# Use of small diameter cores in evaluation of in-situ concrete strength in Eastern Saudi Arabia

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Civil Engineering

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Abstract

Deterioration of concrete structures in the Arabian Gulf region is the major problem facing the construction industry in this region. Assessment of concrete structures is important necessity to evaluate the safety of these existing structures. To determine various physical and chemical characteristics of the concrete, core specimens must be retrieved from the structure. Determining the concrete quality along with compressive strength of structure using cores is considered the best technique at present. A review of the literature indicates that as the sample size increases, greater costs are incurred, and, more significantly, the risk of unduly weakening the structure increases. Though large specimens will ensure a reasonable ratio of specimen size to maximum aggregate size, it is impracticable to obtain such cores. Consequently, small cores may have to be adopted.

This research work is aimed to obviate the need of larger diameter cores and to make viable small diameter cores. To achieve this objective, 50 mm diameter cores were used to estimate the "standard" cylinder strength. The compressive strength of cast cylinder was statistically correlated with the 50 mm diameter core strength. The effect of the mixture design variables such as aggregate type maximum aggregate size, blended cements, water-cement ratio and age, was investigated. Results of the present investigation indicated that a linear model can be best used to estimate the in-situ concrete strength using the 50 mm diameter core strength. Moreover, a conversion factor was proposed to convert the 75 mm diameter core strngth into 75 mm diameter cylinder strength.

# Use of Small Diameter Cores in Evaluation of In-Situ Concrete Strength in Eastern Saudi Arabia

by

Naseer Ahmed Mohiuddin

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
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# USE OF SMALL DIAMETER CORES IN EVALUATION OF IN-SITU CONCRETE STRENGTH IN EASTERN SAUDI ARABIA

MS Thesis

By

*Naseer Ahmed Mohiuddin*

June, 1995

Dedicated to

*my beloved parents*

whose prayers, inspiration and love led to this accomplishment

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In the name of Allah, Most Gracious, Most Merciful. Read in the name of thy Lord and Cherisher, Who Created man from a {*leech-like* } clot. Read and thy Lord is Most Bountiful. He Who taught {the use of} the pen. Taught man that which he knew not. Nay, but man doth transgress all bounds. In that he looketh upon himself as self-sufficient. Verily, to thy Lord is the return {of all }. (The Holy Quran, Surah Al-A'alaq, No.96)

First and foremost, all praise to Allah, *subhanahu-wa-ta-Aala*, the Almighty, Who gave me an opportunity, courage and patience to carry out this work. I seek His mercy, favor, and forgiveness. I feel priviledged to glorify His name in the sincerest way through this small accomplishment. May He, *subhanahu-wa-ta-Aaala*, guide me and the whole humanity to the right path *(Aameen)*.

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# ABSTRACT

**Title:** **Use of Small Diameter Cores in Evaluation of In-Situ Concrete Strength In Eastern Saudi Arabia**

*Deterioration of concrete structures in the Arabian Gulf region is the major problem facing the construction industry in this region. Assessment of concrete structures is important necessity to evaluate the safety of these existing structures. To determine various physical and chemical characteristics of the concrete, core specimens must be retrieved from the structure. Determining the concrete quality along with compressive strength of structure using cores is considered the best technique at present. A review of the literature indicates that as the sample size increases, greater costs are incurred, and, more significantly, the risk of unduly weakening the structure increases. Though large specimens will ensure a reasonable ratio of specimen size to maximum aggregate size, it is impracticable to obtain such cores. Consequently, small cores may have to be adopted.*

*This research work is aimed to obviate the need of larger diameter cores and to make viable small diameter cores. To achieve this objective, 50 mm diameter cores were used to estimate the "standard" cylinder strength. The compressive strength of cast cylinder was statistically correlated with the 50 mm diameter core strength. The effect of the mixture design variables, such as aggregate type, maximum aggregate size, blended cements, water-cement ratio and age, was investigated. Results of the present investigation indicated that a linear model can be best used to estimate the in-situ concrete strength using the 50 mm diameter core strength. Moreover, a conversion factor was proposed to convert the 75 mm diameter core strength into 75 mm diameter cylinder strength.*

# Abstract (Arabic)

# ملخص الرسالة


## العنوان

## استعمال عينات لبية ذات أقطار صغيرة في التقييم الميداني لقوة الخرسانة بالمنطقة الشرقية من السعودية

إنّ تدهور المنشآت الخرسانية في منطقة الخليج العربي هو المشكلة الأساسية التي تواجه صناعة الإنشاءات في هذه المنطقة ويعتبر تقييم المنشآت الخرسانية ضرورة هامة لتقدير سلامة هذه المنشآت القائمة ولتحديد مختلف الخواص الفيزيائية والكيماوية للخرسانة لابد من أخذ عينات لبية من المنشأ ويعتبر تحديد نوعية الخرسانة وقوة الضغط للمنشأ - بإستعمال العينات اللبية - الأسلوب الأفضل في الوقت الحاضر وقد دلت مراجعة الأبحاث المنشورة أن زيادة حجم العينة يؤدي لزيادة التكلفة كما يرفع من درجة المخاطرة بإضعاف المنشأ . وفي حين أن العينة ذات الحجم الكبير تؤمن نسبة معقولة ما بين حجمها إلى حجم الحبيبات الحصوية المستعملة فيها إلا أنه من غير العملي الحصول على مثل هذه العينات لذلك ربما يصبح استخدام عينات لبية أمراً ضرورياً .

يهدف هذا البحث إلى تفادي الحاجة لإستخدام عينات ذات أقطار كبيرة واستعمال عينات صغيرة القطر بدلاً منها . ولتحقيق هذا الهدف استعملت عينات لبية أقطارهم ٥٠ مم لتقدير المتانة الاسطوانية المعيارية وقد تم ربط قوة ضغط القالب الاسطواني مع متانة العينات اللبية ذات القطر ٥٠ مم .

كما جرى تقصي أثر المتغيرات في خليط التصميم مثل : نوع الحصى وحجمها ، مزيج الاسمنت ، نسبة الماء إلى الاسمنت والعمر . وقد بينت نتائج التحريات الحالية أن نموذجاً خطياً يمكن استخدامه لتقدير المتانة الميدانية للخرسانة بإستخدام متانة عينات لبية بقطر ٥٠ مم . بالإضافة لذلك فقد تم اقتراح معامل لتحويل متانة عينة لبية بقطر ٧٥ مم إلى المتانة الاسطوانية بنفس القطر .

# Chapter 1

# INTRODUCTION

The *in-situ* compressive strength of concrete is one of the obligatory needs most frequently encountered whenever it is necessary to assess a structure. Compressive strength of concrete is an excellent indicator of concrete quality and it invariably forms the most important basis of specification and quality control, as many other properties are directly or indirectly related to it. A wide variety of destructive and non-destructive tests are used to determine the strength. The most widely accepted and oldest method for determining the in-place strength of portland cement concrete in existing structures and pavements is the testing of core specimens obtained by drilling with a diamond core bit. The procedure is standardized under the Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete (ASTM C 42). Compared to other methods, core testing has one cardinal advantage in that the estimation of the average *in-situ* concrete strength is obtained directly from the analysis of the tests performed on the concrete being considered.

Core testing is still viewed as the safest method to determine the compressive

strength of concrete despite the fact that the results obtained are influenced by a great number of parameters which may result in considerable interpretation errors due to variations in L/D (length/diameter) ratio, position and direction of drilling, damage caused by drilling the specimen, preparation, etc. Even the diameter of the core has a considerable effect on the test results. According to the most commonly used international standards, codes of practice and recommendations currently in force, the minimum core diameter is generally fixed at 100 mm.

The ASTM C 42 and the BS:1881 standards specify that the core diameter should be at least three times the nominal maximum size of the coarse aggregate in the concrete. For the concrete most widely used in the building industry, with a minimum "maximum" size coarse aggregate of 1/2 inch (12.5 mm), this entails a lower limit which decreased the minimum recommended diameter to 75 mm. Though the recommendations ensure a reasonable ratio of specimen size to maximum aggregate size, it is sometimes impractical to obtain such cores, due to either the small size of the structural member or the critical reinforcement locations, etc. Consequently, cores of smaller diameters are often needed. Small diameter cores exhibit a greater number of advantages such as being relatively cheap, quick to obtain, requiring less storage space, causing less damage to the structure and more accessible. Growing need of maintenance and repair of concrete structures in eastern Saudi Arabia and the other Arabian Gulf countries, has focused attention in the assessment of *in-situ* concrete for which core testing is often necessary. This research is planned to obviate

the need of 75 mm diameter cores by prescribing strength prediction models based on 50 mm diameter cores.

## 1.1 Literature Review

The *in-situ* coring method is an effective way of obtaining considerable amount of test data to assess the properties of concrete. The problem of evaluating the *in-situ* compressive strength using cores has been studied for a long time. In this review of the literature only references pertinent to testing of cores to evaluate the concrete compressive strength and the corresponding influential factors are reported. The procedure for testing core specimens obtained by drilling with a diamond bit is well standardized in ASTM [1]. This procedure has been established using 100 mm or 150 mm diameter cores and is also recommended in BS:1881 [2] and in the Concrete Society technical report [3]. The factors which influence the relationship between the compressive strength of a core and the corresponding actual cube or cylinder compressive strength of concrete are described fully in Part 5 of the Concrete Society report [3]. This report also summarizes the past research on the topics pertinent to the usage of small cores until 1975.

Research conducted by Meninger et. al. [4] suggests that the measured concrete strength of specimens made with a L/D ratio of less than 2 yields a higher strength than specimens having L/D = 2 , and therefore the strength must be multiplied by correction factors less than unity to normalize the strength to the equivalent

"standard" L/D= 2 condition. The ASTM C 42 is entirely based on the results of Meninger et al. [4].

Chung [5] studied the effect of L/D ratio on the compressive strength of concrete cores via a semi-rational approach and compared his results with the existing test data of ASTM C 42-77, BS:1881 and Concrete Society. The following empirical formula has been deduced:

$$k = \frac{2}{1.5 + (1/\lambda)}$$

where:

k = strength correction factor: and

$\lambda$ = Length/diameter (L/D) ratio of concrete core

Chung concluded that the restraint, exerted by the steel platens of the compression testing machine on the end surfaces of the concrete core during the compression test, limits the lateral expansion of the core and creates a state of triaxial stress in the concrete, thus, increasing the compressive strength of the core when the L/D ratio decreases. He demonstrated nearly the same correction factors as those given by the ASTM standard. The proposed formula, which is semi-rational in nature, is based on experimental findings about concrete under triaxial compression, and yet it fits well the test data as shown in Table 1.1.

Table 1.1: Strength Correction Factors for Different L/D Ratios [5]

| L/D Ratio | ASTM Standard C 43-77 | British Standard BS 1881 | Proposed Formula |
|---|---|---|---|
| 1.0 | 0.87 | 0.92 | 0.83 |
| 1.25 | 0.93 | 0.94 | 0.90 |
| 1.5 | 0.96 | 0.96 | 0.95 |
| 1.75 | 0.98 | 0.98 | 0.99 |
| 2.0 | 1.00 | 1.00 | 1.00 |

Bungey [6] carried out an experimental program using 44 mm diameter cores to examine the influence of specimen size, aggregate size, length to diameter (L/D) ratio and orientation effects on the compressive strength of concrete. He compared the relationships between core strength and cube strength with those normally used for larger cores. It is shown that the core strength is affected by both specimen size and aggregate size, and it is proposed that the conversion to corresponding cube strengths should take this fact into account. The variability of results is also assessed in relation to the above factors, and an estimate is made of the accuracy of predicted actual cube strength which is likely to be achieved from testing cores of this size. The effect of L/D ratio is closer to the values proposed by the Concrete Society [3] pertinent to large cores. Bungey's results indicated that the sensitivity analysis of small cores to the many factors outlined above revealed that the variability of results is likely to be so large that the use of such cores to assess the strength of *in-situ* concrete is of doubtful value in many practical situations.

The investigation conducted by Lewis [7] justifies the usage of 75 mm diameter cores, which have already been permitted by the Australian Standards [8]. Lewis confirms the need to use small cores in some circumstances and emphasizes the importance of the core diameter to aggregate size ratio. The results of Lewis agree with Bungey's for securing and testing of cores from hardened concrete structures.

Bowman [9] highlighted the importance of using small cores. In order to compare the variability of his results from large and small diameter cores taken from an actual

structure, 50 mm diameter cores were taken from positions as near as possible to the 150 mm diameter cores. Both types were tested under compression. 50 mm diameter cores exhibited higher strength and greater variability when compared to 150 mm diameter cores. Although the size of aggregate was not reported, the strength and coefficients of variation of the data followed the pattern suggested by Bungey [6]. He concluded that the 50 mm diameter cores, being relatively cheap and quick to obtain, should continue to be used, not only for visual checks, but also for strength assessment of the cast-in-place concrete.

Swamy and Al-Hamed [11] used 50 mm diameter cores to determine *in-situ* concrete compressive strength. The cores, with length to diameter (L/D) ratios of 1 and 2, were drilled vertically from slabs which were cured in an uncontrolled internal environment to simulate conditions in practice. The variables investigated included level of concrete strength, mix proportions, age, type of coarse aggregate and type of concrete, i.e. normal and light weight. The core strength results were compared with cube strength, pulse velocity and windsor probe test results. They found that the variability of the test results increased with the size and the type of aggregate. The estimated strength of 50 mm diameter cores varied from 72% to 85% of the dense, wet cured concrete and from 80% to 90% for light weight concrete.

Yip and Tam [15] investigated the use of 50 mm diameter cores. The compressive strength of these cores was compared with the strength of 100 mm diameter cores and control cubes. Other factors were also investigated including diameter.

length/diameter ratio, direction of drilling, curing conditions, age of concrete and location of cored specimens. The results were compared with available published data. They found that the measured strength of the 50 mm diameter cores do not differ significantly from those of the 100 mm diameter cores tested under the same conditions and for the same grade of concrete. The effect of L/D ratio on the strength of both 50 mm and 100 mm diameter cores are similar to those reported by other researchers and the correction factors are closer to those of ASTM [1] than those of BS 1881 [2]. They suggested that a larger number of cores would reduce the variability of results associated with testing of small diameter cores. Typically, the variability in strength of five 50 mm diameter cores was very similar to that of three 100 mm diameter cores. This supports the viability of using 50 mm diameter cores to assess the *in-situ* strength of hardened concrete.

A virtually non-destructive method of testing based on the strength of microcores (28 mm diameter) obtained from existing structures was developed by Indelicato [19] for the determination of cube strength of concrete types commonly used in the building industry. From a statistical examination of the data derived from compression tests on 480 microcores and 240 cubes, a linear correlation was obtained together with the relative confidence intervals, for both cube and microcore strengths. There after, confidence intervals for future individual observations were worked out so as to be able to predict, to a pre-determined confidence level, the estimated *in-situ* mean strength on the basis of mean microcore strength. The maximum aggregate

size used was 30 mm. The correlation coefficient between mean cube strength and mean microcore strength was calculated (r = 0.89). Figure 1.1 shows the correlation between the two types of strength. The conclusion was that the correlation between the mean cube strength and the microcore strength is linear. It is characterized by a high correlation coefficient and by a regression coefficient whose confidence interval is very narrow. He concluded that microcores can be used as a non-destructive means to assess the cube strength of concrete with a maximum aggregate size of 30 mm.

A comprehensive research program on *in-situ* determination of concrete strength was undertaken by Goncalves to study the influence of core dimension on the mean compressive strength and its dispersion [20]. Tests were conducted on 140 mm, 110 mm, 90 mm and 50 mm diameter cores. The 28 day strength results showed that the variation in concrete strength increases with the increase in the maximum aggregate size and decrease of core diameter. However, the mean compressive strengths of cores were the same as those of cubes and were not influenced by the core diameter. The compressive strength of the 90 mm and 50 mm diameter cores is equal to that of the 200 mm cubes, at least for strength levels of about 30 MPa and for a maximum aggregate size of 25.4 mm. Indelicato suggested that the mean strength of concrete can be estimated with about the same degree of accuracy by testing 4 cores with 90 mm diameter or 6 cores with 50 mm diameter, for the strength level considered. Thus, the use of small diameter cores may be possible.

