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Mechanical properties of self-consolidating concrete with pozzolanic materials

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MECHANICAL PROPERTIES OF SELF-CONSOLIDATING CONCRETE

WITH

POZZOLANIC MATERIALS

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Indra Prasad Chapagain

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To: Interim Dean Amir Mirmiran
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This thesis, written by Indra Prasad Chapagain, and entitled Mechanical Properties of Self-Consolidating Concrete with Pozzolanic Materials, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

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DEDICATION

This thesis is dedicated to Gyanisara Chapagain, Apoorva Chapagain and Kamana Chapagain.

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ABSTRACT OF THE THESIS

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by

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Professor N. Suksawang, Major Professor

Self-consolidating concrete has been described as the most revolutionary development in concrete technology in several decades with the ability to flow freely through closely spaced reinforcements, expel entrapped air and self compact without vibration. Since it was first developed in Japan in the early 1980's, major development in the chemical admixture technology has made SCC more viable.

An experimental study was conducted to identify the mechanical properties of SCC by optimizing the use of pozzolanic materials and local aggregates with some proposed statistical models. The research was focused to investigate compressive strength, splitting tensile strength, modulus of elasticity and drying shrinkage behavior of concrete. The results were established experimentally and compared with the available SCC research data based on extensive literature study.

Besides the improved mechanical performance, results indicate that the use of pozzolanic materials and local aggregate in SCC is recommended in terms of its cost benefit value.

TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

f'_c = Compressive strength

f'_{st} = Splitting tensile strength

E = Modulus of elasticity of concrete

L = Length of specimen

d = Diameter of specimen

F = Applied force

w_c = Density of normal concrete

oz = Ounce

W/b = Water binder ratio

ε = Strain (Longitudinal)

SCC = Self-Consolidating concrete

NC = Normal concrete

OPC = Ordinary Portland cement

ASTM = American Society of Testing Materials

SP = Superplasticizer

VMA= Viscosity modifying agent

AEA= Air entraining admixtures

LP = Limestone powder

NA= Not applicable

CHAPTER 1

INTRODUCTION

1.1 Self-Consolidating Concrete

Self-consolidating concrete (SCC) can be defined as a fresh concrete that possesses superior flowability under maintained stability (i.e. no segregation), thus allowing self-compaction (Goodier, winter 2002/2003). It is a fluid mixture, which is suitable for placing in complex structures with congested reinforcement without vibration. It is characterized by high powder content. The resulting concrete has an excellent surface finish (Subramanian and Chattopadhyay, 2002).

The development of SCC begun in Japan in 1983 when the aim was to build durable concrete structures with a reduced number of skilled workers. The initial fundamental investigations were carried out at Tokyo University by Ojawa and Maekawa in 1989 (Okamura and Ouchi, 1989).

Opportunities obviously exist for SCC in rapid pavement repair, precast application in highway or bridge construction because of its rapid strength gain, long service life and no noise (therefore making highway night working possible) are all vital to highway construction and repair, and so SCC is an ideal material (Mullarky and Vanikar).

The mix composition of SCC generally differs from that of a normal concrete through a higher proportion of ultrafines and through the use of highly effective superplasticizers. In principle, there are three approaches to the production of SCC:

- Raising the ultrafines content by addition of fine fractions in the form of fly ash or stone powder.

- Use of suitable stabilizing additives and or superplasticizer (viscosity agent type);
- Combination of above –mentioned measures (combination type).

Neither the water nor the cement content of SCC differs substantially from those of normal concrete. The water to cement (W/C) value remains on the normal range between 0.45 and 0.60. The addition of ultrafines of high specific surface area significantly increases the mortar volume, but at the same time reduces the relative percentage of water in the cement paste. Addition of superplasticizers is therefore essential to give the fresh concrete adequate flowability. Newly developed additives based on polyacrylates and multycarboxylate ethers are particularly suitable in this respect. Concrete additive based on polycarboxylates offer the following advantages for SCC application.

- Significant reduction of the water demand n the mix
- Little loss of consistency
- Short setting times
- High early strength
- Low tendency to segregation. (Brameshuber, 2001)

SCC that flows into formwork and through reinforcement under the influence of its own weight can be made such that no external vibration is required. Although careful proportioning and batching are needed, SCC can be produced with locally available materials. Concrete with a high slump flow are prone to segregation and bleeding. Tests should be conducted with the material used for a specific project to establish that the SCC flows sufficiently but will not segregate, bleed, or require additional consolidation. Segregation is the tendency for coarse aggregate to separate

from the sand-cement mortar due to vibration, transportation or handling and bleeding is the water gain due to the settlement of solid materials in concrete. To minimize segregation, a large amount of fine material, a small nominal maximum aggregate (NMA) size, uniform grading, and low water cementitious material ratios are needed or conventional mixtures with viscosity modifying agent (VMA) may be used. To mitigate high drying shrinkage, a large NMA size, a large amount of coarse aggregate, and lower water cement are needed. To avoid an improper air-void system that would reduce freeze-thaw resistance either larger air content or conventional air content with the proper selection of admixtures that will lead to a reduced void size and spacing is needed. (Ozyildirim and Lane, 2003).

Fresh concrete can be described as a particle suspension, although rather complex. The liquid phase is normally defined as either mortar or cement paste. As in all particle suspensions, the balance between flowability and segregation is vital. SCC is extending the flowability, with maintained stability of the suspension, to such a degree that the concrete can flow through openings, fill moulds and consolidate itself without any added external energy input. To achieve this behavior it is necessary to have:

- Appropriate flowability
- Stability(non-segregations)
- No blocking tendency(passing through openings between bars)

The main mechanism to achieve appropriate flowability is a reduction of the inter-particle friction with the use of superplaticizing admixtures. The physical and mineralogical properties of the fine particle materials are also very important. The stability is achieved by designing the liquid phase with appropriate rheological

properties. This is achieved through careful particle packing design and/or the use of viscosity modifying admixtures.

The size and shape of the coarse aggregate as well as the volume of the liquid phase are important factors to prevent blocking for different reinforcement configurations. The type of superplasticizer is of outmost importance. It shall be selected from the requirements needed for each type of product. An accelerator can be needed in the superplasticizer for example for walls so that the surface finishing can take place at an early age. (Gunnar Rise, 2001).

1.2 Purpose of the Research

A large volume of research regarding normal concrete has been performed; a comparatively much smaller quantity of research regarding self-consolidating concrete is available. Inadequate homogeneity of the cast concrete due to poor compaction or segregation may drastically lower the performance of the matured concrete. The strength and durability of concrete can be improved with the addition of pozzolanic materials and chemical admixtures. The pozzolanic materials are finer materials than even Portland cement which reduces porosity and increases its strength and durability.

