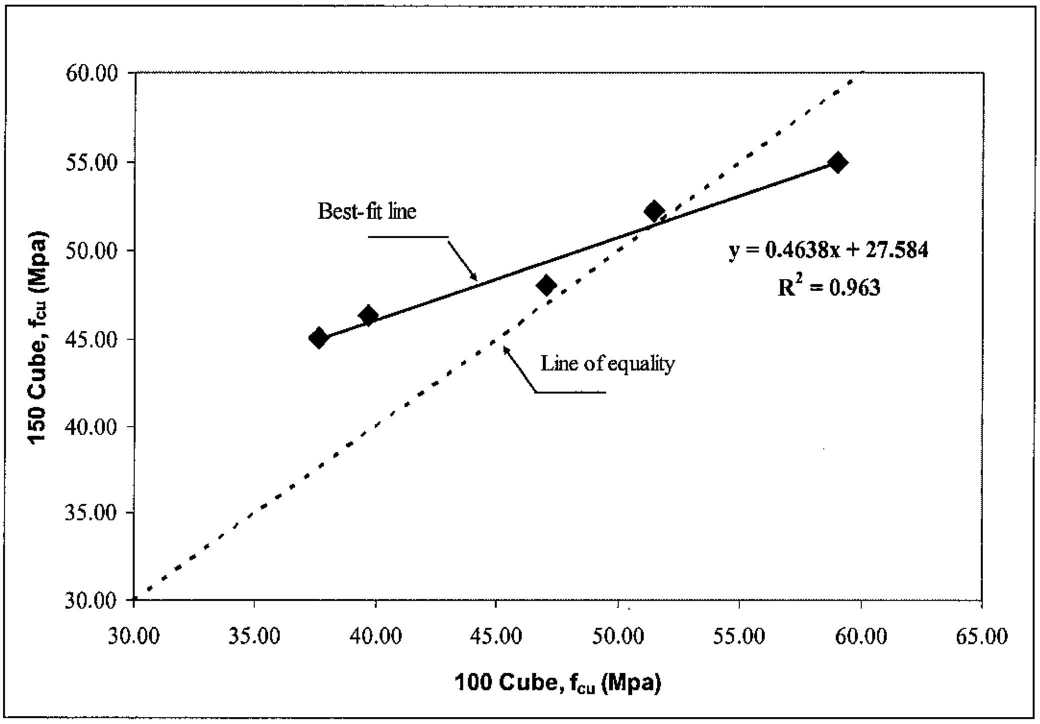

Figure 4.14: 150mm Cube vs. 100mm Cube 28days Strengths

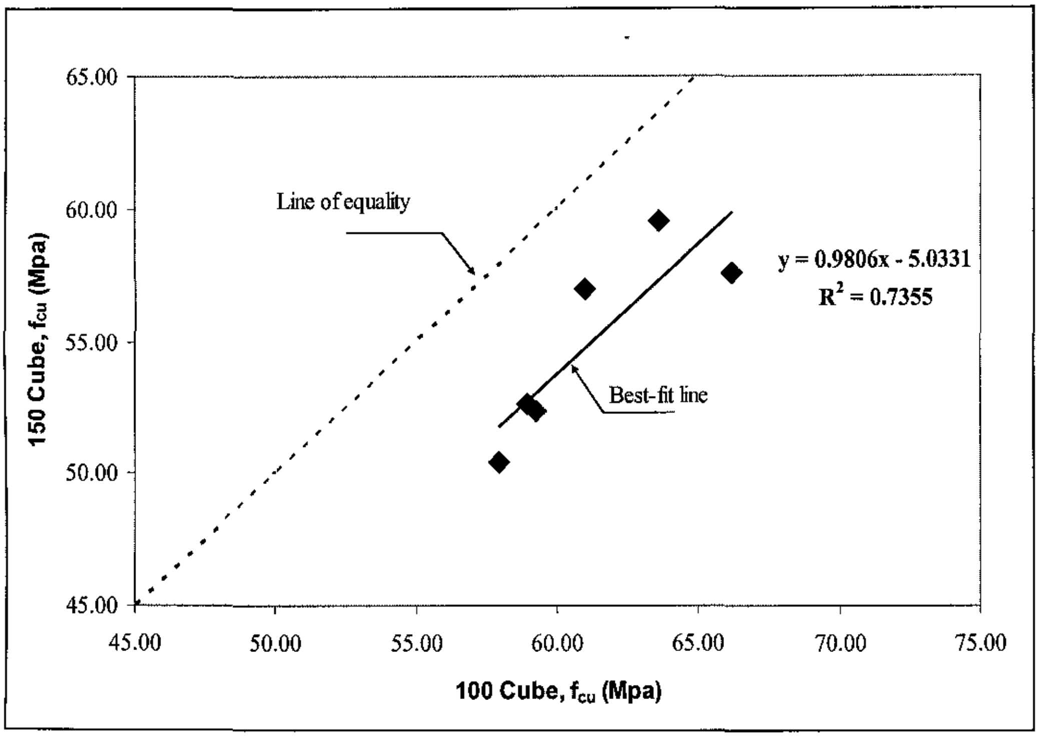

Figure 4.15: 150mm Cube vs. 100mm Cube 90days Strengths

Figures 4.4 to 4.15 are plotted based on data in table 4.2 and the relationship obtained from these Figures together with general relationships obtained from Figure 4.1 to 4.3 are summarized in Table 4.3 as followings:

Table 4.3: Summary of Relationships of Strengths

Relationship Between	Concrete Age	Equation	Correlation coefficient	Equation Number
150x300mm Cylinder vs. 150mm Cube	General	$(f_c')_{150x300} = 0.5179\ (f_{cu})_{150} + 11.206$	0.7796	1
	3days	$(f_c')_{150x300} = 0.9490(f_{cu})_{150} - 2.3772$	0.7597	4
	7days	$(f_c')_{150x300} = 0.4834(f_{cu})_{150} + 14.613$	0.8322	5
	28days	$(f_c')_{150x300} = 0.4886(f_{cu})_{150} + 10.88$	0.8465	6
	90days	$(f_c')_{150x300} = 0.6886(f_{cu})_{150} + 0.9696$	0.7979	7
150x300mm cylinder and 100mm cube	General	$(f_c')_{150x300} = 0.6233\ (f_{cu})_{100} + 11.392$	0.7537	2
	3days	$(f_c')_{150x300} = 1.4490(f_{cu})_{100} - 16.5460$	0.7274	8
	7days	$(f_c')_{150x300} = 1.8967(f_{cu})_{100} - 40.170$	0.7290	9
	28days	$(f_c')_{150x300} = 0.4309(f_{cu})_{100} + 19.5020$	0.7491	10
	90days	$(f_c')_{150x300} = 1.8717(f_{cu})_{100} - 65.5060$	0.8245	11
150mm Cube and 100mm Cube	General	$(f_{cu})_{150} = 0.8655(f_{cu})_{100} + 3.0901$	0.8788	3
	3days	$(f_{cu})_{150} = 0.9487(f_{cu})_{100} - 1.6942$	0.9488	12
	7days	$(f_{cu})_{150} = 0.9526(f_{cu})_{100} - 2.0405$	0.7001	13
	28days	$(f_{cu})_{150} = 0.4638(f_{cu})_{100} + 27.584$	0.9630	14
	90days	$(f_{cu})_{150} = 0.9806(f_{cu})_{100} - 5.0331$	0.7355	15