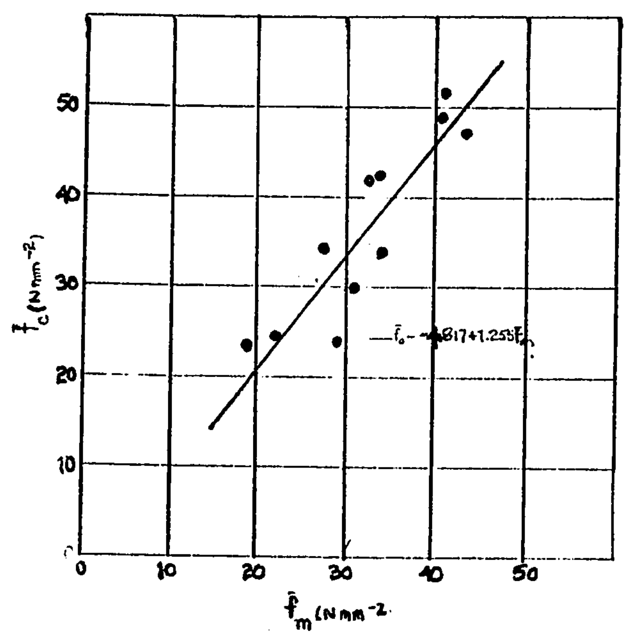


Figure 1.1: Regression Line of Mean Cube Strength and Mean Microcore Strength [19]

Bartlett and MacGregor [21] have recently conducted an extensive investigation to determine length to diameter correction factors for concrete cores and to outline the precision of these factors. The data represented strength tests of core specimens, all 100 mm in diameter, obtained from 10 different elements cast form ordinary portland cement concretes with strengths between 2,000 and 14,000 psi (13.80 and 96.5 MPa). Strength correction factors are determined in order to convert the strength of a core with an L/D ratio between 1 and 2 to the strength of an equivalent standard specimen with an L/D of 2.

The data reported by Bartlett and MacGregor [21] indicates that both the core moisture condition and the core strength significantly affects the strength correction factors [21]. The proposed strength correction factors differ only slightly from those currently recommended in ASTM C 42 [1]. They concluded that the required strength correction factor is significantly reduced for high-strength concrete. As the concrete strength increases, correction factors closer to 1.0 are appropriate. The results fit well the current set of strength correction factors in ASTM C 42 for air-dried cores. Further, there is no difference between the observed coefficient of variation of strength for standard cores with L/D = 2, and the strengths of cores with L/D = 1. The observations are corroborated by the ratios of observed to predicted correction factors, as evidenced in Table 1.2.

Table 1.2: Ratio of Actual to Predicted Compressive Strength Correction Factors [21]

| Method | L/D = 1.00 | | L/D = 1.25 | | L/D = 1.50 | | L/D = 1.75 | | L/D = 2.00 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Avg. | V,% | Avg. | V,% | Avg. | V,% | Avg. | V,% | Avg. | V,% |
| Proposed Formula | 1.00 | 3.2 | 1.02 | 2.8 | 1.00 | 2.50 | 1.00 | 1.5 | 1.00 | 2.6 |
| Chung(89) | 1.07 | 3.9 | 1.02 | 2.8 | 1.00 | 2.30 | 1.00 | 1.5 | 1.04 | 4.4 |
| Chung(79) | 1.08 | 3.7 | 1.04 | 2.8 | 1.02 | 2.30 | 1.01 | 1.4 | 1.04 | 3.9 |
| Concrete Society | 1.12 | 3.8 | 1.08 | 2.8 | 1.05 | 2.30 | 1.03 | 1.4 | 1.08 | 4.4 |
| ASTM C 42-68 | 0.99 | 3.4 | 1.00 | 2.8 | 1.00 | 2.40 | 1.01 | 1.5 | 1.00 | 2.9 |
| ASTM C 42-77 | 1.03 | 3.4 | 1.01 | 2.8 | 1.02 | 2.40 | 1.02 | 1.5 | 1.02 | 2.9 |

Bartlett and MacGregor [22] have also analyzed the core strength data reported by others to investigate the effect of diameter of test specimens on compressive strength of cores. The various explanations of the diameter effect which were reported earlier by other researchers were reviewed to forecast whether they are corroborated by the core strength data. The data from the previous research indicates that the effect of damage to the cut surface of the core counteracts and overwhelms any effect that might be attributed to systematic bias caused by testing procedures. Based on their statistical analyses [22], the predicted strength of a 50 mm diameter core is 94 % of the predicted average strength of a 100 mm diameter core and 92 % of that of a 150 mm diameter core. These overall average values do not reflect the considerable scatter of the data and therefore should be used with caution. The large variability attributed to the usage of small-diameter cores is often caused by the large variability of the *in-situ* concrete strength within the element being cored. They also indicated that the effect of the core L/D ratio on the compressive strength is more significant for 50 mm diameter cores than for 100 mm diameter cores.

In a few special cases, some provisional authorities such as the International Organization of Standards [16] and the American Concrete Institute [17] provide allowances for using smaller diameter cores down to 50 mm but the core diameter is still required to be at least 3 times the maximum aggregate size.

## 1.2 Scopes and Objectives

The above literature review reveals that small diameter cores can be potentially used to predict the concrete strength. The strength of hardened cement concrete used in the Eastern Province of Saudi Arabia varies from place to place, mainly due to job requirements and partly due to variation of construction procedures and the available materials. In the eastern region, the concrete construction is done using poor aggregates as these types are locally available. This results in deterioration of concrete structures. Assessment of concrete thus becomes an urgent necessity for these structures. In many cases, the determination of *in-situ* strength is invariably based on testing of cores, although this methodology is expensive when compared to the other non-destructive methods. This is because the level of confidence is very high when cores are used.

As the cost of assessment of the compressive strength of concrete structures is growing, this method will certainly reduce the cost considerably when compared to the "standard" 75 mm diameter cores or to other destructive methods such as ultrasonic pulse velocity, pull out. capo tests etc. It is more important to note that the damage done to the structure from which the 50 mm diameter core is obtained is also much less. Moreover, it is easier to core, transport, and store these small specimens. The chances of avoiding correction factors due to variations in L/D ratio, position and direction of drilling, due to the small size of the member and

congestion of the reinforcement, etc. are more.

The main objective of this research program is to develop strength prediction models for estimation of *in-situ* compressive strength of concrete in the Eastern Province of Saudi Arabia using 50 mm diameter cores.

The following are the primary objectives of this work:

1. Based on a large number of test data gathered from a variety of concrete mixtures with different levels of strength, correlation between the strength of 50 mm diameter cores, 75 mm diameter cores and 75 mm diameter "standard" cylinders will be established.

2. Strength prediction equations will be developed for evaluation of *in-situ* concrete strength based on 50 mm diameter cores. The degree of reliability associated with these prediction equation will also be examined.

The aim of testing 50 mm diameter cores is to support the viability of using these cores to estimate the *in-situ* strength of concrete. The influence of water-cement ratio, aggregate type, maximum size of aggregate, cement content, age and mineral admixtures will be examined. The core and cylinder strengths developed will also be compared. The experimental findings will be statistically analyzed to develop a correlation between the strength values of the different concretes, and finally, empirical equations will be established to estimate, within a confidence level, the *in-situ* strength of concrete on the basis of 50 mm diameter core strength.

In order to fulfill the objectives of this test program, 35 concrete mixtures producing a total of 720 specimens were cast. The steps involved are:

1. Preparing 500 x 500 x 150 mm and 460 x 400 x 100 mm slabs and 75 mm x 150 mm cylinders incorporating all mixture design variables. The wide range of strength is achieved by varying the water-cement ratio and the cement content.

2. Curing the specimens initially in the laboratory for 7 days and there after exposing them to the ambient environment at the exposure site to comply with the requirements of ARAMCO and the Royal Commission.

3. Drilling cores of 50 mm and 75 mm diameters and testing the cores and cylinders in compression after 28 days and 6 months of exposure.

4. Analyzing the test results statistically using regression analysis techniques in order to correlate the 50 mm diameter core strength and 75 mm diameter core strength with the 75 mm diameter cylinder strength in order to develop best-fit equations to predict the strength of concrete structures on the basis of 50 mm diameter core strength.

In this work, two commonly used aggregates and two different cement contents will be used with a w/c ratio varying from 0.30 to 0.65 to generate a wide range of data covering a variety of concrete strength levels.

# Chapter 2

# EXPERIMENTAL PROGRAM

This research program was primarily designed to generate a sufficient amount of data on core strength and "standard" cylinder strength for concrete with a wide range of compressive strength. The data generated was intended to develop a correlation model between the compressive strength of the 50 and 75 mm diameter cores and the 75 mm diameter cylinders. To achieve this objective, the data was obtained for various mixture design parameters, including cement content, maximum size and type of the coarse aggregate and water to cement ratio. Blended cements, incorporating mineral admixtures such as fly ash and silica fume, were also used to generate some compressive strength data. This chapter describes comprehensively the details of the test program. It outlines the test methods used in this investigation. Wherever possible, standard ASTM test methods have been followed.

## 2.1 Mixture Design Variables

Concrete mixtures were designed in accordance with absolute volume method, and proportioning of the materials was carried out on weight basis. Since the compressive strength of concrete varies with coarse to total aggregate (CA/TA) ratio, concrete cylinders with different CA/TA ratio ranging from 0.30 to 0.75 were cast. After testing, the maximum strength was attained at an CA/TA ratio of 0.62 for the Abu-Hadriyah aggregate and at 0.60 for the Riyadh aggregate. Fig. 2.2 shows the effect of CA/TA ratio on compressive strength for the two types of aggregates. These values are in general accordance with Maslehuddin [10] and Al-Gahtani [12] who reported an optimum CA/TA ratio of 0.625 for Abu-Hadriyah aggregate.

The mixtures were designed to produce strengths ranging from 15 MPa to 60 MPa. To achieve this range of strength, the effective water to cement (w/c) ratio was varied from 0.30 to 0.65. Two cement contents were used, namely 300 kg/m$^3$ and 400 kg/m$^3$. Table 2.1 shows the variation of w/c ratio, cement content and also the type of aggregate. Allowance for evaporation is not considered since it is almost negligible as the casting was carried out in the laboratory environment.

Blended cements incorporating silica fume and fly ash at different cement replacements were also used to find their influence on the strength of both cylinder and core specimens. The total cement content, the water-cement ratio, aggregate type and the max aggregate size were the same for all these mixes. Table 2.2 shows

the proportions of the various mixtures with the variation in the content of silica fume and fly ash.

To examine the effect of maximum aggregate size, three different mixes with different maximum aggregate size were cast. The maximum aggregate sizes used were of size 1 in., 3/4 in. and 3/8 in. The cement content, the water-cement ratio and aggregate type were the same for all these mixes. Table 2.3 shows the proportions of the various mixtures with the variation in the maximum aggregate size.

## 2.2 Materials and Molds

The coarse aggregates used in the concrete mixtures were brought from Abu-Hadriyah and Riyadh which typically represent the commonly used coarse aggregates in the Eastern Province of Saudi Arabia. The aggregates used were sieved and thereafter washed throughly before use.

The cement used was normal type V Portland cement. KFUPM sweet water was used in mixing and curing all concrete specimens. Grading of the coarse aggregates was done according to ASTM C 33. Tables 2.4 to 2.7 show the gradation of coarse aggregates according to ASTM C 33, for a maximum size of 1 in., 3/4 in. and 1/2 in. and 3/8 in., respectively.

### 2.2.1 Properties of Coarse Aggregate

As seen in Table 2.8 the absorption of the Abu-Hadriyah aggregate and the Riyadh aggregate were found to be 3 % and 2 % respectively. It means they demand an increase of the water content ratio to compensate for the absorption of the aggregates.

### 2.2.2 Properties of Fine Aggregate

The fine aggregate used was typical beach sand of 2.70 specific gravity and 0.23 percent absorption. It is a very fine sand with a fineness modulus of 1.8 which is less than the minimum value of 2.3 specified in ASTM C 33. It has a greater surface area, and thus requires greater quantity of water to achieve the desired workability.

Table 2.1: Summary of Mixture Design Parameters.

| Mix Designation | Cement Content ($kg/m^3$) | Aggregate Type | W/C Ratio |
|---|---|---|---|
| H1 | 300 | H* | 0.45 |
| H2 | 300 | H | 0.50 |
| H3 | 300 | H | 0.55 |
| H4 | 300 | H | 0.60 |
| H5 | 300 | H | 0.65 |
| H6 | 400 | H | 0.45 |
| H7 | 400 | H | 0.50 |
| H8 | 400 | H | 0.55 |
| H9 | 400 | H | 0.60 |
| H10 | 400 | H | 0.65 |
| H12 | 400 | H | 0.30 |
| H13 | 400 | H | 0.35 |
| H14 | 400 | H | 0.40 |
| R1 | 300 | R** | 0.45 |
| R2 | 300 | R | 0.50 |
| R3 | 300 | R | 0.55 |
| R4 | 300 | R | 0.60 |
| R5 | 300 | R | 0.65 |
| R6 | 400 | R | 0.45 |
| R7 | 400 | R | 0.50 |
| R8 | 400 | R | 0.55 |
| R9 | 400 | R | 0.60 |
| R10 | 400 | R | 0.65 |

Maximum Size of Aggregate = 1/2 in., * H = Abu-Hadriyah Aggregate, ** R = Riyadh Aggregate .

Table 2.2: Summary of Mixture Design Parameters (Blended Cements).

| Mix Designation | T.C.C.* ($kg/m^3$) | Aggregate Type** | W/C Ratio |
|---|---|---|---|
| HS1 | 400 (5% SF) | H(1/2 inch max. size) | 0.45 |
| HS2 | 400 (10% SF) | H(1/2 inch max. size) | 0.45 |
| HS3 | 400 (15% SF) | H(1/2 inch max. size) | 0.45 |
| HF1 | 400 (20% FA) | H(1/2 inch max. size) | 0.45 |
| HF2 | 400 (30% FA) | H(1/2 inch max. size) | 0.45 |
| HF3 | 400 (40% FA) | H(1/2 inch max. size) | 0.45 |

* T.C.C. is the total cementitious materials content (including blending materials)
** H = Abu-Hadriyah aggregate

Table 2.3: Summary of Mixture Design Parameters (Varying Maximum Size of the Aggregate)

| Mix Designation | C.C.* (kg/m$^3$) | Aggregate Type** | W/C Ratio |
|---|---|---|---|
| H6A | 400 | H(3/8 inch Max. size) | 0.45 |
| H6B | 400 | H(3/4 inch Max. size) | 0.45 |
| H6C | 400 | H(1 inch Max. size) | 0.45 |

*C.C. is the cement content, ** H = Abu-Hadriyah aggregate.

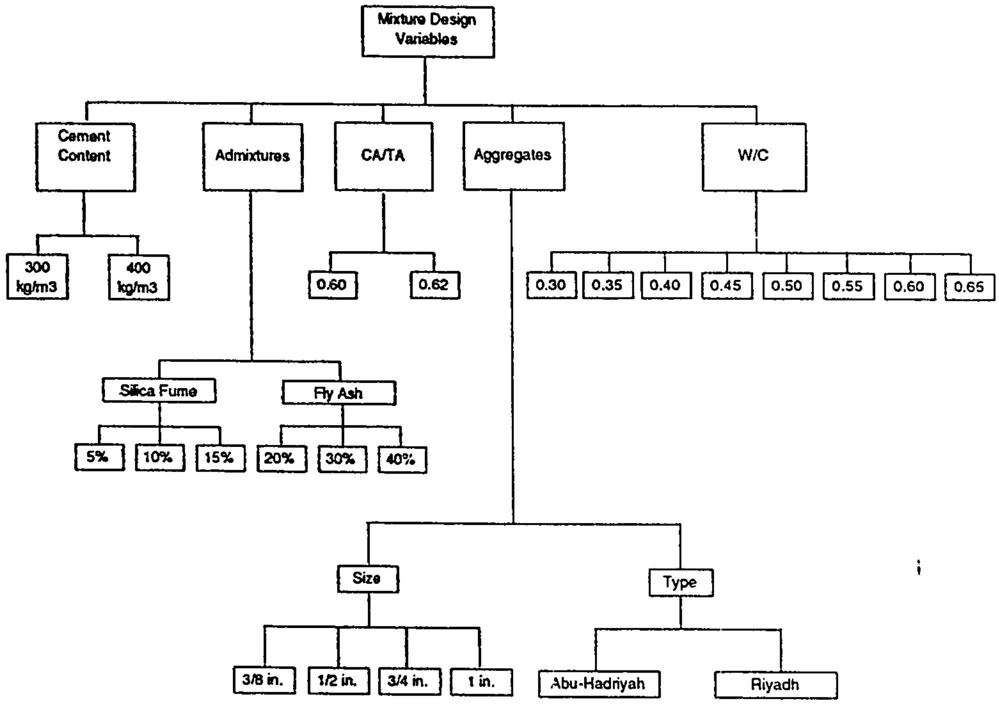


Figure 2.1: Flow Chart Showing the Mixture Design Variables

Table 2.4: Gradation of Coarse Aggregate with 1 inch Maximum Size

| Sieve Size | Percentage Passing * | Cumulative Percentage Passing | Percentage Retained |
|---|---|---|---|
| 1 inch | 90 to 100 | 95 | 5 |
| 3/4 inch | 40 to 85 | 85 | 10 |
| 1/2 inch | 10 to 40 | 35 | 50 |
| 3/8 inch | 0 to 15 | 15 | 20 |
| #4 | 0 to 5 | 5 | 10 |
| #8 | | 0 | 5 |

* According to ASTM C 33

Table 2.5: Gradation of Coarse Aggregate with 3/4 inch Maximum Size

| Sieve Size | Percentage Passing * | Cumulative Percentage Passing | Percentage Retained |
|---|---|---|---|
| 3/4 inch | 90 to 100 | 90 | 10 |
| 1/2 inch | | 55 | 35 |
| 3/8 inch | 20 to 55 | 20 | 35 |
| #4 | 0 to 5 | 5 | 15 |
| #8 | | 0 | 5 |