The purpose of this study is to investigate the behavior and relationship of mechanical properties of diverse SCC mixes with the use of new fillers i.e. pozzolanic materials. In this study, the mechanical properties include compressive strength, tensile splitting strength, modulus of elasticity and shrinkage which are needed for designing reinforced concrete structures. The mixes are based on the proportion used by the 'Core slab Structures', Miami based SCC Plant, Pozzolanic materials in

different trial proportions are additionally used in these mixes which consist of fly ash and silica fume to reduce shrinkage, permeability and increase durability. Silica fume is capable of reducing permeability and helps to minimize aggregate segregation whereas fly ash significantly improves mechanical properties and durability of concrete. (Xie et al., 2002; Bouzoubaa and Lachemi, 2001; and Ho et al., 2003).

1.3 Thesis Summary

Chapter one gives a brief introduction to self-consolidating concrete, purpose of the research and outline of thesis summary. Chapter two presents literature review that includes background of self-consolidating concrete, its mix design, influence of mixing procedures and summary of literature review. Chapter three explains constituent materials of self-consolidating concrete e.g. Portland cement, aggregates, pozzolanic materials and superplasticizer. Chapter four explains the experimental program that includes introduction, material properties, description of each constituent material in accordance with ASTM standard, spread test, compressive strength test, splitting tensile test, modulus of elasticity test and drying shrinkage test. Chapter five covers test results. The test results are summarized for compressive strength, splitting tensile strength, modulus of elasticity and drying shrinkage. Diagrams have been provided for splitting tensile strength vs. percent fly ash, modulus of elasticity vs. percent fly ash and time vs. percent drying shrinkage. Chapter six shows a model comparison of splitting tensile test and modulus of elasticity with the available research and codes such as ACI 318, ACI 363 and Eurocode 2. Chapter seven describes the conclusion of the overall research.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Inadequate homogeneity of the cast concrete due to poor compaction or segregation may drastically lower the performance of mature concrete. SCC has been developed to ensure adequate compaction and facilitate placement of concrete in structures with congested reinforcement and in complex areas where compaction may not be possible. (Bouzoubaa and Lachemi, 2001). It can also be used in situations where it is difficult or impossible to use mechanical compaction for fresh concrete, such as underwater concreting, cast in-situ pile foundations, machine bases and columns and walls with closely spaced reinforcements. The high flowability of SCC makes it possible to fill the formwork without vibration. Since its inception, it has been widely used in large construction in Japan (Okamura and Ouchi, 2003). Recently, this concrete has gained wide use in many countries for different applications and structural configurations (Bouzoubaa Lachemi, 2001).

SCC can also be regarded as "the most revolutionary development in concrete construction for several decades. Originally developed to offset a growing shortage of skilled labor, it is now taken up with enthusiasm across European countries for both site and precast concrete work. (Krieg, Oct. 2003; EFNARC, Feb 2002).

SCC has gained widespread attention in the United States in the last few years for its obvious advantages of savings in labor costs, shortened construction time, better finish and improved work environment (Gaimster and Foord, 2000; Khayat, 1999).

SCC was developed in Japan in the early 1980's. The roots of the development were dictated by three main factors, one being the need for flowing concrete to compensate proper filling within the intricate reinforcement design in seismic members. The others are the decreasing number of skilled craftsmen in Japan and the need to reduce the cost and time of construction. With the growing use of concrete in special architectural configurations and closely spaced reinforcing bars, it is very important to produce concrete that ensures proper filling ability, good structural performance, and adequate durability (Hayakawa et al., 1993).

2.2 Mix Design of SCC

In order to understand the mix design and its phenomena in connection with the properties and quality of SCC, we need to be familiar with the tests and results, research and experiments that have been done to date. An attempt has been made to cover up multiple tests with varieties of mixes, so as to make a finer distinction with the comparison.

The basic components for the mix composition of SCC are the same as used in conventional concrete. However, to obtain the required properties of fresh concrete, in SCC a higher proportion of ultra fine materials and the incorporation of chemical admixtures, in particularly an effective superplasticizer, are necessary. Ordinary and approved fillers are fly ash, limestone powder, blast furnace slag, and silica fume and quartzite powder (Holschemacher and Klug, 2002). Fillers are fine particles than Portland cement, which helps in reducing porosity and improves durability and strength of concrete.

The result in mixes compared to conventional workability concrete, contain:

- Lower coarse aggregate contents
- Increased paste contents
- High power (materials<0.125mm) contents,
- Low water/powder ratios
- High superplasticizer doses
- (Sometimes) a viscosity-modifying agent.

SCC is based on a new concept that fulfils the deficiencies of normal concrete. It has proved beneficial economically because of a number of reasons:

Table 2.1 Advantages and Disadvantages of SCC

Advantages	Disadvantages
▪ Faster construction ▪ Reduction in manpower ▪ Uniform consistency of concrete ▪ Easier placing ▪ Greater flexibility in design ▪ Better surface finishing ▪ Increased bond strength ▪ Improved durability ▪ Reduced noise levels, due to absence of vibration ▪ Safe working environment	▪ Greater quality-assurance effort in production ▪ Higher costs for materials for the plasticizers and additives ▪ Properties are not well known ▪ Can only be used on flat surfaces ▪ Non-uniform formwork pressure

(Krieg 2003, and ENFARC 2002, Leiberum 2002)

2.3 Influence of Mixing Procedures on the Production of SCC

The mixing procedure is critical in producing concrete of the desired properties. All materials are weighed preciously and added in a sequence to the mixture. The sequence of mixing must allow sufficient time for the thorough mixing of all the ingredients without losing moisture due to wind and temperature effects.

Besides technical problems as for example the composition, there are as well administrative barriers in the foreground. During the SCC's production in mixtures, it is necessary to produce a concrete which has good flow qualities and a high passing and form filling quality with an excellent cohesion quality. According to Beitzel, H. there is three groups of mixing parameters:

System technical:

- mixing space,
- mixing tools,
- Process rate

Service technical:

- Dosage sequence
- Mixing time
- Length of cycle

Concrete technical:

- Material items
- Various characteristics, (Beitzel, H., 2001)

2.4 Summary of Literature Review

The mechanical properties and qualities of SCC mainly depend on its mix design within the recommended standard tests. There are many factors that are still unknown for the better strength and modulus of elasticity. Materials, its quality and proportion are the root three factors that change the behavior of mechanical properties of concrete. Size, fineness modulus (grading) and quantity of fine and coarse aggregate, w/b ratio, cement and chemical are the known factors that are responsible to change the property of SCC. Hence, an approach have been made to cover up a wide range of mix design from different world class literatures, seminars and even local plant to obtain and compare especially the mechanical properties. Some important summary and conclusions have been drawn with respect to the performance of SCC.