Comparing all the relationships of strength obtained as shown in table 4.3, the equations for 28days are more conservative than the general equations for all the three cases because the equations for 28days give lower coefficients compared to the general equations.

This is because the additive materials were used in the mixes e.g. PFA. This additive material has affected the early strengths of concrete for instant 3days and 7 days strengths. However the 28days strengths of concrete is not very much affected by that. In general equations, all strengths of every age are lumped together. So the equations obtained might not represent the real design strengths. To be at the safe side, the design should be more conservative. Therefore the equations for 28days should be used rather than the general equations.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

As discussed in previous chapter, the equations for 28days strengths should be used to represent the relationships of the strengths for conservative purpose. Hence, the relationship between concrete strengths of different shape and size can be presented by the following equations:

- For 150x300mm cylinder and 150mm cube:

$$(f_c')_{150x300} = 0.4886(f_{cu})_{150} + 10.88 \quad (6)$$

- For 150x300mm cylinder and 100mm cube:

$$(f_c')_{150x300} = 0.4309(f_{cu})_{100} + 19.5020 \quad (10)$$

- For 150mm cube and 100mm cube:

$$(f_{cu})_{150} = 0.4638(f_{cu})_{100} + 27.584 \quad (14)$$

Where f_{cu} and f_c' are cube and cylinder strength in MPa respectively; and the subscripts denote the size of the specimens in mm.