* According to ASTM C 33

Table 2.6: Gradation of Coarse Aggregate with 1/2 inch Maximum Size

| Sieve Size | Percentage Passing* | Cumulative Percentage Passing | Percentage Retained |
|---|---|---|---|
| 1/2 inch | 90 to 100 | 90 | 10 |
| 3/8 inch | 40 to 70 | 40 | 50 |
| #4 | 0 to 15 | 5 | 35 |
| #8 | 0 to 5 | 0 | 5 |

* According to ASTM C 33

Table 2.7: Gradation of Coarse Aggregate with 3/8 inch Maximum Size

| Sieve Size | Percentage Passing* | Cumulative Percentage Passing | Percentage Retained |
|---|---|---|---|
| 3/8 inch | 85 to 100 | 85 | 15 |
| #4 | 40 to 70 | 45 | 50 |
| #8 | 0 to 15 | 15 | 20 |
| #16 | 0 to 5 | 0 | 15 |

* According to ASTM C 33

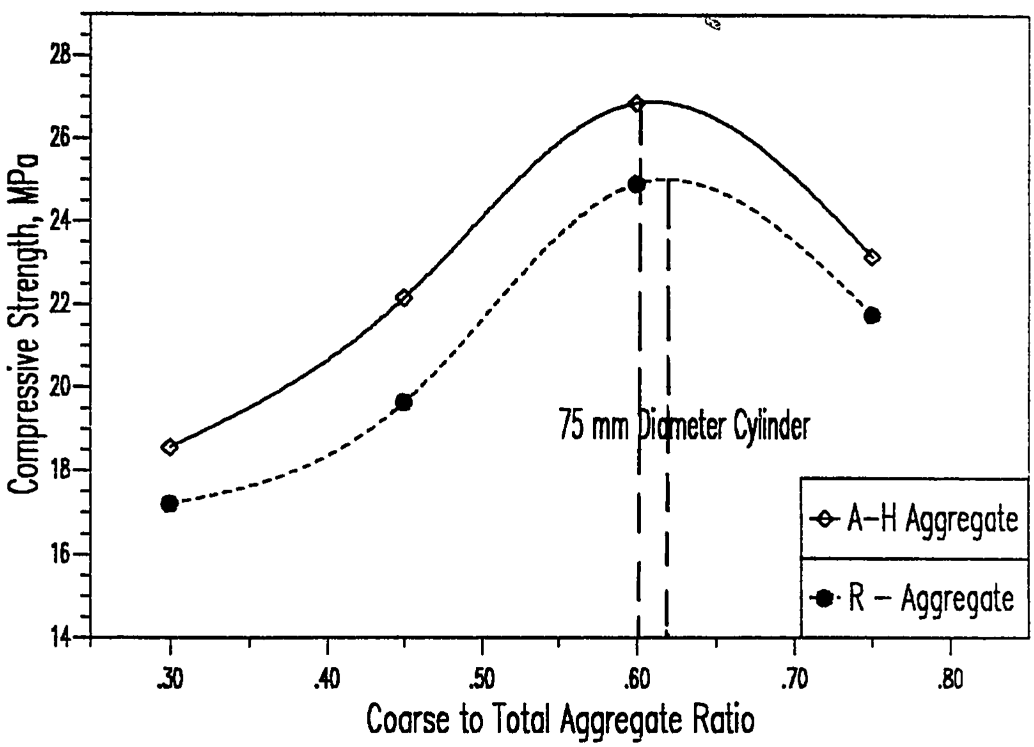


Figure 2.2: Effect of CA/TA Ratio on Compressive Strength of Concrete

Table 2.8: Specific Gravity and Absorption of Coarse Aggregates

| Serial No. | Aggr. Type | Maximum Size of the Aggr. | A | B | C | $G_s =$ A/(B-C) | Absorption in % = (B-A)/Ax100 |
|---|---|---|---|---|---|---|---|
| 1 | H | 1 inch | 3976 | 4095 | 2478.2 | 2.46 | 3.0 |
| 2 | R | 1 inch | 3969 | 4052 | 2503.5 | 2.56 | 2.0 |
| 3 | H | 3/4 inch | 2983 | 3070 | 1863.6 | 2.47 | 2.9 |
| 4 | R | 3/4 inch | 2976 | 3035 | 1877.2 | 2.57 | 2.0 |
| 5 | H | 1/2 inch | 1986 | 2045 | 1239 | 2.46 | 3.0 |
| 6 | R | 1/2 inch | 1972 | 2014 | 1242 | 2.55 | 2.1 |
| 7 | H | 3/8 inch | 1988 | 2046 | 1240 | 2.47 | 2.9 |
| 8 | R | 3/8 inch | 1971.5 | 2013.8 | 1247 | 2.57 | 2.0 |

A= Weight of oven-dry test sample in air, grams;
B= Weight of saturated surface dry test sample in air, grams;
C= Weight of saturated test sample in water, grams;
Gs= Specific gravity of the sample;
H= Abu-Hydriyah aggregate;
R= Riyadh aggregate:
Aggr.= Aggregate.

### 2.2.3 Concrete Casting

Two types of specimens were used in this experimental study, standard cylinders and panels. The size of cylinders was 75 x 150 mm. Since the L/D ratio was kept invariant in this research program and maintained between 1.95 and 2.05, panels of sizes 500 x 500 x 150 mm and 450 x 450 x 100 mm were used. The molds for panels were made from arborize plywood. They were designed for repetitive use and they were non absorptive.

The measured quantities of the concrete constituents were mixed in a half cubic meter electrically-operated drum-type concrete mixer. After the coarse and fine aggregates and cement were mixed dry in the mixer, measured amounts of sweet water were added and the constituents were mixed throughly for about three minutes from the time of adding water. Superplasticizer was added whenever necessary in order to make the concrete mix workable.

The molds were filled in approximately three equal layers and vibrated on table vibrator. The cylinders were cast according to ASTM C 192. The vibration was continued until complete consolidation was assumed to have occurred (when a thin film of mortar appeared on the concrete surface). All the cylindrical molds and panels were oiled prior to placing the concrete. After casting, the specimens were covered with wet burlap inside the laboratory ( $26 \pm 2^oC$) for about 24 hours then demolded. The concrete specimens were then labeled with the designations and

thereafter completely immersed in water for 7 days. The specimens containing Abu-Hadriyah aggregate were kept outside to analyse the effect of the exposure condition on the specimens.

For each concrete mixture, fourteen cylinders and two panels (one for producing 50 mm diameter cores and the other one for producing 75 mm diameter cores) were cast. Cylinders and cores were tested 28 days, 3 months and 6 months after casting. The results at each period was based on three cylinders and six cores ( three of 75 mm diameter and three of 50 mm diameter cores). The remaining cylinders and cores were left for testing at later ages. A small computer program (shown in Appendix A) was developed to obtain the weights of different quantities used in each mix.

## 2.3 Compressive Strength Determination

Two types of specimens (cores and cylinders) were tested under compression:

**a) Compressive Strength of Cylinders:** Compressive strength was determined by testing 75 x 150 mm "standard" cylinders in accordance with ASTM C 39. The loading rate was kept constant at 3.3 Kn/s. The compressive strength of these specimens is calculated by dividing the maximum load attained by the cross-sectional area of the specimen. All the cylinders used to determine compressive strengths were capped with sulfur based capping compound 48 hours before testing

in accordance with ASTM C 174. Each result is based on the average value of the compressive strength of three cylinders.

**b) Compressive Strength of Cores:** Cores for testing at 28 days were drilled one or two weeks before the test. Cores for testing at 90 and 180 days were drilled two to three weeks before the test. Specimens were air-dried and capped approximately 48 hours before testing. All cores were tested in their dry state. This procedure was adopted to maintain uniformity of moisture condition at the time of testing. For both the 75 mm and 50 mm diameter cores, each result is based on the average value of the compressive strength of three cores.

All cores were drilled keeping the core axis parallel to the direction of casting. The cores were cut by means of a rotary cutting diamond bit which was operated electrically. The coring machine was clamped against the concrete panel in order to prevent it from relative moment, and water was used continuously during the coring process. The cores had 75 x 150 mm and 50 x 100 mm nominal dimensions.

The compressive strength for the 75 mm and the 50 mm cores were measured according to ASTM C 42 so as to compare them with each other and also with the corresponding values of the standard cylinders. A load rate of 3.3 kN/s was kept invariant in all the tests.

# Chapter 3

# TEST RESULTS

The results of this investigation are presented numerically in Tables 3.1 through 3.6. These tables identify the role of the different concrete mixture design variables. that included w/c ratio, cement content, cement type, aggregate type, maximum size of aggregate and curing period, on the compressive strength of the concrete cylinders as well as of the 75 mm and 50 mm diameter cores. The results indicate that the compressive strength of cores is consistently less than that of cast cylinders. This is due to the effect of damage during the coring process on cores which resulted in a reduction of the compressive strength of cores [23].

There are three main effects that contribute to the lower strengths of the core tests.

- The first effect involves the effective cross-sectional area of the core. In a concrete cylinder, every particle is completely bonded to the cement matrix.



23

however, in a concrete core, the majority of the aggregate particles adjacent to the cut surface are only partially bonded. Consequently, the core has essentially a smaller effective cross-sectional area as compared to a cylinder thereby resulting in a lower strength.

- The second effect involves the destructive nature of the coring process itself. Some of the energy and effort used to cut and remove the specimen invariably causes damage to the core. This could be in the form of microcracking, weakening, or breaking of the bond between the cement matrix and the surface of the aggregate particles, or by causing major cracks or damage to the core. Again, this results in a lower strength.

- The third effect involves the different placement and compaction methods between a structure and a cylinder. Since all the specimens were cast under the laboratory conditions it can be assumed that this effect was small.

The results also indicate that the compressive strength of most of the 50 mm diameter cores is less than that of the 75 mm diameter cores. Bungey [6] suggested that during drilling, small cores would be more likely to suffer from loosened aggregate particles, and that the concrete would be less homogeneous than in a larger core. This would result in 50 mm diameter cores being relatively weaker than the 75 mm diameter cores. Moreover, if the damage during the coring process is assumed to weaken a constant thickness of a specimen then for a smaller diameter core the

percentage of damage done will be more when compared with a larger diameter core. Thus, a 50 mm diameter core would give less strength when compared with that of a 75 mm diameter core obtained from the same structure and tested under the same conditions.

Table 3.1: Compressive Strength of 28 Day Cores and Cylinders

| Mix Designation | Compressive Strength (MPa) | | |
|---|---|---|---|
| | 75 mm cylinder | 75 mm core | 50 mm core |
| H1 | 35.16 | 32.81 | 31.39 |
| H2 | 30.92 | 28.61 | 27.36 |
| H3 | 25.03 | 23.74 | 24.22 |
| H4 | 21.33 | 20.69 | 21.72 |
| H5 | 17.45 | 16.71 | 13.53 |
| H6 | 43.32 | 43.25 | 42.77 |
| H7 | 39.10 | 33.86 | 33.77 |
| H8 | 27.97 | 27.24 | 26.48 |
| H9 | 22.85 | 22.06 | 21.98 |
| H10 | 19.19 | 18.53 | 16.78 |
| H12 | 58.01 | 54.17 | 54.24 |
| H13 | 56.15 | 53.20 | 54.01 |
| H14 | 50.89 | 46.87 | 46.00 |
| R1 | 27.62 | 26.69 | 26.50 |
| R2 | 27.33 | 25.70 | 24.28 |
| R3 | 23.87 | 21.81 | 18.74 |
| R4 | 20.62 | 18.06 | 17.98 |
| R5 | 17.29 | 15.37 | 14.45 |
| R6 | 33.24 | 29.55 | 30.53 |
| R7 | 30.66 | 26.97 | 27.93 |
| R8 | 27.44 | 23.62 | 22.77 |
| R9 | 23.83 | 21.08 | 20.89 |
| R10 | 20.45 | 16.56 | 15.40 |

Table 3.2: Compressive Strength of 90 day Cores and Cylinders

| Mix Designation | Compressive Strength (MPa) | | |
|---|---|---|---|
| | 75 mm cylinder | 75 mm core | 50 mm core |
| H1 | 42.69 | 39.34 | 42.24 |
| H2 | 36.76 | 33.32 | 33.66 |
| H3 | 29.57 | 27.57 | 26.50 |
| H4 | 25.25 | 24.01 | 23.83 |
| H5 | 20.43 | 19.10 | 17.62 |
| H6 | 54.14 | 51.27 | 50.62 |
| H7 | 44.72 | 40.40 | 39.62 |
| H8 | 37.23 | 33.25 | 35.80 |
| H9 | 27.30 | 26.35 | 26.59 |
| H10 | 22.86 | 21.48 | 19.30 |

Table 3.3: Compressive Strength of 180 Day Cores and Cylinders

| Mix Designation | Compressive Strength (MPa) | | |
|---|---|---|---|
| | 75 mm cylinder | 75 mm core | 50 mm core |
| H1 | 45.94 | 41.70 | 45.58 |
| H2 | 40.40 | 35.50 | 38.38 |
| H3 | 31.35 | 29.50 | 29.71 |
| H4 | 26.55 | 25.66 | 26.18 |
| H5 | 22.58 | 22.24 | 19.33 |
| H6 | 58.29 | 52.60 | 55.13 |
| H7 | 48.39 | 43.30 | 43.08 |
| H8 | 42.00 | 37.35 | 37.78 |
| H9 | 29.35 | 28.91 | 27.32 |
| H10 | 24.66 | 24.42 | 21.21 |

Table 3.4: Compressive Strength of 28 Day Cores and Cylinders (Silica Fume)

| Mix Designation | Compressive Strength (MPa) | | |
|---|---|---|---|
| | 75 mm cylinder | 75 mm core | 50 mm core |
| HS1 (5%) | 54.36 | 52.27 | 50.03 |
| HS2 (10%) | 61.52 | 60.17 | 57.67 |
| HS3 (15%) | 67.02 | 66.64 | 62.72 |

Table 3.5: Compressive Strength of 28 Day Cores and Cylinders ( Fly Ash)

| Mix Designation | Compressive Strength (MPa) | | |
|---|---|---|---|
| | 75 mm cylinder | 75 mm core | 50 mm core |
| HF1 (20%) | 44.26 | 43.77 | 42.80 |
| HF2 (30%) | 42.90 | 42.08 | 41.81 |
| HF3 (40%) | 39.66 | 38.70 | 39.52 |

Table 3.6: Compressive Strength of 28 Day Cores and Cylinders with Different Maximum Aggregate Size

| Mix Designation | Compressive Strength (MPa) | | |
|---|---|---|---|
| | 75 mm cylinder | 75 mm core | 50 mm core |
| H6A (3/8in) | 50.86 | 48.93 | 47.96 |
| H6 (1/2in) | 51.07 | 47.07 | 44.76 |
| H6B (3/4in) | 49.85 | 45.90 | 41.07 |
| H6C (1in) | 39.83 | 36.33 | 30.53 |

# Chapter 4

# PREDICTION OF CONCRETE STRENGTH

In this Chapter, the laboratory generated data of the 75 mm and 50 mm diameter core strengths and the 75 mm diameter cylinder strength were statistically analyzed. These data were statistically analyzed to determine the best predictive model that could be used to predict the compressive strength of *in-situ* concrete structures if and when 50 mm diameter cores are to be used. SAS (Statistical Analysis Software) was used to perform the analyses. The regression analysis was performed using available SAS program package, in the DPC library of KFUPM.

## 4.1 Estimation of Concrete Strength Using the 50 mm Cores

Actual *in-situ* concrete compressive strength is often determined by 75 mm diameter cores taken from the structure. It is, therefore, necessary to establish a correlation between the strength of 50 mm diameter cores and the 75 mm diameter cylinders. This should be established in order to convert the 50 mm diameter core strength into the 75 mm cylinder strength for the purpose of better estimation of concrete compressive strength.

A comparison between 75 mm diameter cylinder and the 50 mm diameter core strengths is presented in figure 4.1. As seen in the figure the 50 mm diameter core strengths were below the line of equality as they predicted less cylinder strength compared to the actual cylinder strengths. The figure also indicates that the cores strengths lie between the line of equality and the line running parallell to the line of equality but passing through the core strength which deviated maximum from the actual cylinder strength. This gave a preliminary indication that there exists a linear correlation between the 75 mm diameter cylinder and 50 mm diameter core strengths. However, a nonlinear correlation was also developed to compare with linear correlation.