- Specifications and guidelines for SCC- EFNARC, 2002 has proposed a crushed aggregate for a better mechanical property of SCC, whereas Petersson O., 1997 suggests opposite one, with the proof of experiment and result, the higher compressive strength obtained for mixes is explained by a better quality of the natural rounded 4/10 aggregate compared to the semi crushed 4/10.
- If the concrete design is not a densely reinforced one, we can ignore the flowability requirement using greater size and quantity of aggregates (by balancing segregation adding viscosity modifying admixtures) so as to increase the strength parameter of SCC, as suggested by Ouchi, Nakamura, Osterson, Hallberg, and Lwin, 2003 ISHPC.
- The equal use of course and fine aggregate tends to reach highest possible compressive strength of SCC (Petersson O. 1997, Swedish Cement and concrete Research Institute).

- The coarse aggregate chosen for SCC is typically rounded small aggregate particles that enhance the flowability and deformability. The smaller aggregate size is also less likely to segregate from the paste. The coarse particles increase the strength of concrete reducing the flowability. The most common max aggregate size used in SCC is in the range of 16-20mm (Peterson O., 1998) depending on the type of construction.
- To minimize segregation, a large amount of fine material, a small nominal maximum aggregate (NMA) size, uniform grading, and low water cementitious material ratios are needed or conventional mixtures with viscosity modifying agent (VMA) may be used. To shrinkage, a large NMA size, a large amount of coarse aggregate, and lower water cement are needed. (Ozyildirim C., 2003).
- If problems develop due to a poor gradation, alternative aggregates, or special screening of existing aggregates, should be considered. The combined gradation can be used to better control workability, pumpability, shrinkage and other properties of concrete (Steven et.al., 2003)
- The maximum size of coarse aggregate used in concrete has a bearing on the economy of concrete. Usually more water and cement is required for small-size aggregate than for large sizes, due to an increase in total aggregate surface area (The European Guidelines for SCC, 2005).
- As the aggregates restrain the creep of the concrete paste, the higher the volume of the aggregate and the higher the E-value of the aggregate, the lower the creep will be (The European Guidelines for SCC, 2005).

- A decrease in the maximum aggregate size which results in a higher paste volume increases the drying shrinkage (The European Guidelines for SCC, 2005).

CHAPTER 3

CONSTITUENT MATERIALS OF SCC

The constituent materials used in the production of SCC are similar to that of the normal vibrated concrete except the reduced aggregate content and increased powder content with the addition of superplasticizer or viscosity modifying agent (VMA).

3.1 Portland Cement

Portland cement is mainly consists of limestone and clay. Limestone is first processed to produce calcium oxide which in turn is combined with the metal oxides produced from clay (silica SiO_2, alumina Al_2O_3, iron oxide Fe_2O_3 etc) to generate the primary products of Portland cement. The major components of Portland cement are:

1. Tricalcium silicate ($3CaOSiO_2= C_3S$)
2. Dicalcium silicate ($2CaOSiO_2= C_2S$)
3. Tricalcium aluminate ($3CaOAl_2O_3=C_3A$)
4. Tetracalcium aluminoferrite ($4CaO. Al_2O_3.Fe_2O_3= C_4AF$)

These chemical compounds of Portland cement are discussed in the following (Mehta, 1986; Mindess and Young, 1981; Bayast et al., 1990 and Huang, 1990).

1. <u>Tri-calcium silicate, C_3S</u>: This product is responsible for the rapid hardening of concrete. With increasing percentage of C_3S in cement, the resulting concrete early strength(less than a week old) increases.
2. <u>Dicalcium silicate, C_2S</u>: C_2S has a significant contribution to the late age strength of concrete.

3. <u>Tricalcium aluminate, C_3A</u>: This product hardens relatively slowly and is characterized by its relatively low contribution to early age strength.
4. <u>Tricalcium aluminoferite, C_4AF</u>: C_4AF acts as a flux during cement production when limestone and clay are subjected to high baking temperature (clinkering). The flux action of C_4AF reduces the clinkering temperature which can be beneficial to energy saving.
5. Based on the relative proportions of the components of Portland cement, it can be classified in five types. Each type, depending on its quality, is designated for its specific field applications. The following Table presents the most important types of Portland cement along with the relative proportions of their components (Mehta, 1986; Mindess and Young, 1981; Bayast et al., 1990 and Huang, 1990).

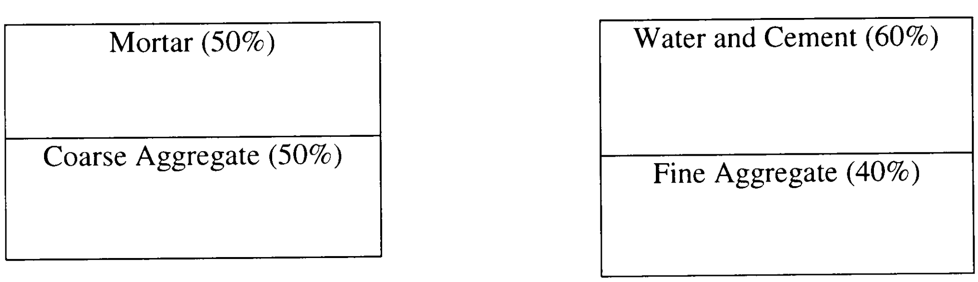
Table 3.1 Composition of Different Types of Portland cement

Type of Portland cement	Compounds percentage				Function
	C_3S	C_2S	C_3A	C_4AF	
Type I	55	19	10	7	Ordinary
Type II	51	24	6	11	Moderate sulphate resisting
Type III	63	19	10	7	High early strength
Type IV	28	49	4	12	Low heat of hydration
Type V	38	43	4	9	Sulphate resisting

Portland cement Type II with specific gravity 3.15 and blain fineness of 377 m^2/kg was used. It is used for general purposes, more especially when moderate sulphate resistance or moderate heat of hydration is desired. It was manufactured by Titan Florida that meets the requirements of ASTM C 150 standard. The chemical and physical properties are listed in Table 3.2 (APPENDICES).

3.2 Aggregate

In order to obtain an economic mix design, the coarse aggregate content should be the maximum possible. However, in order to increase the passing ability and reduce interparticle collision, the volume of coarse aggregate should be decreased, and the paste volume should be increased. To achieve an optimized SCC mixture, coarse aggregate is limited to 50% of the solid volume and fine aggregate is fixed at 40% of the mortar content (Okamura, 1997).



(a) Solid Volume (b) Mortar Volume

Fig 3.1 Recommended Values for Coarse Aggregate Volume and Fine Aggregate Volume (Okamura, 1997).

The aggregate particles larger than 4.75 mm (0.2 in) are termed as coarse aggregate, whereas the particles smaller than 4.75 mm but larger than 0.075 mm (0.003 in) are called fine aggregates. The finer aggregates are responsible for the enhancement of workability and uniformity of the mixture. The maximum size and grading of the aggregates depends on the particular application. However, the maximum size of coarse aggregate is usually limited to 20 mm. (Mehta, 1986; Mindess and Young, 1981; Bayast et al., 1990 and Huang, 1990).