5.2 RECOMMENDATIONS

After getting through this project, there are certain points to be recommended:

- If possible the aggregates should be stored in a proper place to keep them clean and good quality.
- More literature reviews should be done in order to gain more knowledge in the project matter deeper and clearer.

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APPENDICES

APPENDIX A
NUMBER AND TYPES OF SPECIMENS CAST FOR EACH MIX

A.1 NUMBER AND TYPES OF SPECIMENS CAST IN FYP1

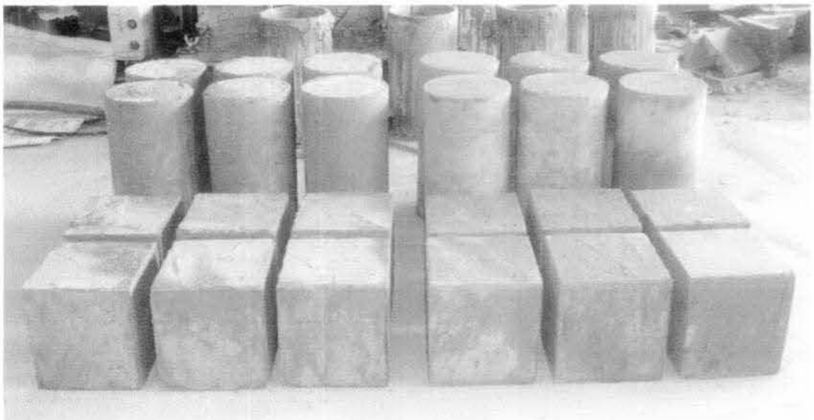