The following are the two equations which were used to develop the correlation models. Equation 4.1 was used to develop the linear correlation model and

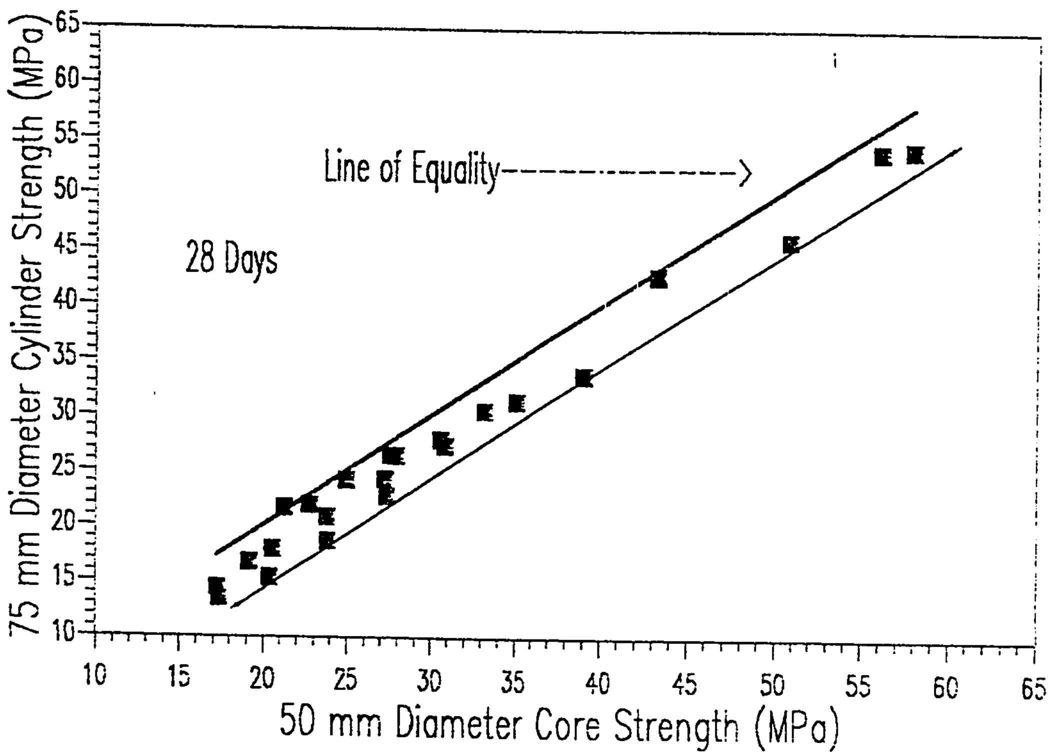


Figure 4.1: Graphical Representation of Comparison between 75 mm Diameter Cylinder and 50 mm Diameter Core Strengths

23

Equation 4.2 was used to develop the non-linear correlation model between core and cylinder strengths.

$$f'c = f_{50} \times a_0 + a_1 \tag{4.1}$$

$$f'c = (f_{50})^n \times a_0 + a_1 \tag{4.2}$$

where:

$f'c$ = compressive strength of the 75 mm diameter cylinder;

$f_{50}$ = compressive strength of the 50 mm diameter core;

n, $a_0$ and $a_1$ = constants

Various values for n were attempted in regression analysis in order to obtain the best fit between the 50 mm diameter core strength and the 75 mm diameter cylinder strength. From trial runs, it was found that the value of n=1.5 showed the best correlation. The values of the two constants $a_0$ and $a_1$, the coefficient of determination ($R^2$), correlation coefficient ($R$) and the standard error of estimates of the strength were determined for each trial Equations 4.1 and 4.2. Table 4.1 shows the regression coefficients and statistical parameters. Fig. 4.2 shows the graphical representation of the linear correlation while Fig. 4.3 shows the error

% for the estimated values of the linear correlation. Fig. 4.4 shows the graphical representation of the nonlinear correlation.

Comparison of the two linear and nonlinear equations indicates that the linear equation gave a relatively better fit. This is evidenced by the values of $R^2$ and $R$, as observed in Table 4.1. However, in view of the simplicity of the linear correlation model and its relatively better fit with the data points, Equation. 4.1 has been adopted as the strength calibration model for estimating the concrete strength using the 50 mm diameter cores.

## 4.2 Estimation of Concrete Strength Using the 75 mm Cores

A comparison between 75 mm diameter cylinder and the 75 mm diameter core strengths is presented in figure 4.5. As seen in the figure the 75 mm diameter cores strengths were below the line of equality as they predicted less cylinder strengths than the actual cylinder strength. The figure also indicates that the cores strengths lie much closer to the line of equality and the line running parallell to the line of equality but passing though the core strength which deviated maximum from the actual cylinder strength. A linear correlation between the strengths of the 75 mm diameter cylinder and the 75 mm diameter core is possible.

Table 4.2 shows the ratio of standard cylinder to core compressive strengths

for different curing periods. The value of m in the table was obtained by taking the average of the ratios between the 75 mm diameter cylinder and the 75 mm diameter core strengths, for different mixes. However, it was observed that mostly the individual ratio between the cylinder strength and the core strength lied between 1.07 - 1.03. Thus an average value of 1.05 could be proposed to convert the 75 mm core strength into similar cylinder strength.

Table 4.1: Regression Coefficients and Statistical Parameters of Correlation Model

| Model | Standard Deviation | | $R^2$ | $R$ | Standard error |
|---|---|---|---|---|---|
| | Actual | Estimated | | | |
| $f'c = f_{50}$ $+2.845(Linear)$ | 11.81 | 11.72 | 0.982 | 0.99 | 0.89% |
| $f'c = (f_{50})^{1.5} \times 0.11$ $+12.691(Nonlinear)$ | 11.81 | 11.68 | 0.979 | 0.98 | 0.70% |

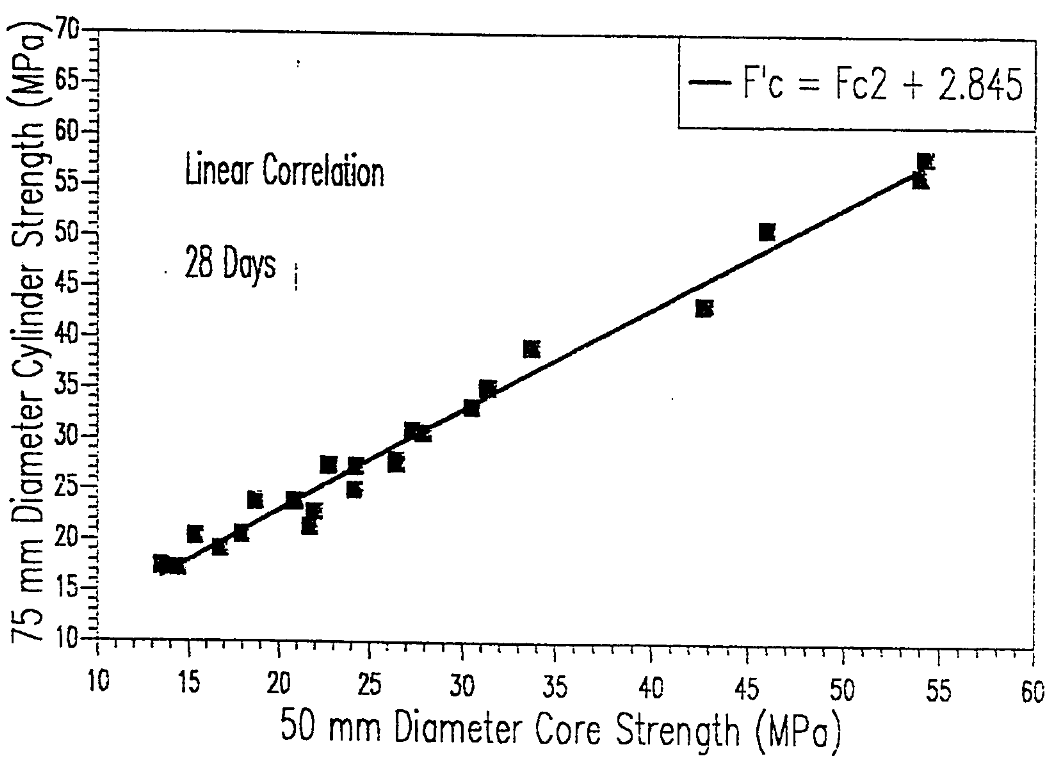


Figure 4.2: Graphical Representation of Linear Correlation between 75 mm Diameter Cylinder and 50 mm Diameter Core Strengths

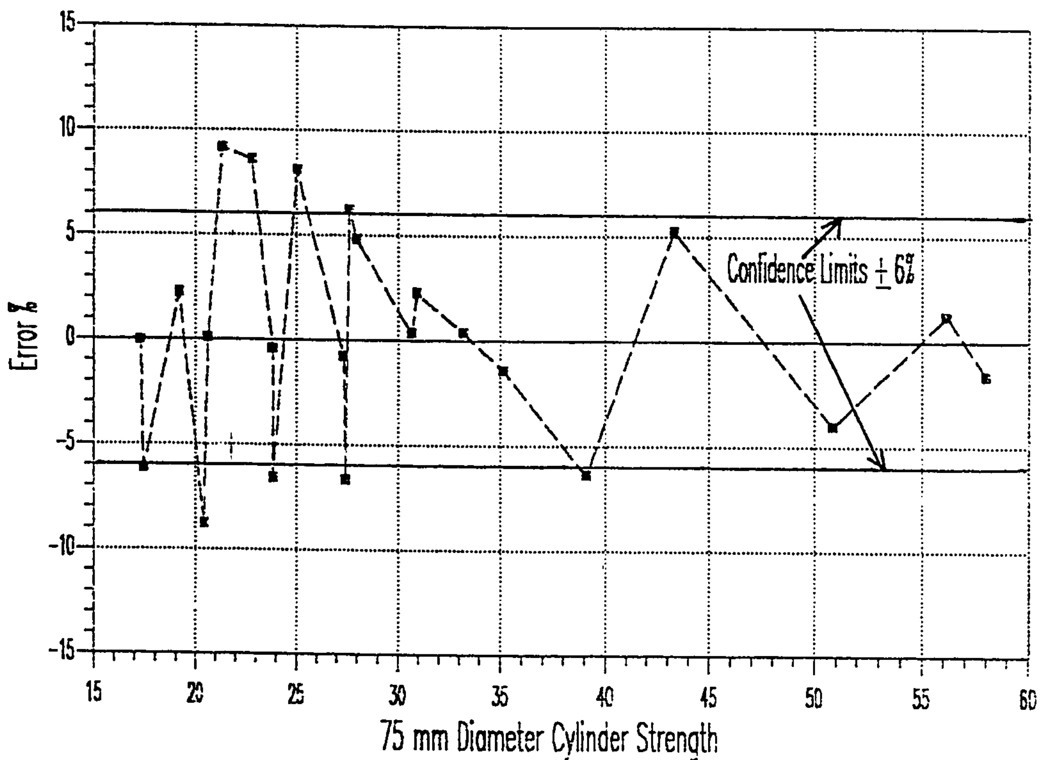


Figure 4.3: Graphical Representation of the Error %

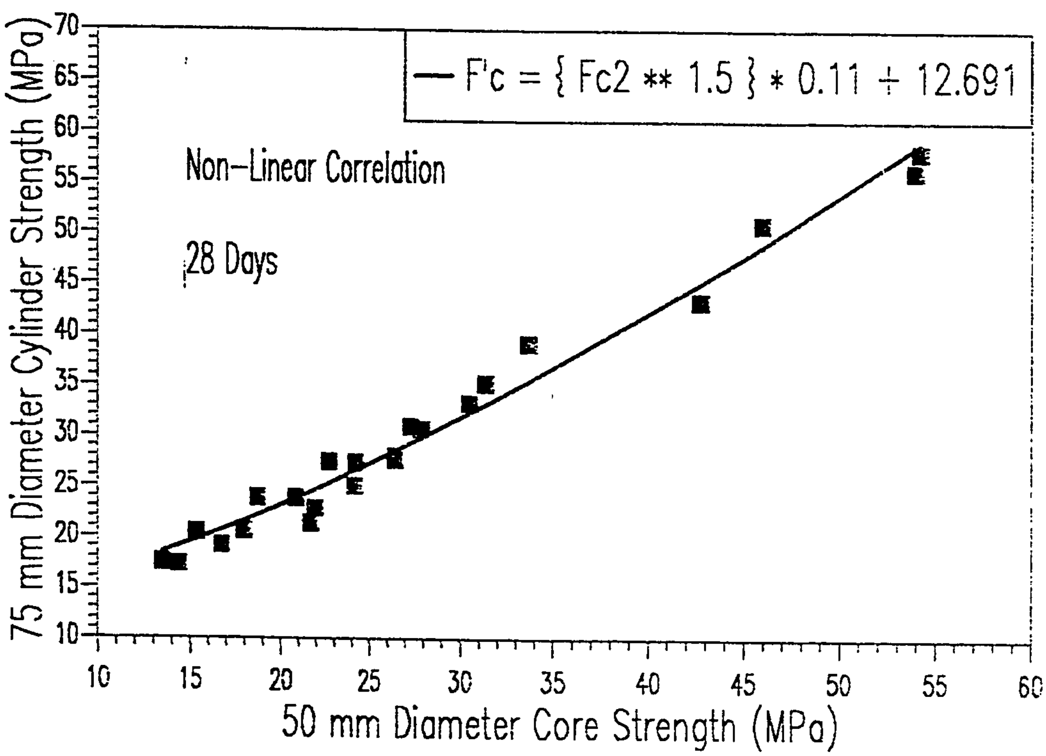


Figure 4.4: Graphical Representation of Non-Linear Correlation between 75 mm Diameter Cylinder and 50 mm Diameter Core Strengths

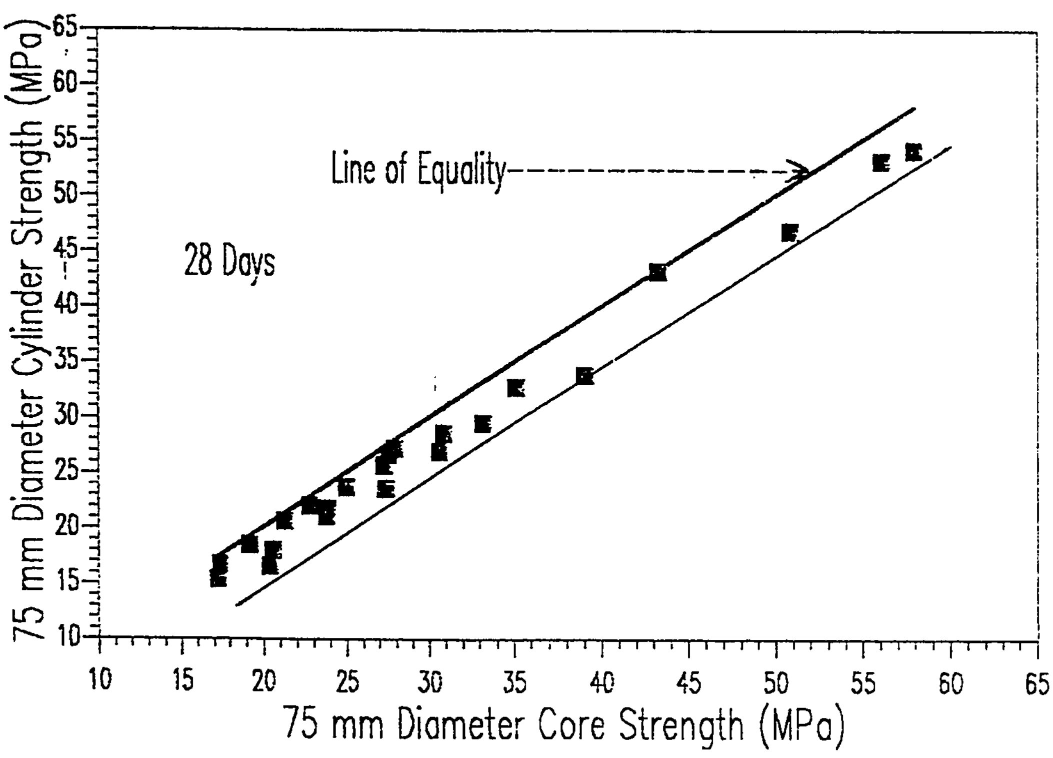


Figure 4.5: Graphical Representation of Comparison between 75 mm Diameter Cylinder and 75 mm Diameter Core Strength

Table 4.2: Ratio of Standard Cylinder to Core Compressive Strengths

| Mix Designation | Curing Period | m |
|---|---|---|
| H1-H10 | 28 days | 1.051 |
| H1-H10 | 90 days | 1.048 |
| H1-H10 | 180 days | 1.050 |
| R1-R10 | 28 days | 1.071 |

where
H is the Abu-Hadriyah Aggregate;
R is the Riyadh Aggregate; and
m is the ratio of standard cylinder strength to the 75 mm diameter core strengths.

# Chapter 5

# DISCUSSION

In this Chapter, the effect of the mixture design variables on the compressive strength of concrete cylinders and cores is discussed. Furthermore, the reliability of the correlation model on the estimation of concrete strength due to the effect of these variables is also discussed.

## 5.1 Effect of Exposure Period

The effect of exposure period and conditions on the strength of concrete specimens were examined. After curing for 7 days in water inside the laboratory, cylinders and panels were exposed at the KFUPM exposure site, near the Ferrocement Laboratory. The exposed cylinders and panels were subjected to three months of severe hot weather conditions during summer and thereafter by three months of winter. The

ten different mixes [H1.............H10] were used to examine the effect of exposure period. The cores and cylinders were tested 3 months and 6 months after casting. Figure 5.1 shows a typical graphical representation of the effect of exposure period on the compressive strength of cores and cylinders. Concrete gains strength with time. Hence age is evidently an important parameter if estimated *in-situ* cylinder strength of concrete at 28 days is to be obtained from core tests carried out at later ages. As seen in figure the strength of the specimens increased at later ages. Yip & Tam [15] showed that smaller cores tend to gain more strength than larger cores at later ages. This trend was also observed in this research. As seen in figure the 50 mm diameter core gained more strength when compared to 75 mm diameter core strength at later ages.