The high volume of paste in SCC mixes helps to reduce the internal friction between the sand particles but a good grain size distribution is still very important. Many SCC mix design methods use blended sands to match an optimized aggregate grading curve and this can also help to reduce the paste content. Regarding the characteristics of different types of aggregate, crushed aggregate tend to improve the strength because of the interlocking of the angular particles, whereas rounded aggregates improve the flow because of lower internal friction. The particle size distribution and the shape of coarse aggregate directly influence the flow and passing ability of SCC and its paste demand. The more spherical the aggregate particles the less they are likely to cause blocking and the greater the flow because of reduced internal friction. However, as per Japanese approach and Orjan Petersson (Swedish Cement and Concrete Research Institute-Date 97-10-27/ line 8) suggests with the proof of experiment and result, the higher compressive strength obtained for mixes is explained by a better quality of the natural rounded 4/10 aggregate compared to the semi crushed 4/10 (EFNARC, 2002; European Guidelines, 2005).

Coarse aggregate used was ASTM#57 FDOT limestone with max nominal size of 19 mm. It is abundantly available and comparatively cheap material in Florida. The aggregate have a SSD (saturated surface dry) mean specific gravity 2.483 and

water absorption 4.8 percent. Fine aggregate used was commercial sand with SSD mean specific gravity 2.564 and water absorption 2.45. Test method for sieve analysis of fine and coarse aggregates meets the standard specification of ASTM C 136. The grain size distributions of both aggregates were listed in Table 3.3 and 3.4.

Aggregate Grading: The grading and grading limits are usually expressed as the percentage of material passing each sieve. There are several reasons for specifying grading limits and nominal maximum aggregate size, they affect relative aggregate proportions as well as cement and water requirements, workability, pumpability, economy, porosity, shrinkage and durability of concrete. Variations in grading can seriously affect the uniformity of concrete from batch to batch. Very fine sands are often uneconomical; very coarse sands and coarse aggregate can produce harsh, unworkable mixtures. In general, aggregates that do not have a large deficiency or excess of any size and give a smooth grading curve will produce the most satisfactory results. However, a perfect gradation does not exist in the field –but we can try to approach it. If problems develop due to a poor gradation, alternative aggregates, or special screening of existing aggregates, should be considered. For example, sometimes midsized aggregate, around the 9.5 mm size, is lacking in an aggregate supply, resulting in a concrete with high shrinkage properties, high water demand, poor workability, poor pumpability, and low strength. The combined gradation can be used to better control workability, pumpability, shrinkage and other properties of concrete (Steven et al., 2003).

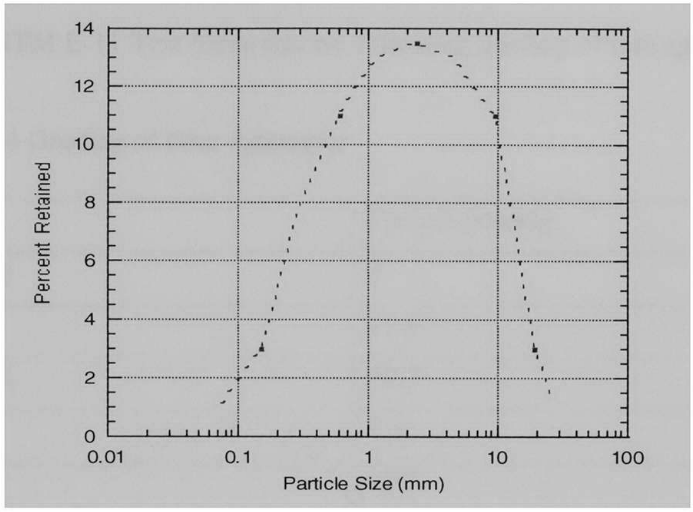


Figure 3.2 Symmetrical Curves for a Combined Gradation

Coarse Aggregate: The coarse aggregate used in this study is ASTM#57, FDOT, limestone. The average value of water absorption is 4.85%. The ASTM E-11 Test Sieve has the following grading result:

Table 3.3 Grading of Coarse Aggregate

Sieve Opening	Percent passing
1 in. (25.4 mm)	0
¾ in. (19 mm)	3.2
½ in. (12.5 mm)	39.7
3/8 in.(9.5 mm)	33.4
3/16 in. (4.75 mm)	22.5

Fine Aggregate: 'Commercial Concrete' sand was used as fine aggregate. It was obtained from Rinker Materials, South Miami Plant, FL. The water absorption was 2.5 %. The ASTM E-11 Test Sieve has the following grading of fine aggregate:

Table 3.4 Grading of Fine Aggregate

Sieve	Percent passing
#4 (4.750 mm)	0
#8 (2.36 mm)	11.4
#16 (1.80 mm)	30.7
#30 (600 μm)	9.5
#50 (300 μm)	15.2
#100 (150 μm)	28.2

3.3 Pozzolanic Materials

Pozzolans are basically composed of siliceous (SiO_2) or siliceous and aluminous (SiO_2 and Al_2O_3) materials which combine with lime [Ca $(OH)_2$] in the presence of moisture (Lemond, ACI SP 79). Fly ash, silica fume, limestone powder and blast furnace slag are the basic pozzolanic materials. Fly ash or limestone powder is used in SCC to replace or reduce the content of cement. These fill the capillary pores in concrete making it denser, thus, increasing the durability of concrete. In addition, some of the pozzolans like fly ash and blast furnace slag can also increase the flowability of concrete which results in the reduction of the amount of superplasticizers (Xie et al., 2002; Bouzoubaa and Lachemi, 2001; and Ho et al., 2003). The particle size of pozzolanic materials is finer than cement; hence it helps to reduce the porosity improving strength and durability of SCC.

3.4 Fly ash

Fly ash is an inorganic by-product obtained from the combustion of pulverized coal and is carried from the combustion chamber of a furnace by exhaust gases. It is classified as pozzolan. Pozzolans are siliceous (SiO_2) and aluminous (Al_2O_3) materials which combine with lime [Ca $(OH)_2$] in the presence of moisture. For use in Portland cement concrete, fly ash is divided into two classes, class C and class F. Class C ash is obtained from the use of sub bituminous and lignite coal in power plants. It is characterized by its relatively high CaO content and tan color. Class F fly ash is generated from burning bituminous and anthracite coals in the electric power plants. It is gray in color and contains relatively high carbon and low lime contents. Class F fly ash was used for the experimentation which matches the requirements of ASTM C 618.