Figure A1: Side View of Specimens Cast in FYP1

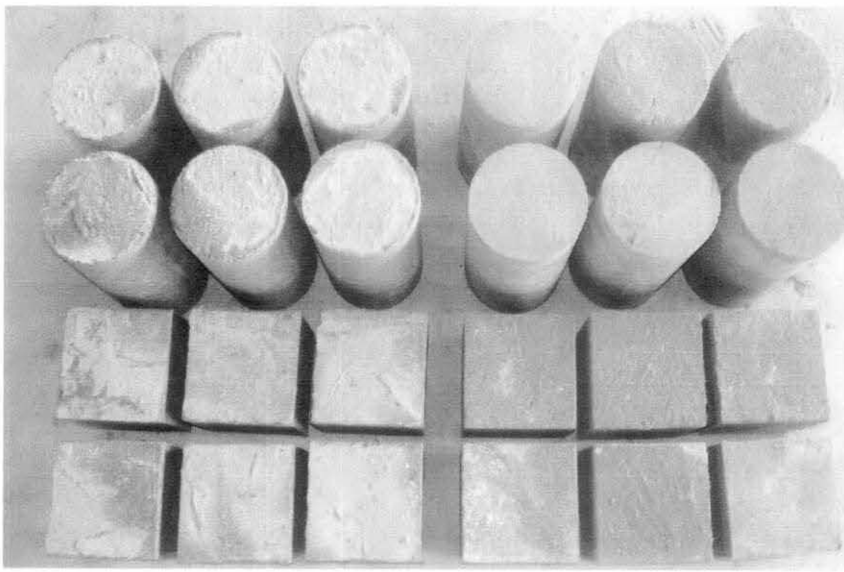

Figure A2: Top View of Specimens Cast in FYP1

A.2 NUMBER AND TYPES OF SPECIMENS CAST IN FYP2

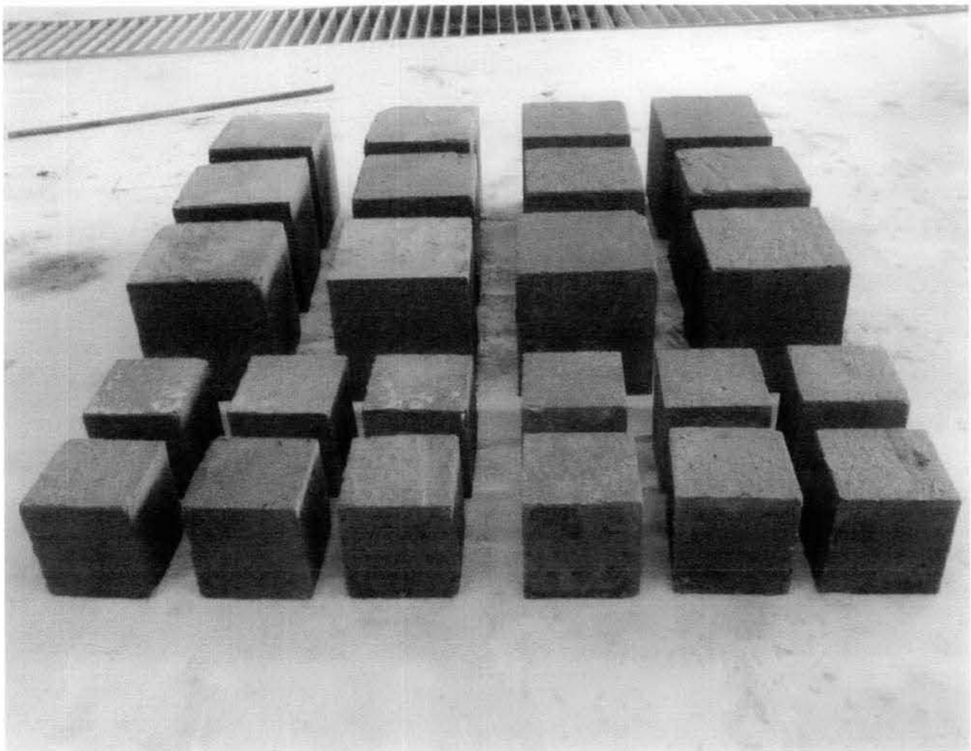

Figure A3: Side View of Specimens Cast in FYP2

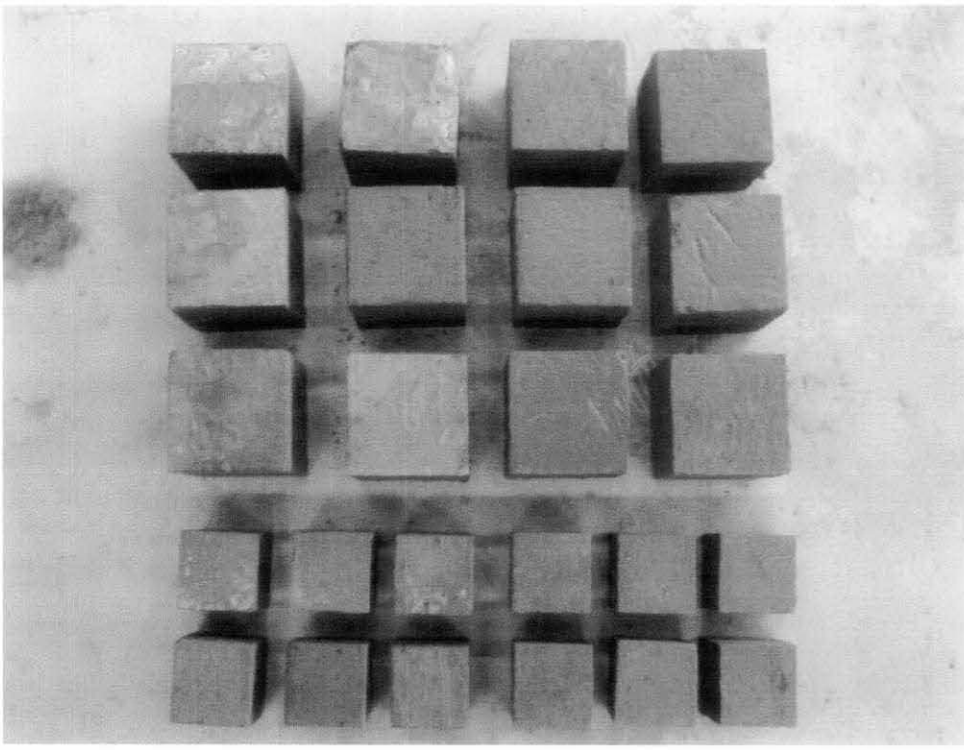

Figure A4: Top View of Specimens Cast in FYP2

APPENDIX B

COMPRESSION TESTING MACHINE

Figure B1: Bench-Height Base Unit and Electrical Control System of Compression Testing Machine