The linear correlation model was to estimate the compressive strength of the 75 mm diameter cylinders using 50 mm diameter cores when used for the data points obtained for 3 months and 6 months strengths, indicated that the model can estimate within the confidence limits of ± 6% for the strength of concrete for both ages. This is evidenced from the Table 5.1 where the ratio between the actual and the estimated cylinder strengths were very close to 1.00. This is expected because at any exposure period, the effect of exposure conditions would be almost the same on both the cylinders and the cores for the same mix charecteristics and tested under same conditions.

Tables 5.1 and 5.2 show the ratio between the actual and the estimated cylinder

strengths using the 50 mm diameter core for the strength values obtained when the specimens were tested 3 months and 6 months after casting, respectively. Figures 5.2 and 5.3 depict the graphical representation of the error % in estimation of the cylinder strengths by 50 mm diameter cores after 3 months and 6 months. Thus it can be concluded that the linear correlation model can be used to estimate the cylinder strengths at later ages also.

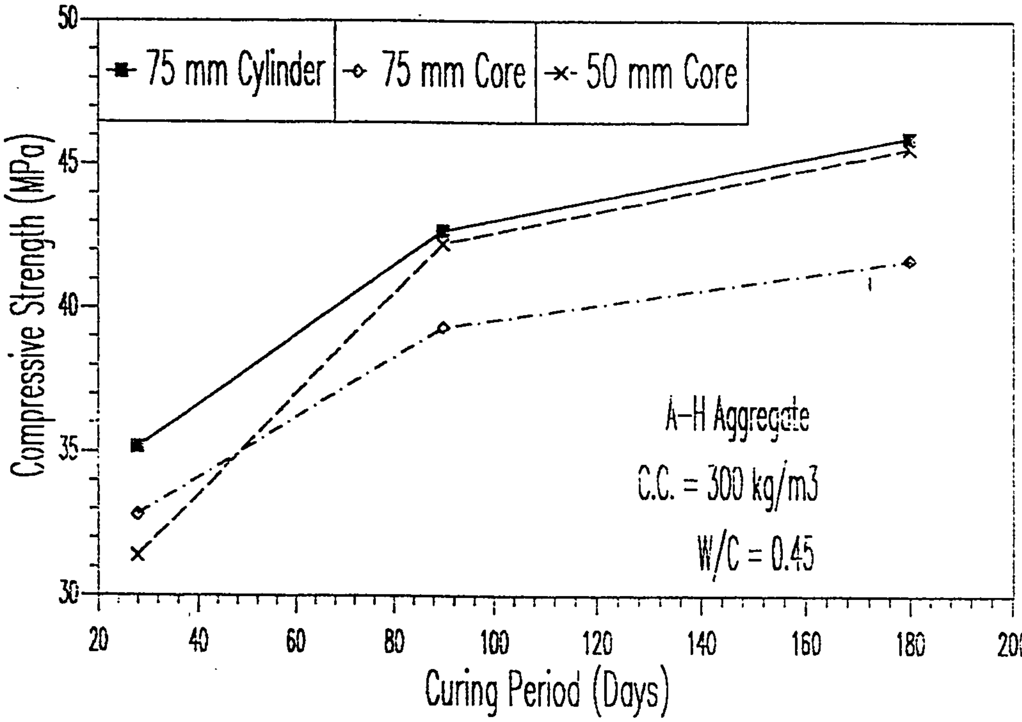


Figure 5.1: Typical Representation of the Effect of Age on Compressive Strength of Cylinder and Cores

Table 5.1: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 50 mm Diameter Core (90 Days)

| Mix Designation | 50 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio = a/e |
|---|---|---|---|---|
| | | Actual (MPa) (a) | Estimated* (MPa) (e) | |
| H1 | 42.24 | 42.69 | 45.085 | 0.947 |
| H2 | 33.66 | 36.76 | 36.505 | 1.007 |
| H3 | 26.50 | 29.57 | 29.345 | 1.008 |
| H4 | 23.83 | 25.25 | 26.675 | 0.947 |
| H5 | 17.62 | 20.43 | 20.465 | 0.998 |
| H6 | 50.62 | 54.14 | 53.465 | 0.988 |
| H7 | 39.62 | 44.72 | 42.465 | 1.053 |
| H8 | 35.80 | 37.23 | 38.645 | 0.963 |
| H9 | 26.59 | 27.30 | 29.435 | 0.928 |
| H10 | 19.30 | 22.86 | 22.145 | 1.032 |

*Estimated values were obtained using the linear correlation model.

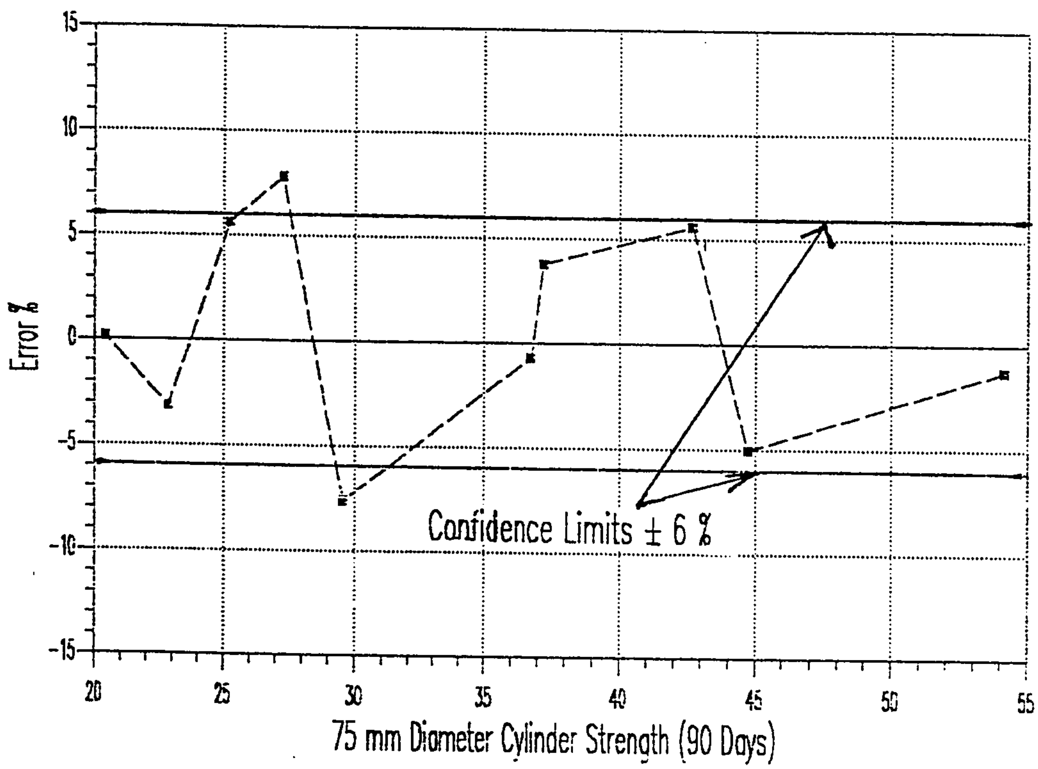


Figure 5.2: Graphical Representation of the Error % (3 Months)

23

Table 5.2: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 50 mm Diameter Core (180 Days)

| Mix Designation | 50 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio = a/e |
|---|---|---|---|---|
| | | Actual (MPa) (a) | Estimated* (MPa) (e) | |
| H1 | 45.58 | 45.94 | 48.425 | 0.949 |
| H2 | 38.38 | 40.40 | 41.225 | 0.980 |
| H3 | 29.71 | 31.35 | 32.555 | 0.963 |
| H4 | 26.18 | 26.55 | 29.025 | 0.915 |
| H5 | 19.33 | 22.58 | 22.175 | 1.018 |
| H6 | 55.13 | 58.29 | 57.975 | 1.005 |
| H7 | 43.08 | 48.39 | 45.925 | 1.054 |
| H8 | 37.78 | 42.00 | 40.625 | 1.034 |
| H9 | 27.32 | 29.35 | 31.755 | 0.924 |
| H10 | 21.21 | 24.66 | 24.055 | 1.025 |

*Estimated values were obtained using the linear correlation model.

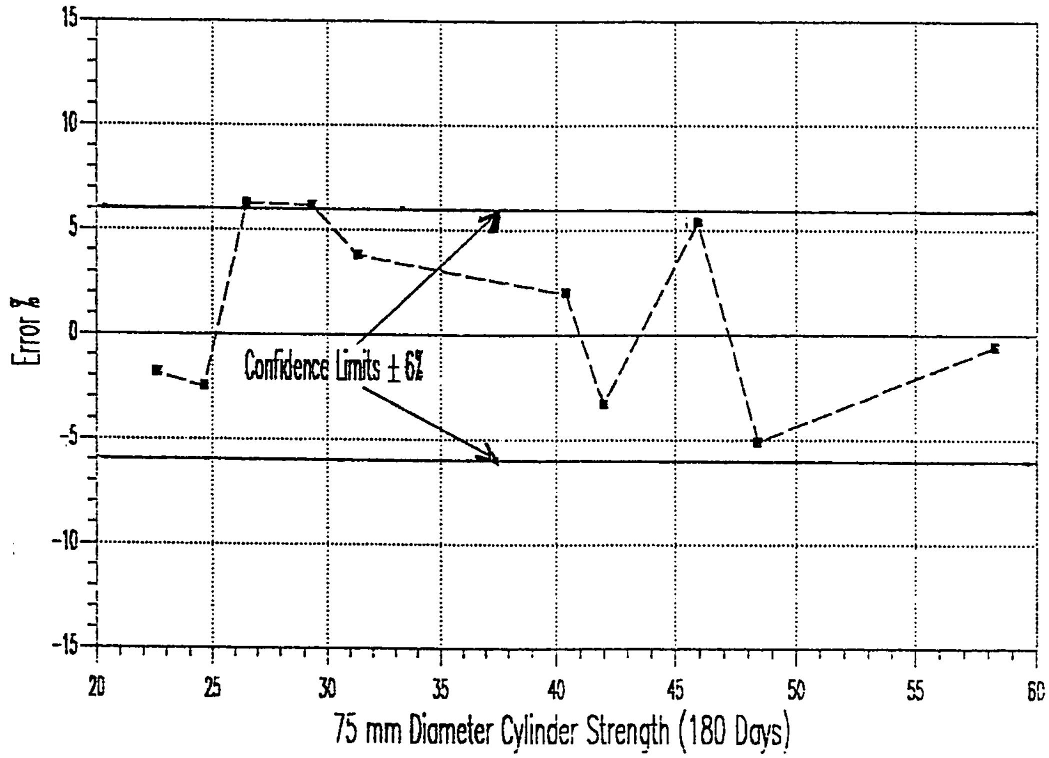


Figure 5.3: Graphical Representation of the Error % (6 Months)

## 5.2 Effect of Maximum Aggregate Size

Figure 5.4 depicts the change in cylinder and core strengths with the maximum size of the coarse aggregate. The strength decreased with an increase in the aggregate size. The difference in the core strength and the cylinder strength was more pronounced as the maximum size of the aggregate increased.

**a) Cylinders:** The strength of the cylinders were almost unaffected with the maximum size of the aggregate upto a size of 3/4", thereafter there was a significant decrease when the maximum size of aggregate was 1". This is due to the fact that the surface area of contact between the cement matrix and the aggregate particles decreases due to the increase in maximum size of the aggregate resulting in decrease of compressive strength.

**b) Cores:** The 75 mm diameter core strengths were more or less similar to the 75 mm diameter cylinder strengths but there was a fundamental difference between the 50 mm and 75 mm diameter core strengths. The 50 mm diameter core strength consistently decreased with the increase in the maximum size of the aggregate. The decrease in strength increased almost linearly in the range of maximum aggregate size of 0.385 to 0.75 inch. Thereafter, when the maximum aggregate size was 1" the decrease in strength was substantial.

The linear correlation model to estimate the compressive strength of the 75 mm diameter cylinders using the 50 mm diameter cores showed that the difference

between the actual and the estimated cylinder increased as the maximum size of the aggregate increased. This is due to the fact that during the coring process, the larger sizes of particles will be affected thereby resulting in greater damage to the bond between the hardened cement matrix and the surface of the aggregate particles. The effect will be even more as the diameter of the specimen decreases. This is evident in Figure 5.4 that indicates a decrease in strength of the 50 mm diameter core is more when compared with the 75 mm diameter core strength. Thus, the diameter of the core drilled from concrete should satisfy the minimum requirements of all codes of practice to estimate better the concrete strength, i.e. the diameter of the core should be atleast three times the maximum nominal size of the aggregate used in the concrete.

Table 5.3 shows the actual and the estimated values of the cylinder strengths. The ratios between the actual and the estimated strengths indicate that the correlation model estimates the strength considerably well the cylinder strengths when the maximum size of aggregate is below 3/4 inch. Figure 5.5 shows the graphical representation of the actual and the estimated strengths of the cylinder when the maximum size of the aggregate is varied. Figure 5.6 shows the graphical representation of the error % in the estimation of the strengths of the cylinder by the 50 mm diameter core via the correlation model.

The conversion factor of 1.05 that has been previously proposed to convert the 75 mm core strength into cylinder strength was used to estimate the cylinder strengths

when the maximum size of the aggregate is varied. Table 5.4 shows the actual and the estimated values of the cylinder strengths. The ratios between the actual and the estimated strengths indicate that the 75 mm core with a conversion factor of 1.05 estimated the 75 mm diameter cylinder strengths considerably well even when the maximum size of aggregate is varied till one inch. Figure 5.7 shows the graphical representation of the actual and the estimated strengths when maximum size of the aggregate is varied. Figure 5.8 shows the graphical representation of the error % in the estimation of the strengths of the cylinder by the 75 mm diameter core using the conversion factor.

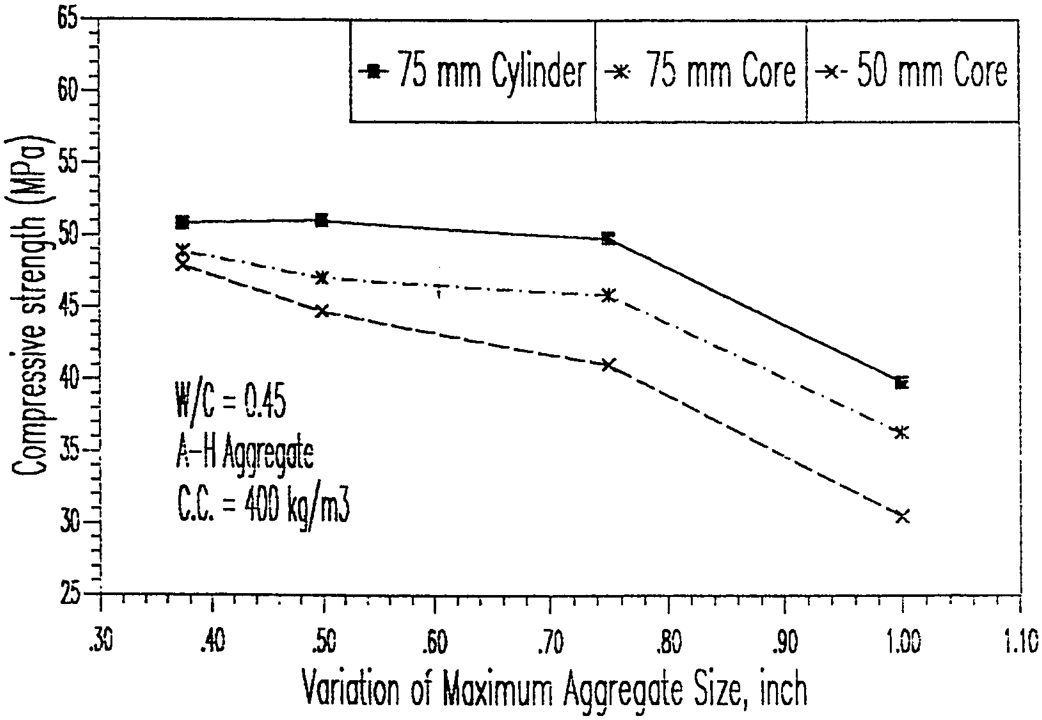


Figure 5.4: Effect of Maximum Aggregate Size on Compressive Strength of Cylinders and Cores

Table 5.3: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 50 mm Diameter Core with Different Maximum Aggregate Size

| Mix Designation | 50 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio |
|---|---|---|---|---|
| | | Actual | Estimated | |
| H6A (3/8in) | 47.96 | 50.86 | 50.805 | 1.000 |
| H6 (1/2in) | 44.76 | 51.07 | 47.605 | 1.073 |
| H6B (3/4in) | 41.07 | 49.85 | 43.915 | 1.135 |
| H6C (1in) | 30.53 | 39.83 | 33.375 | 1.193 |