Fly ash is used as a partial replacement of cement in concrete. Ratio of fly ash to binder (cement plus fly ash) ranges from 20 to 60%. However, 20 to 30% is usually considered optimum for strength. For class F fly ash, this ratio is considered optimum for workability also. Typical chemical composition of fly ash class F and Portland cement are described in Table 3.5 (Lemond; Bayasi and Soroushian, 1988-1989; Popovics, 1982; Sturrup, 1983; Ravina, 1984; Portland Cement Association, 1979).

Properties of Fly Ash: Fly ash particles are spherical and vary in size from 1 to 100 microns with a typical average size of 9 to 15 microns. The density of fly ash ranges from 2.2 to 2.8 g/cm^3.

The pozzolan consists of heterogeneous combination of crystalline and amorphous oxides, unhydrated lime and carbon. For use in Portland cement concrete,

fly ash is divided into two classes, C and F. Class C ash is generated from the use of sub-bituminous and lignite coal in power plants. It is characterized by its relatively high CaO content and Tan color. On the other hand, burning bituminous and anthracite coals in power plants produces a grey class F ash with relatively high carbon and low lime contents.

Table 3.5 Typical Chemical Compositions of Fly Ash and Portland Cements

Compound	Quantity (%)		
	Fly Ash		Portland Cement
	Class F	Class C	
SiO_2	50-55	38-45	20-25
Al_2O_3	20-27	15-18	2-5
Fe_2O_3	5-10	5-10	1-5
CaO (lime)	5-10	15-25	60-65
MgO	0.5-2	2-6	1-4
SO_3	0-2	2-6	2-5

For use in concrete, the optimum percentage of SiO2 and CaO are 45-65% and 10-20%, respectively. Uniformity is especially important because fly ash is a waste material from coal burning where electricity is the principal product of the operation. The finer particles of fly ash, especially those less than 10 microns, are more beneficial for microstructure. The finer particles also contain less carbon which is harmful to concrete in any amount (Lemond, SP 79; Bayasi and Soroushian, 1988-1989; Popovics, 1983; Sturrup et al., 1983; Ravina 1984; PCA, 1979).

Fly ash is used as a partial replacement of cement in concrete. Ratio of fly ash to binder (cement + fly ash) ranges from 20 to 60%. Generally, 20 to 30% is

considered optimum for strength and microstructure. For class F fly ash this ratio is usually optimum for workability. However, with case C ash, improvements in workability continue consistently with increasing the ratio of fly ash to binder (Lemond SP 79; Bayasi and Soroushian, 1988-1989; Popovics, 1983; Sturrup et al., 1983; Ravina 1984; PCA, 1979).

Advantages of Fly Ash in Concrete: The addition of fly ash increases workability, flowability, mobility and uniformity because the spherically shaped fly ash particles act as ball bearings between the surfaces of neighboring cement particles. Compared to larger particles, fly ash particles less than 10 microns are generally more effective as ball bearings. Since class C fly ash contains larger quantities of particles smaller than 10 microns compared to class F ash, class C fly ash in particular is very effective in improving concrete workability. The improvements in flowability and mobility resulting from fly ash addition also improve pumpability of concrete. Furthermore, the additional binding material and improved workability of fly ash concrete permit mix designs with relatively low water to binder ratios which yield concrete mixtures with more compressive strength.

Fly ash provides concrete with more SiO_2 which improves the stability and uniformity of the mix. The increase of binder volume by the application of fly ash retards setting time resulting delay of the finishing process because it has lower reactivity than cement. Finishing of concrete surfaces usually causes an accumulation of fines which may block bleed water movement to the surface and cause plastic shrinkage cracking (Lemond, SP 79; Bayasi and Soroushian, 1988-1989; Popovics, 1983; Sturrup et al., 1983; Ravina 1984; PCA, 1979).

3.5 Silica Fume

It is the finely divided residue resulting from the production of silicon or silicon containing alloys that are carried from the furnace by exhaust gases. Silica fume is composed of round spherical shape particles with diameters going from about 0.1 μm and up to 1 or 2 μm. The mean diameter of silica fume is 100 times smaller than the mean diameter of cement (Aitcin, P.C., 2001).

Many researchers are using this silica fume in concrete as a partial replacement of cement not only for improving the quality of concrete but also for consuming this industrial waste material which is harmful to human health (ACI Committee 234). The use of less than 10% of silica fume in concrete has a fludifying effect on very low w/cm mixtures. The use of silica fume can sharply reduce viscosity given the morphology of silica fume particles (ball-bearing effect). Silica fume particles displace some of the water present among the flocculated cement grains, thus increasing the amount of water available to fluidify concrete (Aitcin, P.C., 2001).

It is used in concrete mainly for ferrosilicon replacement of cement improving the quality of concrete. The silica fume used in the experiment was a product of 'GRACE Construction 'under the trade name of 'Force 10,000D' densified microsilica.

The concentration of amorphous SiO_2 is very high in silica fume. Silica fume is characterized by its extremely fine spherical particles of about 0.1 micron. The higher the silicon dioxide content in silica fumes, the more reactive it will be in concrete. Since the color of silica fume is dark, concrete containing silica fume is grey dark in color compared to normal concrete. By increasing the amount of silica fume, water demand increases to a very large extent. The reason is that the small particles of

silica fume have large surface areas which absorb large amounts of water. Mixes containing above 10% silica fume (by mass) replacement of cement are sticky, cohesive and hard to handle. (Bayast et al., 1990; Huang, 1990; ACI Committee 234, Journal, 2000). It meets the requirements of ASTM C 1240 standards. The general physical and chemical properties of silica fume are given in Table 3.6.

Properties of Fresh Silica Fume Concrete: Because of its fineness, the silica fume particles can fill the voids between the larger cement particles resulting dense microstructures and good bond between the hydrated cement paste and aggregates. With this enhanced microstructure of the interstitial transition zone, silica fume increases the compressive strength of concrete, especially between 7 and 28 days. Moreover, as silica fume reduces the porosity of cement paste at its interface with aggregate, the concrete permeability is greatly reduced (Aitcin, P.C., 2001).

Silica fume damages the workability of fresh concrete. The reason is that the small particles of silica fume have large surface areas which absorb large amounts of water. This problem is solved by using water reducing agents or superplasticizers rather than using high water-cement ratio because the latter will have negative effects on concrete. By increasing the amount of silica fume, water demand increases to a very large extent. Mixes containing above 10% silica fume replacement of cement (on a mass basis) are sticky, cohesive and hard to handle (Bayast et al., 1990; Huang, 1990; ACI Committee 234 Journal, 2000).