Figure B2: Close-Up Look of Bench-Height Base Unit

APPENDIX C

RESULTS OF REJECTED MIXES

Table C1: Results of Cylinder Strength of the 2nd Mix

Concrete Age	Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)
3days	407.30	23.05
	401.70	22.73
	404.68	22.90
Average	**404.56**	**22.89**
7days	266.60	15.09
	387.20	21.91
	303.40	17.17
Average	**319.07**	**18.06**
28days	331.10	18.74
	323.70	18.32
	487.30	27.58
Average	**380.70**	**21.54**

Table C2: Results of the Supposed-to-Be 3rd Mix

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	396.80	17.64	378.30	21.41
	252.90	11.24	467.10	26.43
	467.80	20.79	362.70	20.52
Average	**372.50**	**16.56**	**402.70**	**22.79**
7days	571.00	25.38	368.30	20.84
	882.60	39.23	642.10	36.34
	869.70	38.65	802.70	45.42
Average	**774.43**	**34.42**	**604.37**	**34.20**

APPENDIX D

RAW DATA RESULTED FROM ACCEPTED MIXES

Table D1: Results of Mix 1 of 150 mm Cube and 150x300mm Cylinder

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	608.77	27.05	457.00	25.87
	548.27	24.37	571.4*	32.33*
	584.47	25.99	389.20	22.02
	642.26	28.54	257.2*	14.55*
Average	**595.95**	**26.49**	**423.10**	**23.95**
7days	964.83	42.89	581.70	32.92
	933.59	41.49	580.50	32.85
Average	**949.21**	**42.19**	**581.10**	**32.89**
28days	1481.00	65.82	804.10	45.50
	1488.00	66.13	587.4*	33.24*
	1577.00	70.11	710.70	40.22
Average	**1515.33**	**67.35**	**757.40**	**42.86**
90days	1691.00	75.16	894.20	50.60
	1801.00	80.06	457.20*	25.87*
	1776.00	78.91	992.50	56.16
Average	**1756.00**	**78.04**	**943.35**	**53.38**

Table D2: Results of Mix 2 of 150 mm Cube and 150x300mm Cylinder

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	780.00	34.70	519.90	29.42
	771.60	34.28	506.70	28.67
	758.90	33.73	496.30	28.08
Average	**770.17**	**34.24**	**507.63**	**28.72**
7days	875.70	38.92	620.80	35.13
	902.00	40.09	605.70	34.28
	923.60	41.05	633.50	35.85
Average	**900.43**	**40.02**	**620.00**	**35.09**
28days	1204.00	53.51	614.60	34.78
	1207.00	53.64	695.50	39.36
	1249.00	55.51	599.20	33.91
Average	**1220.00**	**54.22**	**636.43**	**36.02**
90days	1465.00	65.11	783.20	44.32
	1403.00	62.36	748.40	42.35
	1429.00	63.51	735.60	41.63
Average	**1432.33**	**63.66**	**755.73**	**42.77**

Table D3: Results of Mix 3 of 150 mm Cube and 150x300mm Cylinder

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	908.66	40.38	479.70	27.15
	813.54	36.16	544.60	30.82
	829.30	36.86	548.10	31.02
Average	**850.50**	**37.80**	**524.13**	**29.66**
7days	1045.00	46.44	617.80*	34.96*
	1001.00	44.49	515.50	29.17
	1075.00	47.78	523.30	29.61
Average	**1040.33**	**46.24**	**519.40**	**29.39**
28days	1326.00	58.94	593.00	33.56
	1182.00	52.55	545.90	30.89
	1329.00	59.06	690.40*	39.07
Average	**1279.00**	**56.85**	**569.45**	**32.22**
90days	1624.00	72.18	1026.00	58.06
	1529.00	67.96	764.00*	43.23*
	1762.00	78.31	1028.00	58.17
Average	**1638.33**	**72.81**	**1027.00**	**58.12**