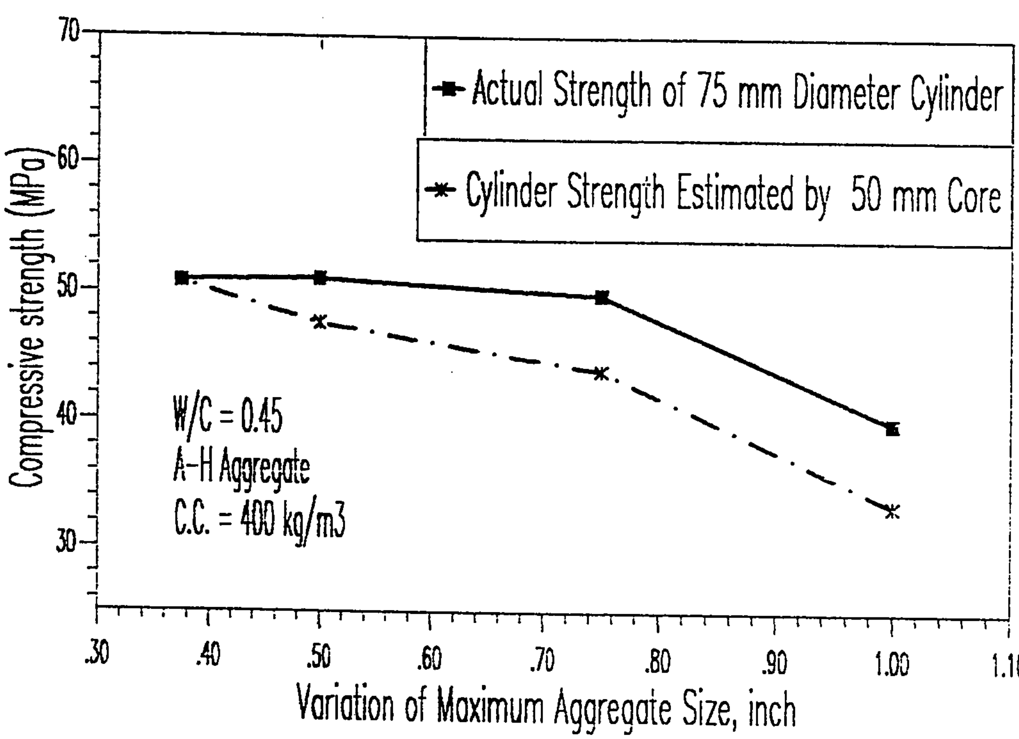


Figure 5.5: Graphical Representation of Actual and Estimated Strengths (by 50 mm Core) of Cylinder Using Different Maximum Aggregate Size

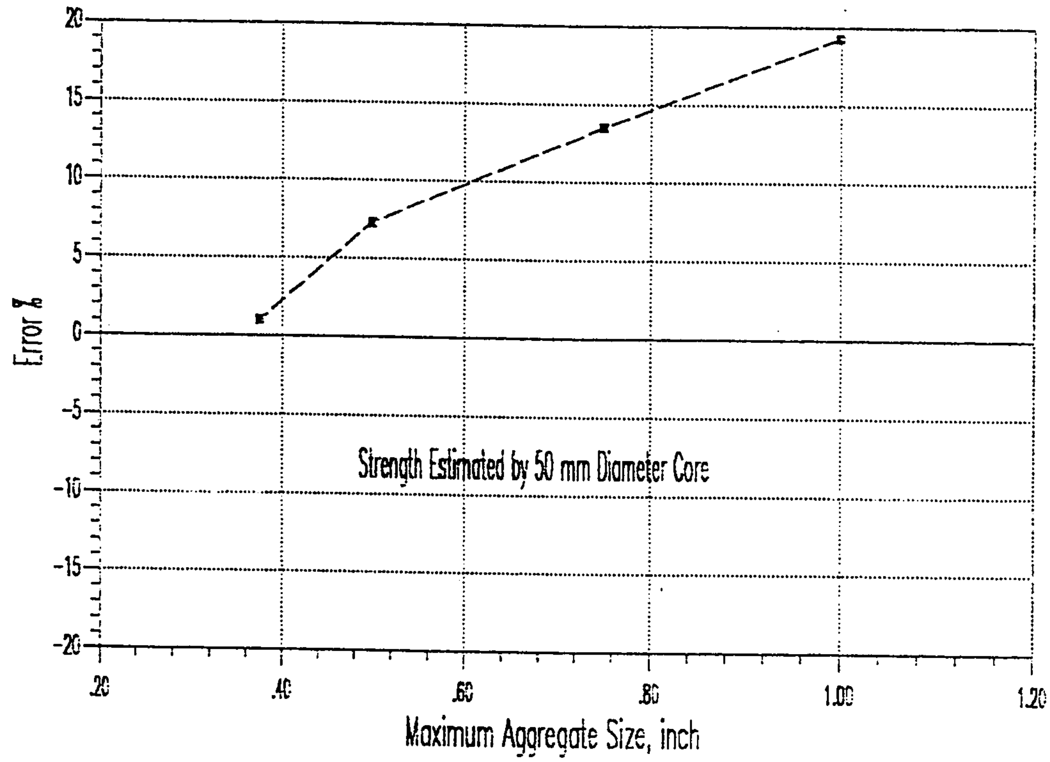


Figure 5.6: Graphical Representation of the Error % (50 mm Core)

Table 5.4: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 75 mm Diameter Core with Different Maximum Aggregate Size

| Mix Designation | 75 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio |
|---|---|---|---|---|
| | | Actual | Estimated | |
| H6A (3/8in) | 48.93 | 50.86 | 51.380 | 0.99 |
| H6 (1/2in) | 47.07 | 51.07 | 49.420 | 1.033 |
| H6B (3/4in) | 45.90 | 49.85 | 48.195 | 1.034 |
| H6C (1in) | 36.33 | 39.83 | 38.147 | 1.044 |

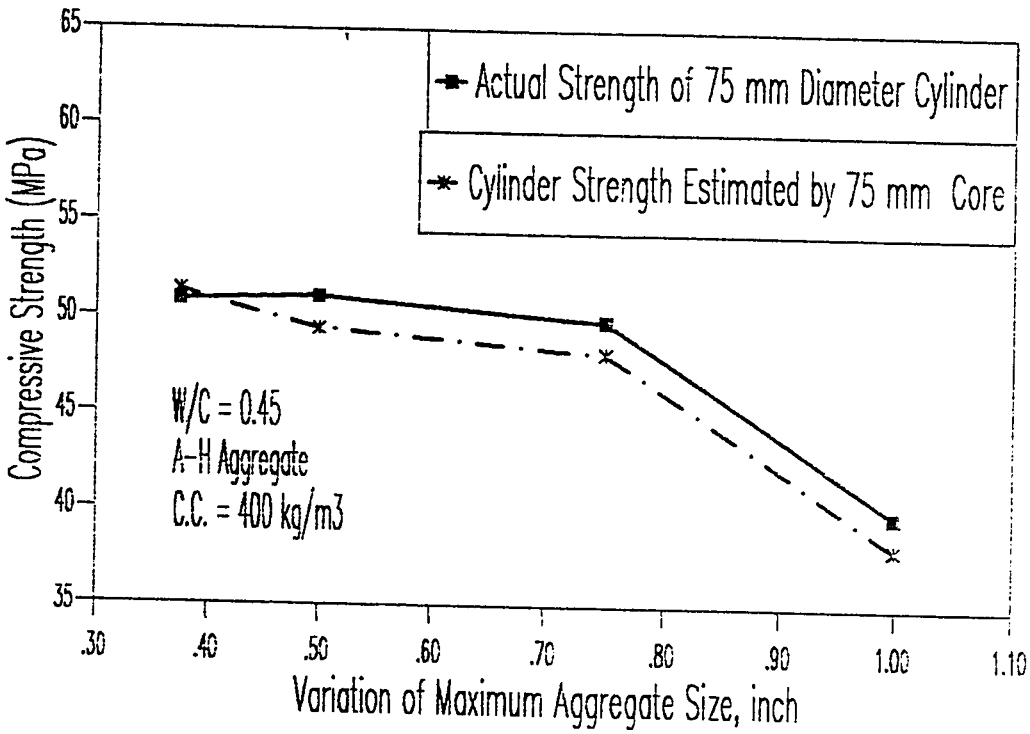


Figure 5.7: Graphical Representation of Actual and Estimated Strengths (by 75 mm Core) of Cylinder Using Different Maximum Aggregate Size

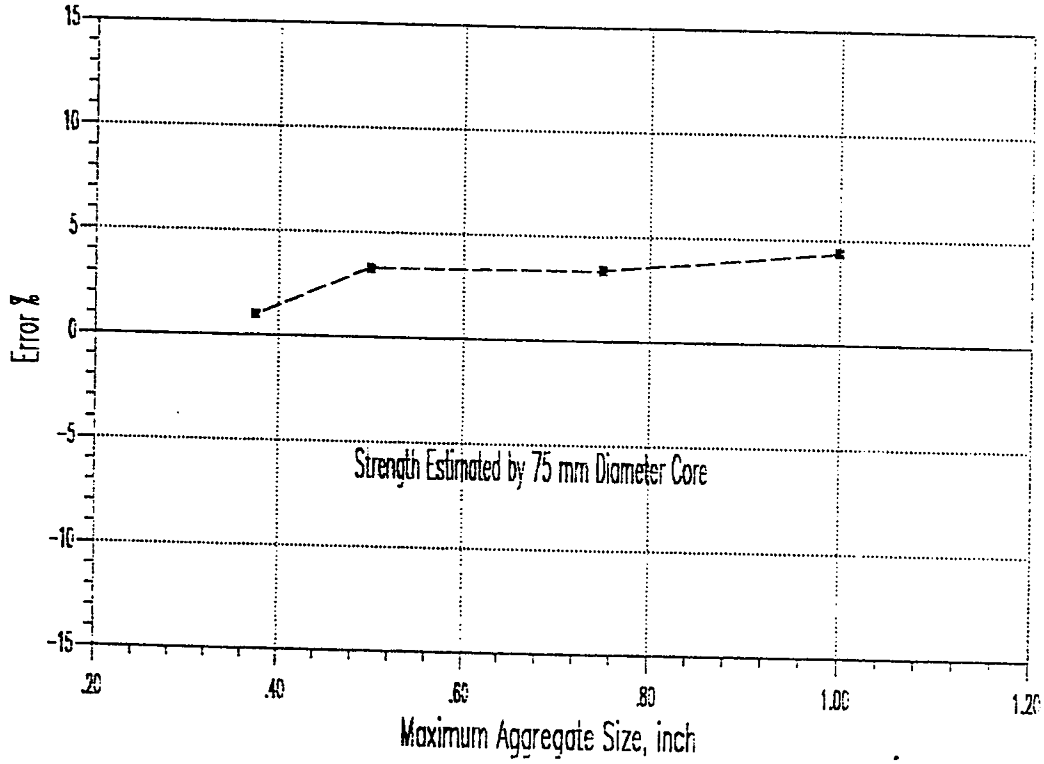


Figure 5.8: Graphical Representation of the Error % (75 mm Core)

## 5.3 Effect of Blended Cements

The effect of blended cements on the 75 mm diameter cylinder, 75 mm diameter core and 50 mm diameter core strengths is presented in Figure 5.9 and 5.10. For all the mixes of the blended cement concretes, the total cementitous materials content was kept invariant at 400 kg/m$^3$.

Figure 5.9 indicates that the strength of both the cylinders and the core significantly increased when the percentage of silica fume is increased [18]. Initially, the difference between the strength of the cylinder and the cores was not significant. However, as the percentage of silica fume increased, the difference between the cylinder and the core strengths increased. It is also observed that the strength of the 50 mm diameter core decreased significantly as the percentage of silica fume increased. This may be attributed to the fact that the percentage of damage done to the smaller diameter core was increased as the value of the strength increased thereby resulting in lower strength of the 50 mm diameter cores.

Figure 5.10 indicates that the strength of both the cores and cylinders increased when the percentage of fly ash was increased to about 20%. Thereafter, there was a reversal in strength as the content of fly ash increased to about 40%. Fly ash concretes normally have low strengths when compared to OPC at early ages. This is attributed to the fact that the chemical reaction (i.e. known as pozzolanic reaction) between the silica and alumina of the fly ash gradually react with the calcium

hydroxide released during the hydration process of the cement [13]. This chemical reaction occurs much more slowly than the hydration of the portland cement, resulting in lower strengths at early ages.

Results indicate that as the percentage of fly ash increased, the difference between the strengths of cores and cylinders remained almost the same. This could be due to the fact that as the strength varied marginally when the percentage of fly ash varied, the reduction of strength due to damage during coring process, remained the same.

The linear correlation model was used to estimate the cylinder strengths when either silica fume or fly ash was used in the concrete mix. Tables 5.5 and 5.6 show the actual and the estimated values of the cylinder strengths either with silica fume or fly ash, respectively was used. The ratios between the actual and the estimated strengths indicate that the correlation model estimates the strength considerably well. However, when the concrete was blended with fly ash, the difference between the actual and the estimated strengths increased as the percentage of replacement of fly ash increased. We can infer that the correlation model can be used to estimate the cylinder strength when concrete is blended with fly ash below 20%. Figures 5.11 and 5.12 show the graphical representation of the actual and the estimated strengths when concrete is blended with silica fume and fly ash, respectively.

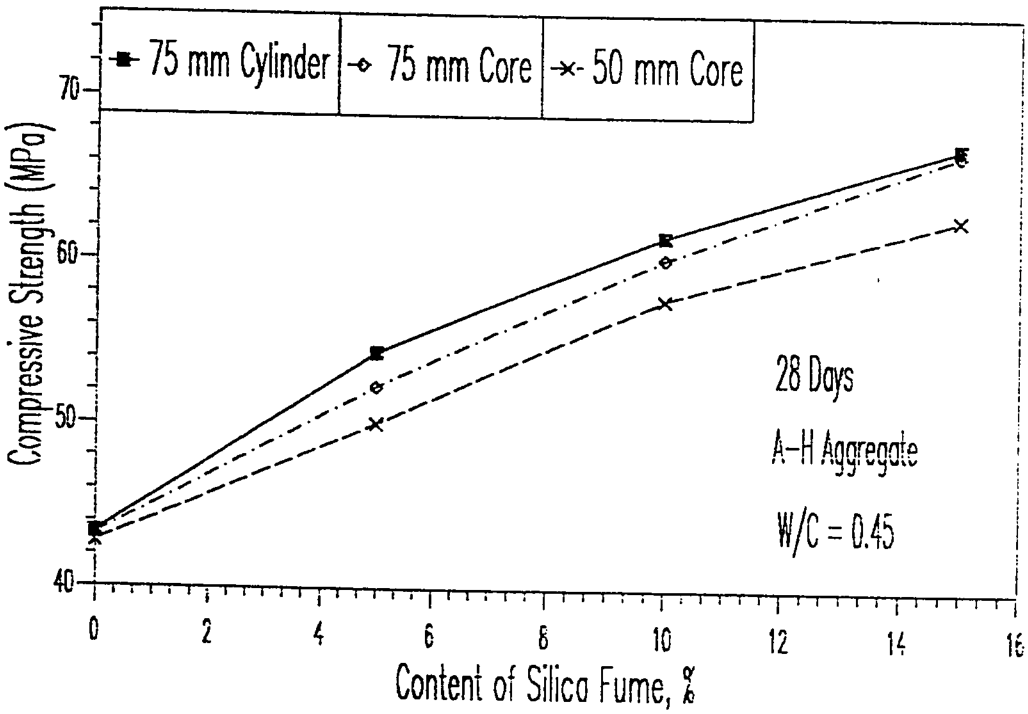


Figure 5.9: Comparison of Cylinder and Core Strengths Using Silica Fume Concretes