Silica fume reduces concrete bleeding by its high affinity for water. As a result, plastic shrinkage cracks may occur when water evaporation rate from fresh concrete surface exceeds the rate at which water rises to the surface by capillary

pressure. Thus, curing becomes significantly important especially at early ages (Bayast et al., 1990; ACI Committee 234 Journal, 2000)

Table 3.6 Physical and Chemical Properties of Silica Fume (Huang, 1990)

[A]: Physical Properties:

Particle Size:	0.1 to 0.2 μm [4x 10 -5 to 8x 10-5 in.]
Bulk Density:	200 to 300 kg/m^3 [14 to 19 lb/ft^3]
Specific Gravity:	2.2 to 2.3
Color:	Light to dark gray

[B]: Chemical Properties:

Chemical Constituent	Percent of Total Weight
S_iO_2	90-98
Al_2O_3	0.5-3.0
Fe_2O_3	0.15-0.8
$M_g O$	0.2-1.5
$C_a O$	0.1-0.5
Na_2O	0.2-0.7
K_2O	0.4-1.0
C	0.5-1.4

3.6 Superplasticizer

Superplasticizing admixtures are often added to cement paste to gain greater fluidity at lower water-cement ratios. The most important property of superplasticizer is its ability to disperse cement particles. In addition to enhancing the flow properties of cement pastes, superplasticizers retard the hydration reaction (Mindess and Young, 1981).

SP is developed to enable the reliable production of SCC, primarily in pre-cast/prestress environments. It produces a concrete with excellent segregation resistance, filling ability and passing ability. It meets the requirements of ASTM C 494 Type F high range water reducing admixture. Additionally, SCC made with ADVA Cast 555 SP exhibits low-water sensitivity normally encountered in concrete production.

SP used in the experiment was Polycarboxylate based under the trade name of ADVA Cast 555. The most important admixtures are the superplasticizers (high range water reducers), used with water reduction greater than 20%. Other types may be incorporated as necessary, such as Viscosity Modifying Admixtures (VMA) gives more possibilities of controlling segregation providing very good homogeneity (typically 2-10 oz/cft); air entraining admixtures (AEA) to improve freeze-thaw resistance, retarders for control of setting, etc. (Beitzel; Zhu et al., 2000).

CHAPTER 4

EXPERIMENTAL PROGRAM

4.1 Introduction

Independent variables were chosen in such a way that the sum of binders i.e. Portland cement, fly ash and silica fume is 100 percent. The ratio of fine and coarse aggregates as well as the water binder ratio were established as same as that of precast SCC plant, Coreslab, Miami. Water binder ratio was chosen as 0.39 (lowest one). The amount of superplasticizer was selected as minimum as possible 14 oz/cft of concrete (1 kg/m^3) by doing several trials with different mixes to determine the flowability of SCC.

The experimental program was started first by performing spread test of the fresh concrete. The test included a base plate and slump cone (called spread test) that conforms to ASTM C-1611 standard test. The target slum flow was established between 24 in to 28 in (600 mm to 700 mm).

Figure 4.1 Concrete Mixer

4.2 Mix Design

SCC mixes must meet three key properties: (1) ability to flow into and completely fill intricate and complex forms under its own weights, (2) ability to pass through and bond to congested reinforcement under its own weight, and (3) high resistance to segregation.

At present time, there is no research approach available that can be used to design SCC with optimum pozzolanic materials. There are no specific mix designs that indicate the best performance in its mechanical properties. Without optimizing the new fillers (i.e. pozzolanic materials) with the locally available aggregates, most economical SCC can't be produced. Therefore, mix designs were developed using six different combinations of fly ash and silica fume to enhance the mechanical properties of concrete and to determine if they were indeed viable with the better strength and durability of concrete. For reference, mix design of SCC with cement, aggregate and water was taken from the Miami based SCC precast plant.

Table 4.1 Mix Design of SCC

Ingredient	Mix (lb/yd^3)	Mix (kg/m^3)
Cement	775	450
Rock	1358	806
Sand	1440	855
Water	307	182

Table 4.2 Trial Mix of Fly Ash, Silica Fume and Ordinary Portland cement

	SCC 1	SCC 2	SCC 3	SCC 4	SCC 5	SCC 6
OPC (%)	100	90	80	70	87	97
FA (%)	0	10	20	30	10	0
SF (%)	0	0	0	0	3	3
Total Filler (%)	100	100	100	100	100	100

4.3 Mixing Procedure

All the mixtures were prepared in a 3 cubic feet capacity mixer. During the mixing time, the mixer should be covered to avoid moisture loss from the fresh concrete. The prepared samples are also protected against wind and sun until brought to a room temperature.

4.3.1 Mixing (ASTM C-192)

The mixing method as per ASTM C-192 utilized was as follows:

- The concrete mixture was dampened lightly with water.
- The coarse aggregate and one-third of the water was introduced in the mixer and rotated for about half a minute.
- The sand was then added followed by cement and pozzolanic materials and the concrete mixer was rotated for about four minutes.
- The remaining water was then added gradually.

- The superplasticizer was then slowly introduced until a consistent mix could be observed.
- The mixing proceeded for about seven minutes from the introduction of coarse aggregate.
- The mixture was then stopped and allowed to keep in rest for about three minutes so as to allow a complete reaction of the mix with pozzolanic materials and superplasticizer.
- Total elapsed time for the mixing sequence was approximately ten minutes.

4.3.2 Spread Test (ASTM C-143)

The spread test consists of a base plate and slump cone that conforms to ASTM C-143 standard. Unlike the standard slump test, the fresh concrete is measured after the removal of the cone to characterize the flowability of the concrete. The diameter of the slump flow is the recorded average of orthogonal axis through the center of the slump flow. This measurement should be greater than 22 in. (560 mm) for the concrete to process good self-consolidation. The recommended slump flow of SCC ranges between 500 and 700 mm diameter i.e. 20 and 28 in. (Nagataki and Fujiwara, 1995). The target slump flow for the SCC was between 24 and 28 in. (600 and 700 mm).

Table 4.3 Results of the Slump Flow (Spread) Test

Mix Number	Slump in.(mm)	Slump Flow Av. Spread value, in.(mm)
SCC 1	-	25.5 (648)
SCC 2	-	27.0 (686)
SCC 3	-	26.0 (660)
SCC 4	-	26.5 (673)
SCC 5	-	25.0 (635)
SCC 6	-	25.5 (648)