Table D4: Results of Mix 4 of 150 mm Cube and 150x300mm Cylinder

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	1051.00	46.71	475.90	26.93
	989.00	43.96	588.70*	33.31*
	1021.00	45.38	458.40	25.94
Average	**1020.33**	**45.35**	**467.15**	**26.44**
7days	960.50	42.69	623.60	35.29
	1086.00	48.27	601.10	34.02
	1076.00	47.82	599.90	33.95
Average	**1040.83**	**46.26**	**608.20**	**34.42**
28days	1134.00	50.40	680.80	38.53
	1085.00	48.22	615.20	34.81
	1168.00	51.91	588.10	33.28
Average	**1129.00**	**50.18**	**628.03**	**35.54**
90days	1490.00	66.22	696.60	39.42
	1454.00	64.62	745.00	42.16
	1406.00	62.49	744.10	42.11
Average	**1450.00**	**64.44**	**728.57**	**41.23**

Table D5: Results of Mix 5 of 150 mm Cube and 150x300mm Cylinder

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	899.44	39.98	692.57	39.19
	918.13	40.81	706.96	40.01
	914.01	40.62	703.79	39.83
Average	**910.53**	**40.47**	**701.11**	**39.67**
7days	1116.05	49.60	859.36	48.63
	1102.31	48.99	848.78	48.03
	1062.91	47.24	818.44	46.31
Average	**1093.76**	**48.61**	**842.19**	**47.66**
28days	1309.00	58.18	751.00	42.50
	1240.00	55.11	844.10	47.77
	1315.00	58.44	729.90	41.30
Average	**1288.00**	**57.24**	**775.00**	**43.86**
90days	1513.00	67.24	950.90	53.81
	1640.00	72.89	824.40	46.65
	1610.00	71.56	943.20	53.37
Average	**1587.67**	**70.56**	**906.17**	**51.28**

Table D6: Results of Mix 6 of 150 mm Cube and 150x300mm Cylinder

Concrete Age	Cube Strength		Cylinder Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	766.13	34.05	536.29	30.35
	810.58	36.03	567.41	32.11
	754.56	33.54	528.19	29.89
Average	**777.09**	**34.54**	**543.96**	**30.78**
7days	1016.42	45.17	711.49	40.26
	1033.32	45.93	723.32	40.93
	997.06	44.31	697.94	39.50
Average	**1015.60**	**45.14**	**704.72**	**39.88**
28days	1313.00	58.36	763.50	43.21
	1377.00	61.20	609.90*	34.51*
	1373.00	61.02	735.80	41.64
Average	**1354.33**	**60.19**	**749.65**	**42.42**
90days	1689.00*	75.07*	823.90	46.62
	1396.00	62.04	575.70*	32.58*
	1335.00	59.33	829.50	46.94
Average	**1365.50**	**60.69**	**826.70**	**46.78**

Table D7: Results of Mix 1 of 150 mm Cube and 100mm Cube

Concrete Age	150 Cube Strength		100 Cube Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	784.90	34.88	393.60	39.36
	867.80	38.57	388.40	38.84
	847.40	37.66	455.40	45.54
Average	**833.37**	**37.04**	**412.47**	**41.25**
7days	927.90	41.24	425.43	42.54
	892.44	39.66	454.32	45.43
	944.10	41.96	436.50	43.65
Average	**921.48**	**40.95**	**430.97**	**43.10**
28days	1217.00	54.09	561.50	56.15
	1178.00	52.36	447.60*	44.76*
	1316.00	58.49	618.60	61.86
Average	**1237.00**	**54.98**	**590.05**	**59.01**
90days	1305.18	58.01	674.60	67.46
	1281.21	56.94	617.70	61.77
	1259.09	55.96	536.40	53.64
Average	**1281.83**	**56.97**	**609.57**	**60.96**

Table D8: Results of Mix 2 of 150 mm Cube and 100mm Cube

Concrete Age	150 Cube Strength		100 Cube Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	705.80	31.37	331.40	33.14
	697.70	31.01	341.80	34.18
	721.70	32.08	335.20	33.52
Average	**708.40**	**31.48**	**336.13**	**33.61**
7days	725.40*	32.24*	401.94	40.19
	855.27	38.01	419.40	41.94
	857.52	38.11	414.54	41.45
Average	**856.40**	**38.06**	**411.96**	**41.20**
28days	988.10	43.92	699.60	69.96
	1099.00	48.84	641.40	64.14
	1379.00*	61.29*	680.60	68.06
Average	**1043.55**	**46.38**	**673.87**	**67.39**
90days	1223.00	54.36	565.10	56.51
	1089.00	48.40	647.70	64.77
	1241.00	55.16	554.80	55.48
Average	**1184.33**	**52.64**	**589.20**	**58.92**