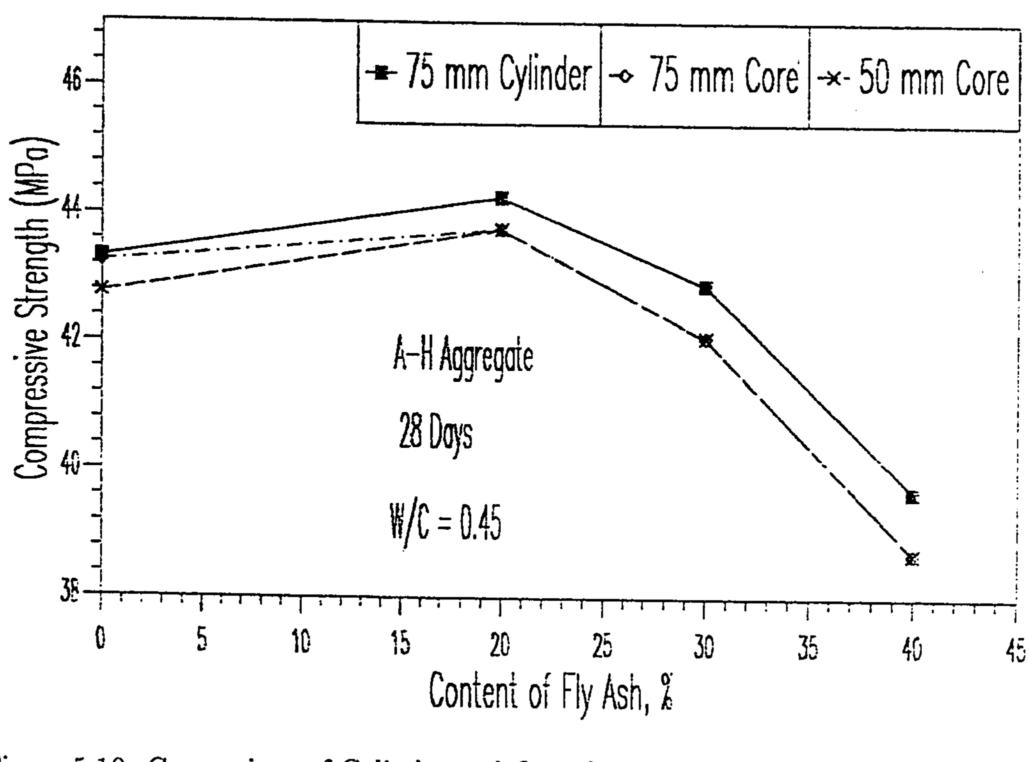


Figure 5.10: Comparison of Cylinder and Core Strengths Using Fly Ash Concretes

Table 5.5: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 50 mm Diameter Core when Blended with Silica Fume

| Mix Designation | 50 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio |
|---|---|---|---|---|
| | | Actual | Estimated | |
| H6 (0%) | 42.77 | 43.32 | 45.615 | 1.053 |
| HS1 (5%) | 50.03 | 54.36 | 52.875 | 1.028 |
| HS2 (10%) | 57.67 | 61.52 | 60.515 | 1.017 |
| HS3 (15%) | 62.72 | 67.02 | 65.565 | 1.022 |

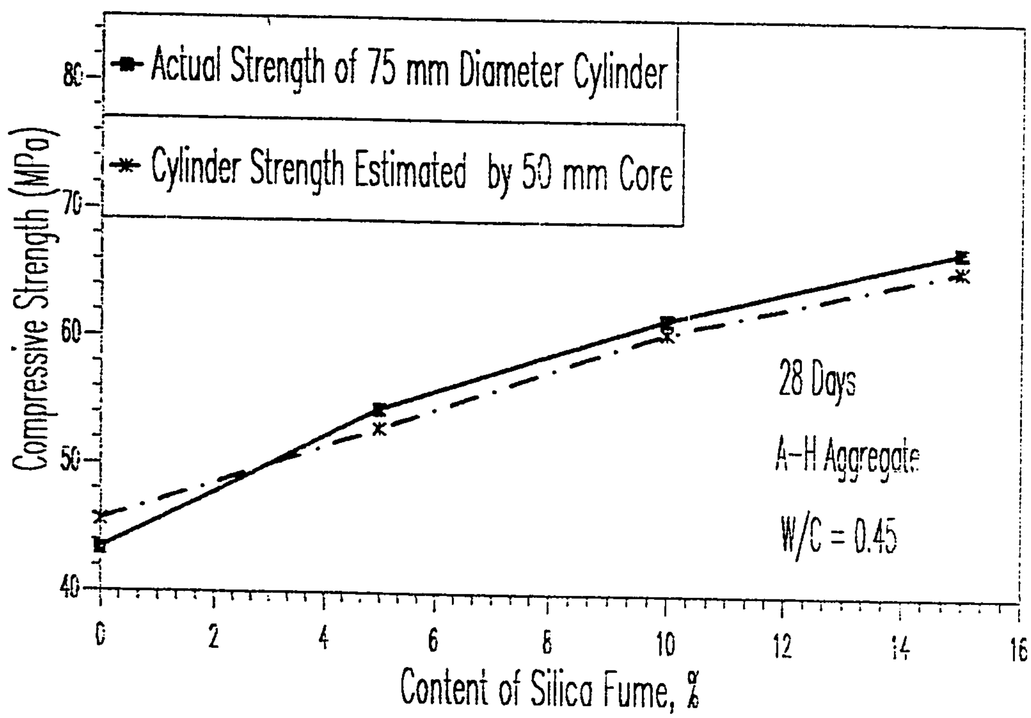


Figure 5.11: Graphical Representation of Actual and Estimated Strengths (by 50 mm Core) of Cylinder Using Silica Fume Concretes

Table 5.6: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 50 mm Diameter Core when Blended with Fly Ash

| Mix Designation | 50 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio |
|---|---|---|---|---|
| | | Actual | Estimated | |
| H6 (0%) | 42.77 | 43.32 | 45.615 | 1.053 |
| HF1 (20%) | 42.80 | 44.26 | 45.645 | 0.969 |
| HF2 (30%) | 41.81 | 42.90 | 44.655 | 0.961 |
| HF3 (40%) | 39.52 | 39.66 | 42.365 | 0.936 |

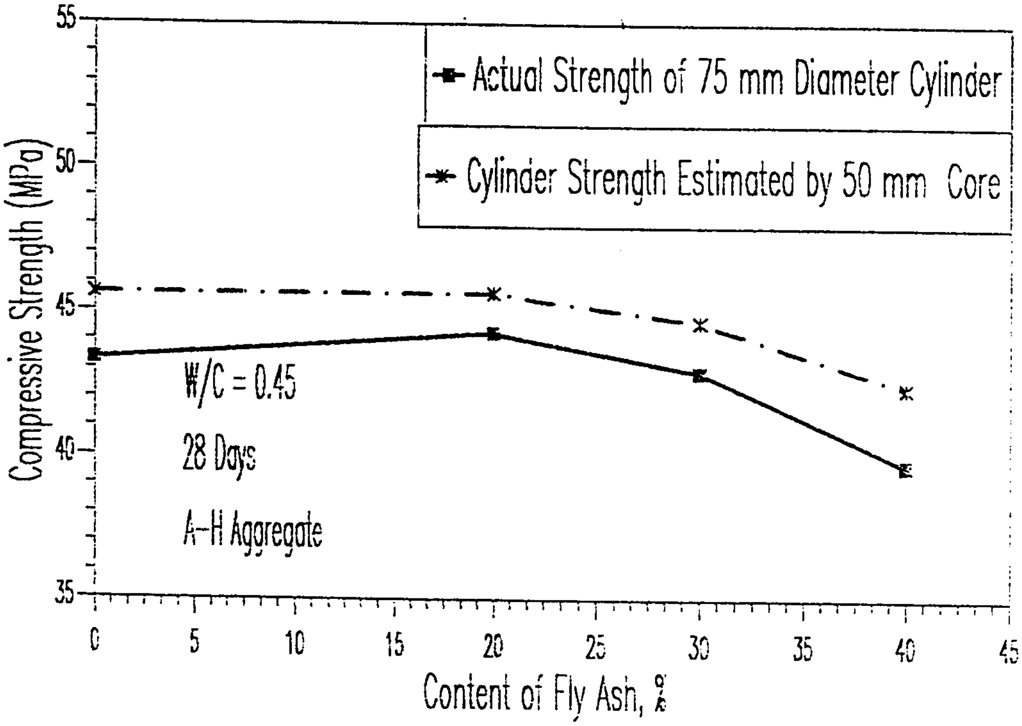


Figure 5.12: Graphical Representation of Actual and Estimated Strengths (by 50 mm Core) of Cylinder Using Fly Ash Concretes

The conversion factor of 1.05 that has been previously proposed to convert the 75 mm core strength into cylinder strength was used to estimate the cylinder strengths when silica fume and fly ash were used in the concrete mixes. Tables 5.7 and 5.8 show the actual and the estimated values of the cylinder strengths when blended with silica fume and fly ash, respectively. The ratios between the actual and the estimated strengths indicate that the 75 mm core with a conversion factor of 1.05 estimates the strength of the 75 mm diameter cylinders considerably well when silica fume and fly ash is used in the concrete mixes. Figures 5.13 and 5.14 show the graphical representation of the actual and the estimated strengths when concrete is blended with silica fume and fly ash, respectively.

## 5.4 Comparison of Actual to Predicted Strengths

Figures 5.15 and Fig. 5.16 depict the summary of all the results obtained during this research program. Fig. 5.15 shows a comparison between the actual strength of the 75 mm diameter cylinders and the estimated strength of these cylinders using the 50 mm cores via the linear correlation model. As can be seen in this figure, all the estimated strengths lie very close to the actual cylinder strengths within the confidence limits of ± 6%. It can be inferred from figure 5.15 that the 50 mm diameter cores can be used to estimate the *in-situ* concrete strength reliably provided that the maximum aggregate size does not exceed 3/4 inch.

Figure 5.16 shows a comparison between the actual strength of the 75 mm diameter cylinders and the estimated strength of these cylinders using the 75 mm diameter cores with the conversion factor of 1.05. As can be seen in this figure, all the estimated strengths lie very close to the actual cylinder strengths within the confidence limits of ± 6%. It can be inferred from figure 5.16 that the 75 mm diameter cores can be used to estimate the *in-situ* concrete strength reliably with the conversion factor of 1.05 provided that the maximum aggregate size is below 1 inch.

Table 5.7: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 75 mm Diameter Core when Blended with Silica Fume

| Mix Designation | 75 mm Core Strength (MPa) | Cylinder Strength (MPa) | | Ratio |
|---|---|---|---|---|
| | | Actual | Estimated | |
| H6 (0%) | 43.25 | 43.32 | 45.412 | 1.048 |
| HS1 (5%) | 52.27 | 54.36 | 54.884 | 0.991 |
| HS2 (10%) | 60.17 | 61.52 | 63.179 | 0.974 |
| HS3 (15%) | 66.64 | 67.02 | 69.972 | 0.958 |

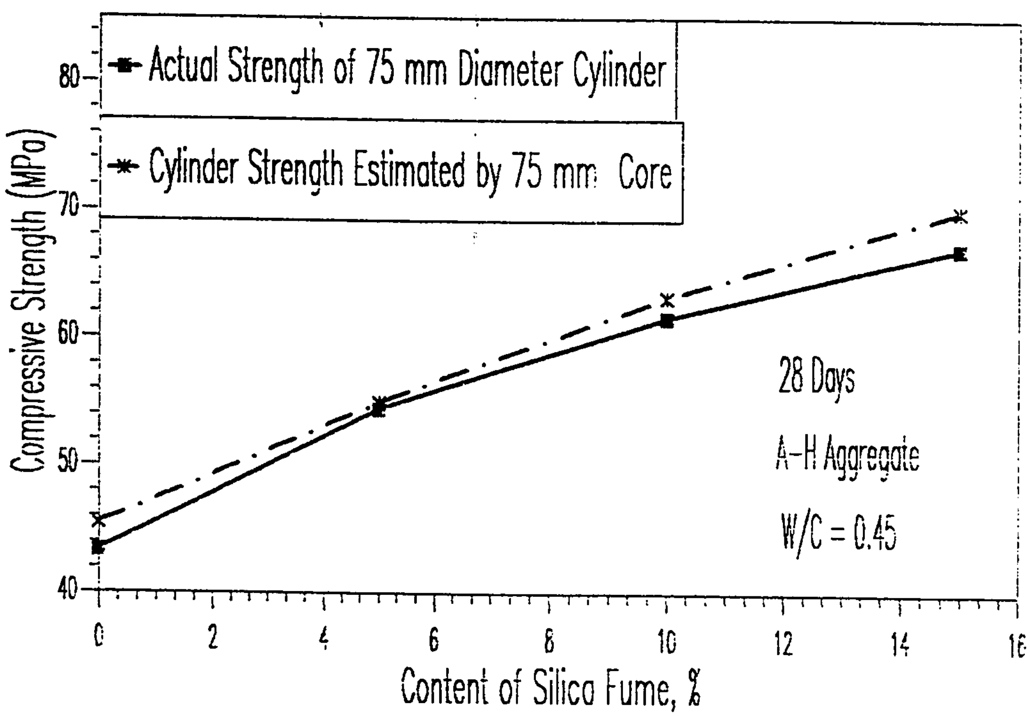


Figure 5.13: Graphical Representation of Actual and Estimated Strengths (by 75 mm Core) of Cylinder Using Silica Fume Concretes

Table 5.8: Ratio of Actual Cylinder to Estimated Cylinder Compressive Strengths Using 75 mm Diameter Core when Blended with Fly Ash

| Mix Designation | 75 mm core Strength (MPa) | Cylinder Strength (MPa) | | Ratio |
|---|---|---|---|---|
| | | Actual | Estimated | |
| H6 (0%) | 43.25 | 43.32 | 45.412 | 1.048 |
| HF1 (20%) | 43.77 | 44.26 | 45.959 | 0.963 |
| HF2 (30%) | 42.08 | 42.90 | 44.184 | 0.971 |
| HF3 (40%) | 38.70 | 39.66 | 40.635 | 0.976 |

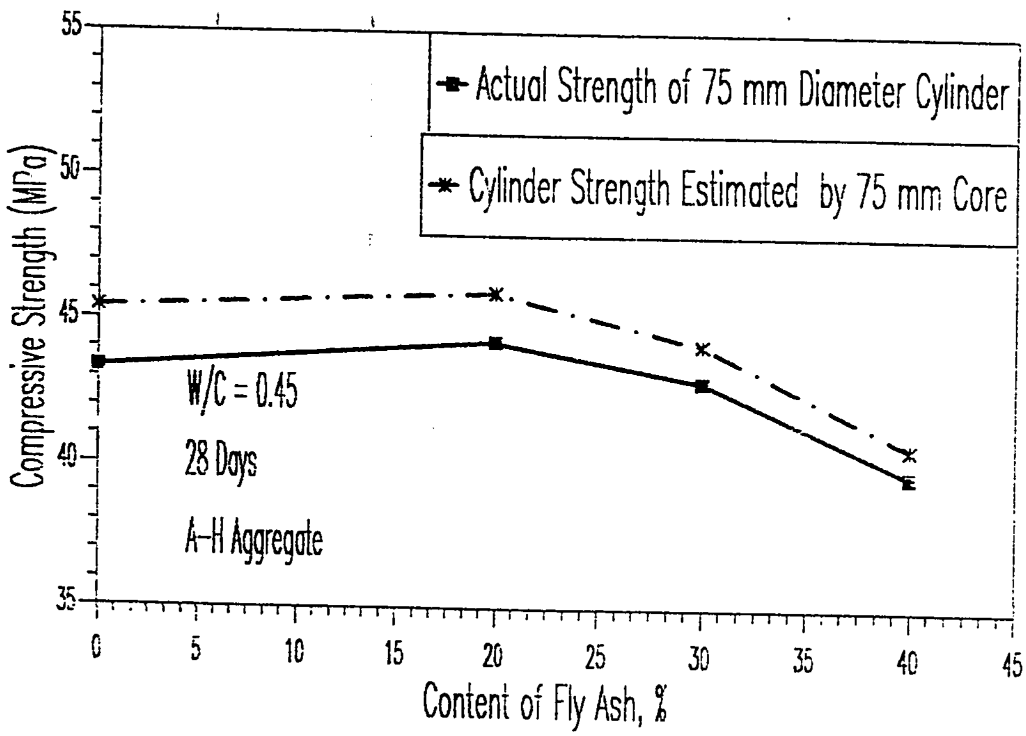


Figure 5.14: Graphical Representation of Actual and Estimated Strengths (by 75 mm Core) of Cylinder Using Fly Ash Concretes

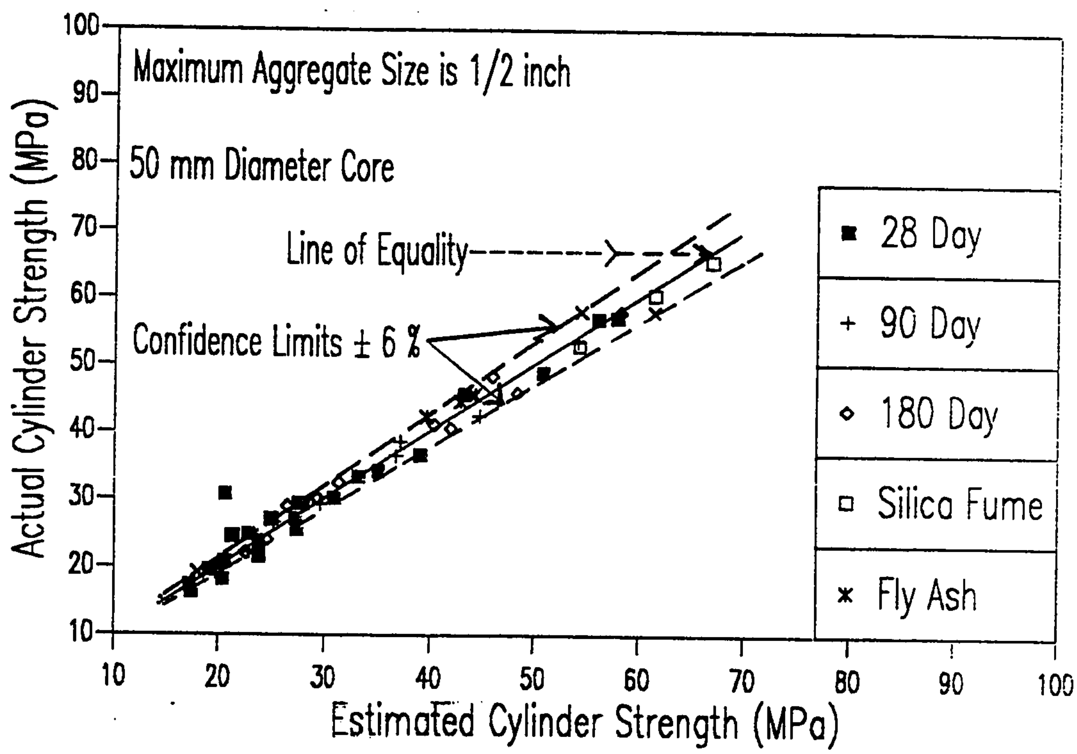


Figure 5.15: Graphical Representation of the Comparison between the Actual and the Estimated Strength of Cylinder by the 50 mm diameter core