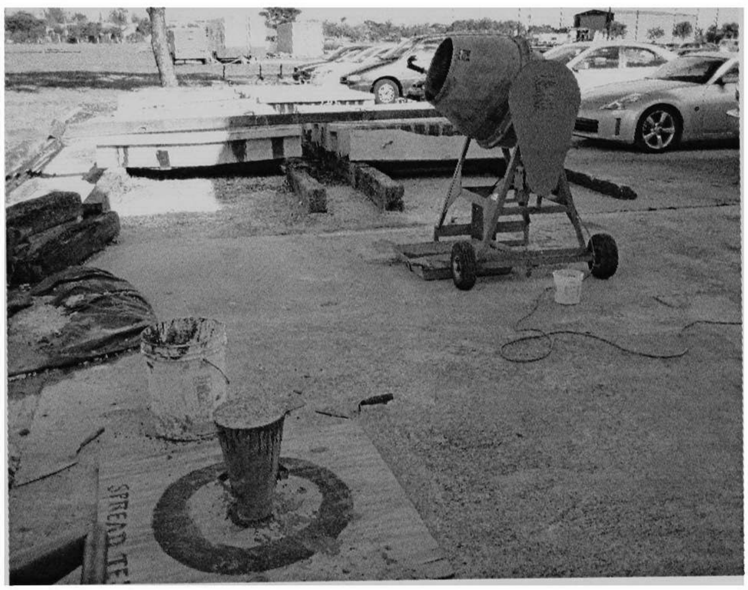


Figure 4.2 Typical Slump Flow for Spread Test

Figure 4.3 Spread Test According to ASTM C-1611

4.3.3 Curing Methods

After 18 to 24 hours of time, the freshly mixed and prepared concrete samples were de-molded and kept in a water tank of laboratory normal temperature as shown Figure 4.4. Two types of curing were performed. The cylindrical SCC samples 4 in×8 in (100 mm×200 mm) and 6 in×12 in (150 mm×300 mm) were kept in water for 7 days and 28 days to determine the compressive strength, splitting tensile strength and modulus of elasticity. The others were SCC prisms of size 4 in×4 in×11.2 in (100 mm×100 mm× 285 mm) cured under water for seven days and then left in air forever. These samples were prepared for the drying shrinkage test. To provide normal and uniform humidity and temperature, the samples were cured inside the laboratory.

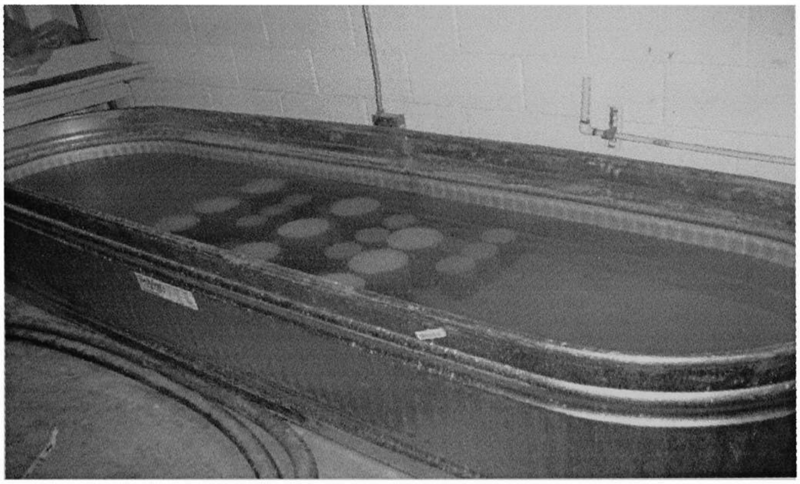


Figure 4.4 SCC Samples Curing in Water

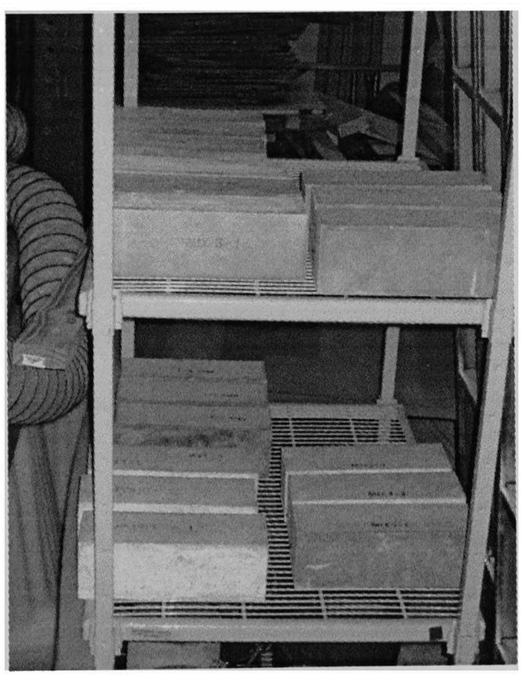


Figure 4.5 Samples for Drying Shrinkage Test

4.4 Compressive Strength Test

Hardened concrete was measured in terms of its performance by means of compressive strength at ages of 7 and 28 days. The 28 day design compressive strength was established as 8000 psi (55 MPa). The average compressive strengths were obtained from three 4 in × 8 in (100 mm×200 mm) cylinders for each batch at each age. The tests were performed in accordance with the ASTM C39 standards.

Self-compacting concrete with a similar water cement or cement binder ratio will usually have a slightly higher strength compared with traditional vibrated concrete, due to the lack of vibration giving an improved interface between the aggregate and hardened paste. The strength development will be similar so maturity testing will be an effective way to control the strength development whether accelerated heating is used or not (European Guidelines for SCC, 2005).

After 28 days compressive strength of SCC and normal vibrated concrete of similar composition does not differ significantly in the majority of the published test results. Some of the published test results show that an increase of the cement content and a reduction of filler content at the same time increase the initial concrete strength and the ultimate concrete strength. Especially if limestone powder is used higher compressive strength are noticeable at the beginning of the hardening process (Holschemacher and Klug, 2002).

4.5 Splitting Tensile Test

The tests were performed by loading the standard 6 in × 12 in (150 mm×300 mm) cylinder by a line load perpendicular to its longitudinal axis with the cylinder placed horizontally on the testing machine platen in accordance with ASTM C 496 standards for all mixes. The tensile splitting strength can be defined as:

$f'_t = 2P/\pi DL$

Where, P= total value of the line load registered by the testing machine

D= diameter of the concrete cylinder

L= cylinder height

The results of all these tests give the designer a measure of the expected strength of the designed concrete in the built structure.

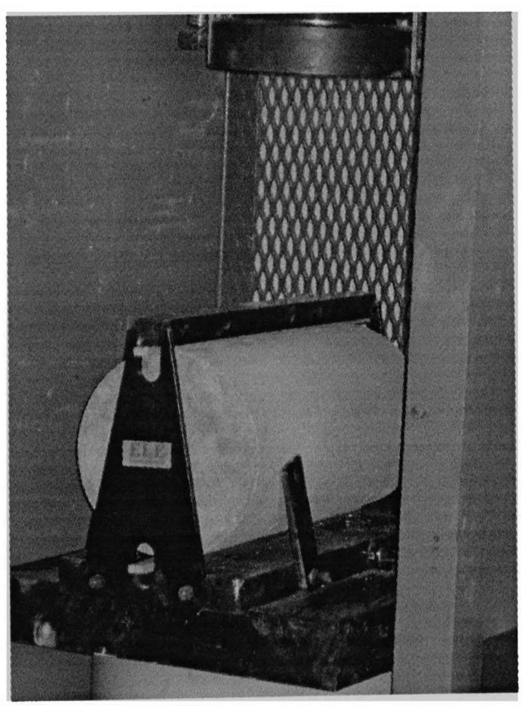


Figure 4.6 Splitting Tensile Test Set Up

4.6 Modulus of Elasticity Test

The elastic modulus tests were evaluated in accordance with the ASTM C469 standard. The modulus of elasticity is used in the elastic calculation of deflection, often the controlling parameter in slab design, and of pre or post tensioned elements. However, increasing the paste volume could decrease the modulus of elasticity. Because SCC often has higher paste content than traditional vibrated concrete, some differences can be expected and the modulus of elasticity may be somewhat lower but this should be adequately covered by the safe assumptions on which the formulae provided in standard code are based.