Table D9: Results of Mix 3 of 150 mm Cube and 100mm Cube

Concrete Age	150 Cube Strength		100 Cube Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	621.00	27.60	332.10	33.21
	675.60	30.03	339.60	33.96
	678.20	30.14	321.20	32.12
Average	**658.27**	**29.26**	**330.97**	**33.10**
7days	884.60	39.32	394.41	39.44
	806.40	35.84	377.07	37.71
	756.20	33.61	375.22	37.52
Average	**815.73**	**36.25**	**382.23**	**38.22**
28days	1209.00	53.73	498.70	49.87
	1150.00	51.11	419.30*	41.93*
	1167.00	51.87	530.30	53.03
Average	**1175.33**	**52.24**	**514.50**	**51.45**
90days	1253.00	55.69	665.13	66.51
	1349.00	59.96	647.03	64.70
	1287.00	57.20	672.20	67.22
Average	**1296.33**	**57.61**	**661.45**	**66.15**

Table D10: Results of Mix 4 of 150 mm Cube and 100mm Cube

Concrete Age	150 Cube Strength		100 Cube Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	622.90	27.68	308.20	30.82
	620.50	27.58	285.90	28.59
	581.20	25.83	293.70	29.37
Average	**608.20**	**27.03**	**295.93**	**29.59**
7days	759.10	33.74	398.30	39.83
	727.00	32.31	381.70	38.17
	758.00	33.69	407.90	40.79
Average	**748.03**	**33.25**	**395.97**	**39.60**
28days	1048.00	46.58	295.60*	29.56*
	1208.00*	53.69*	475.20	47.52
	1007.00	44.76	526.00	52.60
Average	**1027.50**	**45.67**	**500.60**	**50.06**
90days	1403.53	62.38	609.09	60.91
	1539.39	68.42	574.84	57.48
	1407.07	62.54	554.76	55.48
Average	**1450.00**	**64.44**	**579.56**	**57.96**

Table D11: Results of Mix 5 of 150 mm Cube and 100mm Cube

Concrete Age	150 Cube Strength		100 Cube Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	755.83	33.59	375.38	37.54
	771.54	34.29	370.60	37.06
	768.08	34.14	372.60	37.26
Average	**765.15**	**34.01**	**372.86**	**37.29**
7days	937.86	41.68	425.66	42.57
	926.31	41.17	488.03	48.80
	893.20	39.70	467.39	46.74
Average	**919.12**	**40.85**	**460.36**	**46.04**
28days	1008.00	44.80	461.00	46.10
	1156.00	51.38	475.20	47.52
	1394.00*	61.96*	475.30	47.53
Average	**1082.00**	**48.09**	**470.50**	**47.05**
90days	1339.00	59.51	681.80	68.18
	1332.00	59.20	631.02	63.10
	1348.00	59.91	595.29	59.53
Average	**1339.67**	**59.54**	**636.04**	**63.60**

Table D12: Results of Mix 6 of 150 mm Cube and 100mm Cube

Concrete Age	150 Cube Strength		100 Cube Strength	
	Max. Load (kN)	Stress (Mpa)	Max. Load (kN)	Stress (Mpa)
3days	576.04	25.60	335.03	33.50
	609.46	27.09	293.76	29.38
	567.34	25.22	291.06	29.11
Average	**584.28**	**25.97**	**306.62**	**30.66**
7days	764.23	33.97	388.16	38.82
	776.93	34.53	326.87*	32.69*
	749.67	33.32	394.47	39.45
Average	**763.61**	**33.94**	**391.32**	**39.13**
28days	788.30*	35.04*	390.30	39.03
	1031.00	45.82	361.80	36.18
	999.00	44.40	461.80*	46.18*
Average	**1015.00**	**45.11**	**376.05**	**37.61**
90days	1223.00	54.36	569.18	56.92
	1139.00	50.62	578.50	57.85
	1171.00	52.04	629.71	62.97
Average	**1177.67**	**52.34**	**592.46**	**59.25**

Note: The results of same age should not be different more than 15%. The results with '' are those exceed this limit and are excluded when finding the average.*