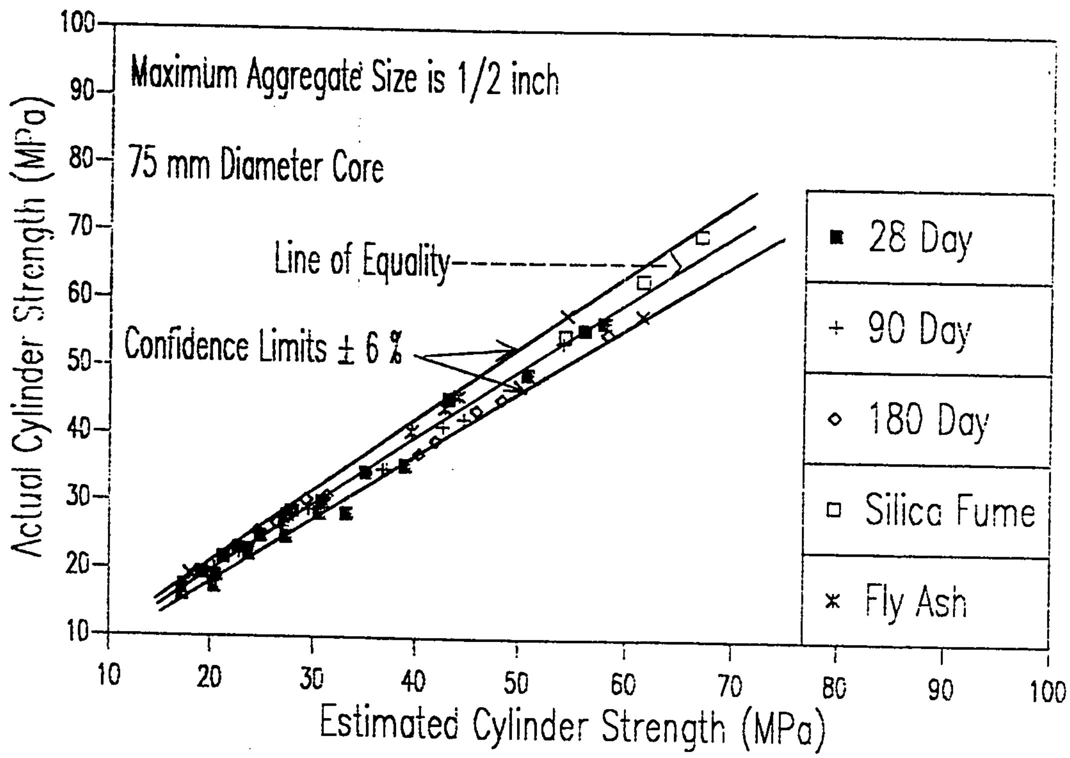


Figure 5.16: Graphical Representation of the Comparison between the Actual and the Estimated Strength of Cylinder by the 75 mm diameter core

# Chapter 6

# CONCLUSIONS

This experimental investigation was aimed at evaluating the *in-situ* concrete strength using a 50 mm diameter core. A linear correlation model was developed to find the 75 mm diameter cylinder strength using the 50 mm diameter core strength. The effect of the mixture design variables on the developed correlation model was also investigated. The following are the main conclusions which could be drawn from this research program:

1. A linear correlation model ($F'c = F_{50} + 2.845$) was proposed to measure the compressive strength of 75 mm diameter cylinders using 50 mm diameter cores. This correlation model appears to predict reliably the compressive strength of these concrete cylinders within the confidence limits of $\pm$ 6%.

2. The reliability of this correlation model is not affected by the various concrete mixture design parameters (i.e. silica fume and fly ash replacements by weight of cement, cement content, aggregate type and exposure period).

3. 50 mm diameter cores should not be used when maximum size of the coarse aggregate exceeds 3/4 inch (19mm).

4. The ratio of the strength of 75 mm diameter concrete cylinder to that of the 75 mm diameter core was found to be in the range of 1.07 to 1.03. The average ratio of 1.05 appears to predict reliably the compressive strength of 75 mm diameter cylinders.

5. The 75 mm diameter cores estimate well the compressive strength of concrete when the maximum aggregate size is below one inch (25mm).

# Chapter 7

# RECOMMENDATIONS

The 50 mm diameter cores are recommended to be used to determine the *in-situ* concrete strength via the usage of the predicted model obtained from this research work provided that the maximum aggregate size does not exceed 3/4 inch. As future research work the effect of various factors on this correlation model such as the direction of drilling process, the curing conditions and the core location can be studied adopting similar procedures used in this research program.

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# APPENDIX A

## COMPUTER PROGRAM

```
C**************************************************************************
C  PROGRAM OF THE MIX DESIGN FOR THE SAMPLES WITH AGGR. OF DIFF. SIZE...
C**************************************************************************
C  MAIN PROGRAM.........
C**************************************************************************
C*************************
C  PROBLEM IDENTIFICATION
C*************************
      READ(5,*) NTYPE,WCRAT, CECON, CAVTA, SGRCE, SGRCA, SGRFA, ABSCA,
     +ABSFA,VOLUM,ITYPE,MTYPE,PBMTR,SGRBM
C**************************************************************************
C  IF ABU-HADRIYAH AGGREGATE IS USED THEN NTYPE = 0 AND IF RIYADH IS
C  USED THEN NTYPE = 1.
C  MTYPE FOR SILICA FUME = 1
C  MTYPE FOR FLYASH = 2
C  MTYPE FOR BLAST FURNACE SLAG = 3
C  MTYPE FOR NONBLENDED CEMENT= 0
C**************************************************************************
      IF(NTYPE.EQ.0)GO TO 34
      IF(NTYPE.EQ.1)GO TO 35
  34  WRITE(6,31)
  31  FORMAT('AGGREGATE USED = ABU-HADRIYAH')
      GO TO 199
  35  WRITE(6,32)
  32  FORMAT('AGGREGATE USED = RIYADH')
 199  IF(MTYPE.EQ.0)THEN
      WRITE(6,132)
 132  FORMAT('NO BLENDED CEMENT IS USED')
      ENDIF
      IF(MTYPE.EQ.1)THEN
      WRITE(6,133)
 133  FORMAT('BLENDED MATERIAL USED = SILICA FUME')
      ENDIF
      IF(MTYPE.EQ.2)THEN
      WRITE(6,143)
 143  FORMAT('BLENDED MATERIAL USED = FLYASH')
      ENDIF
      IF(MTYPE.EQ.3)THEN
      WRITE(6,139)
 139  FORMAT('BLENDED MATERIAL USED = BLAST FURNACE SLAG')
      ENDIF
  36  WRITE(6,3) WCRAT, CECON, CAVTA, SGRCE, SGRCA, SGRFA, ABSCA,
     +ABSFA, VOLUM,ITYPE,MTYPE,PBMTR,NTYPE,SGRBM
```

```
26    3   FORMAT('SUMMARY OF THE MIX DESIGN VARIABLES:'//
        .        'NET WATER CEMENT RATIO.............= ',F10.2/
        .        'CEMENTITIOUS CONTENT................= ',F10.2,1X,'KG-CUM'/
        .        'RATIO OF CA/TA.....................= ',F10.2/
        .        'SPECIFIC GRAVITY OF CEMENT.........= ',F10.2/
        .        'SPECIFIC GRAVITY OF COARSE AGGREGATE= ',F10.2/
        .        'SPECIFIC GRAVITY OF FINE AGGREGATE..= ',F10.2/
        .        'ABSORBTION OF COARSE AGGREGATE......= ',F10.2,1X,'%'/
        .        'ABSORBTION OF FINE AGGREGATE........= ',F10.2,1X,'%'/
        .        'VOLUME OF THE MIX..................= ',F10.3,'CUM'/
        .        'ITYPE.............................= ',I2/
        .        'MTYPE.............................= ',I2/
1       .        'PERCENTAGE OF BLENDED MATERIAL USED.= ',F10.2,1X,'%'/
        .        'NTYPE.............................= ',I2,1X/
        .        'SPECIFIC GRAVITY OF BLENDED MATERIAL= ',F10.2//)
27        A = (CECON*(1-(PBMTR/100))/SGRCE)+((PBMTR/100)*CECON/SGRBM)
28        B = WCRAT*CECON
29        C = CAVTA/SGRCA
30        D = (1 - CAVTA )/SGRFA
31        TA = (1000 - A - B)/(C + D )
32        CA = CAVTA* TA
33        FA = ( 1 - CAVTA ) * TA
34        WCE = CECON * VOLUM
35        WCA = CA * VOLUM
36        WFA = FA * VOLUM
37        GWCRA = WCRAT + (ABSCA*WCA)/(100*WCE)+(ABSFA*WFA)/(100*WCE)
38        WW=GWCRA * WCE
39        WBMTR=(PBMTR/100)*WCE
40        AWCE=WCE-WBMTR
41        TOTW= WCE + WCA + WFA + WW

42        WRITE(6,9)WCA,WFA,WCE,GWCRA,WW,WBMTR,AWCE,TOTW
43    9   FORMAT('WEIGHT OF COARSE AGGREGATE .........=',F10.2,1X,'KGS' /
        .        'WEIGHT OF FINE AGGREGATE ...........=',F10.2,1X,'KGS'/
        .        'WEIGHT OF CEMENTITIOUS MATERIAL.....=',F10.2,1X,'KGS'/
        .        'GROSS WATER CEMENT RATIO............=',F10.2,1X,/
        .        'WEIGHT OF THE WATER.................=',F10.2,1X,'KGS'/
        .        'WEIGHT OF THE BLENDED MATERIAL......=',F10.2,1X,'KGS'/
        .        'WEIGHT OF THE CEMENT USED...........=',F10.2,1X,'KGS'/
        .        'TOTAL WEIGHT OF THE MIX.............=',F10.2,1X,'KGS')
C*************************************************************************CC
C
C  NOTE:- IF THE MAXIMUM SIZE OF THE AGGREGATE IS 1/2 INCH THEN ITYPE
C         WILL BE 0,IF THE MAXIMUM SIZE OF THE AGGREGATE IS 3/4 INCH
C         THEN ITYPE IS 1, IF THE MAXIMUM SIZE OF THE AGGREGATE IS
C         1 INCH THEN ITYPE IS 2 AND IF THE MAXIMUM SIZE OF THE
C         AGGREGATE IS 3/8 INCH THEN ITYPE IS 3.
C*************************************************************************CC
```

```
      IF(ITYPE.EQ.0)GO TO 13
      IF(ITYPE.EQ.1)GO TO 14
      IF(ITYPE.EQ.2)GO TO 15
      IF(ITYPE.EQ.3)GO TO 16
 13   E = (0.1)* WCA
      F = (0.5)* WCA
      G = (0.35)* WCA
      H = (0.05)* WCA
      WRITE(6,5)E,F,G,H
  5   FORMAT('WEIGHT OF THE 1/2 INCH SIZE AGGR... =',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE 3/8 INCH SIZE AGGR... =',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE NO. 4 SIZE AGGR...... =',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE NO. 8 SIZE AGGR.......=',F10.2,1X,'KGS'/)
      GO TO 100
 14   E = 0.1*WCA
      F =0.35* WCA
      G =0.35* WCA
      H =0.15* WCA
      P =0.05* WCA
      WRITE(6,6)E,F,G,H,P
  6   FORMAT('WEIGHT OF THE 3/4 INCH SIZE AGGR... =',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE 1/2 INCH SIZE AGGR... =',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE 3/8 INCH SIZE AGGR... =',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE NO. 4 SIZE AGGR......=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE NO. 8 SIZE AGGR......=',F10.2,1X,'KGS')
      GO TO 100
 15   E = .05* WCA
      F = .10* WCA
      G = .50* WCA
      H = .20* WCA
      P = .10* WCA
      Q = .05* WCA
      WRITE(6,7)E,F,G,H,P,Q
  7   FORMAT('WEIGHT OF THE 1 INCH SIZE AGGR......=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE 3/4 INCH SIZE AGGR....=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE 1/2 INCH SIZE AGGR....=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE 3/8 INCH SIZE AGGR....=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE NO. 4 SIZE AGGR.......=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE NO. 8 SIZE AGGR.......=',F10.2,1X,'KGS'/)
      GO TO 100

 16   E = .20* WCA
      F = .50* WCA
      G = .20* WCA
      H = .10* WCA
      WRITE(6,19)E,F,G,H
 19    FORMAT('WEIGHT OF THE 3/8 INCH SIZE AGGR...=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE # 4 INCH SIZE AGGR....=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE # 8 INCH SIZE AGGR....=',F10.2,1X,'KGS'/
     .       'WEIGHT OF THE #16 INCH SIZE AGGR....=',F10.2,1X,'KGS'/)
      GO TO 100
100   STOP
      END
```

```
5<0
5<0.45
5<350.0
5<0.62
5<3.15
5<2.46
5<2.54
5<1.52
5<0.57
5<0.0402
5<0
5<3
5<20
5<2.5
6>AGGREGATE USED = ABU-HADRIYAH
6>BLENDED MATERIAL USED = BLAST FURNACE SLAG
6>SUMMARY OF THE MIX DESIGN VARIABLES:
6>NET WATER CEMENT RATIO..............=        0.45
6>CEMENTITIOUS CONTENT................=      350.00 KG-CUM
6>RATIO OF CA/TA......................=        0.62
6>SPECIFIC GRAVITY OF CEMENT..........=        3.15
6>SPECIFIC GRAVITY OF COARSE AGGREGATE=        2.46
6>SPECIFIC GRAVITY OF FINE AGGREGATE..=        2.54
6>ABSORBTION OF COARSE AGGREGATE......=        1.52 %
6>ABSORBTION OF FINE AGGREGATE........=        0.57 %
6>VOLUME OF THE MIX...................=       0.040CUM
6>ITYPE...............................=   0
6>MTYPE...............................=   3
6>PERCENTAGE OF BLENDED MATERIAL USED.=       20.00 %
6>NTYPE...............................=   0
6>SPECIFIC GRAVITY OF BLENDED MATERIAL=        2.50
6>
6>
6>WEIGHT OF COARSE AGGREGATE .........=       45.03 KGS
6>WEIGHT OF FINE AGGREGATE ...........=       27.60 KGS
6>WEIGHT OF CEMENTITIOUS MATERIAL.....=       14.07 KGS
6>GROSS WATER CEMENT RATIO............=        0.51
6>WEIGHT OF THE WATER.................=        7.17 KGS
6>WEIGHT OF THE BLENDED MATERIAL......=        2.81 KGS
6>WEIGHT OF THE CEMENT USED...........=       11.26 KGS
6>TOTAL WEIGHT OF THE MIX.............=       93.87 KGS
6>WEIGHT OF THE 1/2 INCH SIZE AGGR... =        4.50 KGS
6>WEIGHT OF THE 3/8 INCH SIZE AGGR... =       22.51 KGS
6>WEIGHT OF THE NO. 4 SIZE AGGR...... =       15.76 KGS
6>WEIGHT OF THE NO. 8 SIZE AGGR.......=        2.25 KGS
```

# APPENDIX B

## MEASURED SLUMP

Measured Slump for Each Mix

| Mix | Slump in mm |
|---|---|
| H1** | 110 |
| H2 | 125 |
| H3 | 180 |
| H4 | C* |
| H5 | 100 |
| H6 | 110 |
| H7 | 150 |
| H8 | 170 |
| H9 | 190 |
| H10 | C |
| H12 | 60 |
| H13 | 65 |
| H14 | 80 |

*C = Collapsed. ** H = Abu-Hadriyah aggregate

Measured Slump for Each Mix

| Mix | Slump in mm |
|---|---|
| R1** | 125 |
| R2 | 145 |
| R3 | 180 |
| R4 | C |
| R5 | C |
| R6 | 115 |
| R7 | 135 |
| R8 | 170 |
| R9 | 185 |
| R10 | C |
| H6A | 125 |
| H6B | 165 |
| H6C | C |
| HS1 | 90 |
| HS2 | 85 |
| HS3 | 75 |
| HF1 | 100 |
| HF2 | 90 |
| HF3 | 95 |

*C = Collapsed, **R = Riyadh aggregate

# Vitae

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