If SCC does have a slightly lower elastic modulus than traditional vibrated concrete, this will affect the relationship between the compressive strength and the camber due to prestressing or post-tensioning. For this reason, careful control should be exercised over the strength at the time when the prestressing and post-tensioning strands or wires are released (The European Guidelines for SCC, 2005).

Since the stress- strain curve is curvilinear at a very early stage of its loading history. Young's modulus of elasticity can be applied only to the tangent of the curve at the origin. The slope of the straight line that connects the origin to a given stress (about $0.4f'_c$) determines the secant modulus of elasticity of concrete. This value, termed in design calculation the modulus of elasticity, satisfies the practical assumption that strains occurring during loading can be considered basically elastic (recoverable on unloading) and that any subsequent strain due to the load is regarded as creep.

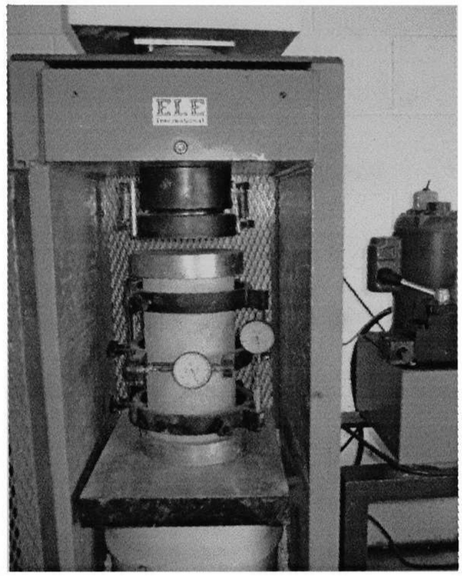


Figure 4.7 Strain Gauge for Modulus of Elasticity Test Set Up

The ACI code gives the following expressions for calculating the secant modulus of elasticity of concrete (E_c) for f'_c upto 6000 psi (40 MPa)

E_c (psi) $= 33w_c^{1.5}\sqrt{f'_c}$ for 90 lb/ft^3(1440 kg/m^3)<w_c<155 lb/ft^3(2480 kg/m^3)

E_c (MPa) $= 0.0143w_c1.5\sqrt{f'_c}$

Where, w_c is the density of concrete in pounds per cubic foot (1 lb/ft^3= 16.02 kg/m^3) and f_c is the compressive cylinder strength in psi. For normal weight concrete,

$E_c= 57000\sqrt{f_c}$ psi or $E_c= 4730\sqrt{f_c}$ N/mm^2

For concrete compressive strength f'_c= 6000 to 12000 psi (40 to 80 MPa)

E_c (psi) $= (40{,}000\sqrt{f'_c} + 1.0x10^6)\ (w_c/145)^{1.5}$

E_c (MPa) $= (3.32\sqrt{f'_c} + 6895)\ (w_c/2320)^{1.5}$ (Nawy, 2005)

An attempt has been made to find a finer distinction between the compressive strength and modulus of elasticity in SCC. Several of the test results of Suksawang et.al, 2005 are graphically represented. In Figure 4.8, 4.10 and 4.12 compressive strength of

SCC is uniformly increasing, whereas modulus of elasticity is dropped suddenly near the seventh day test. Although Figure 4.8 shows similar nature of compressive strength and modulus elasticity in SCC, Figure 4.9, 4.11, 4.12 and 4.13 state that after about two months of maturity in concrete, the uniform nature of compressive strength and modulus of elasticity is suddenly changed. From this phenomenon, we can clearly say that the increase in compressive strength in concrete not necessarily means the increase in modulus of elasticity.

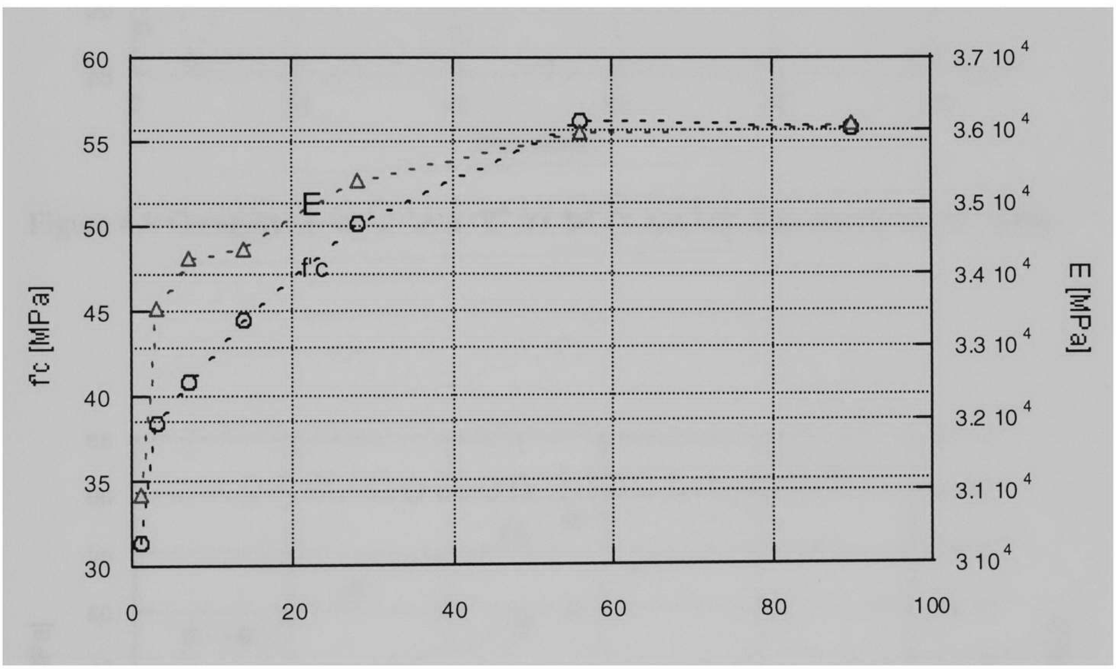


Figure 4.8 Comparison of f'_c and E for NC mix (N. Suksawang et. al., 2006)

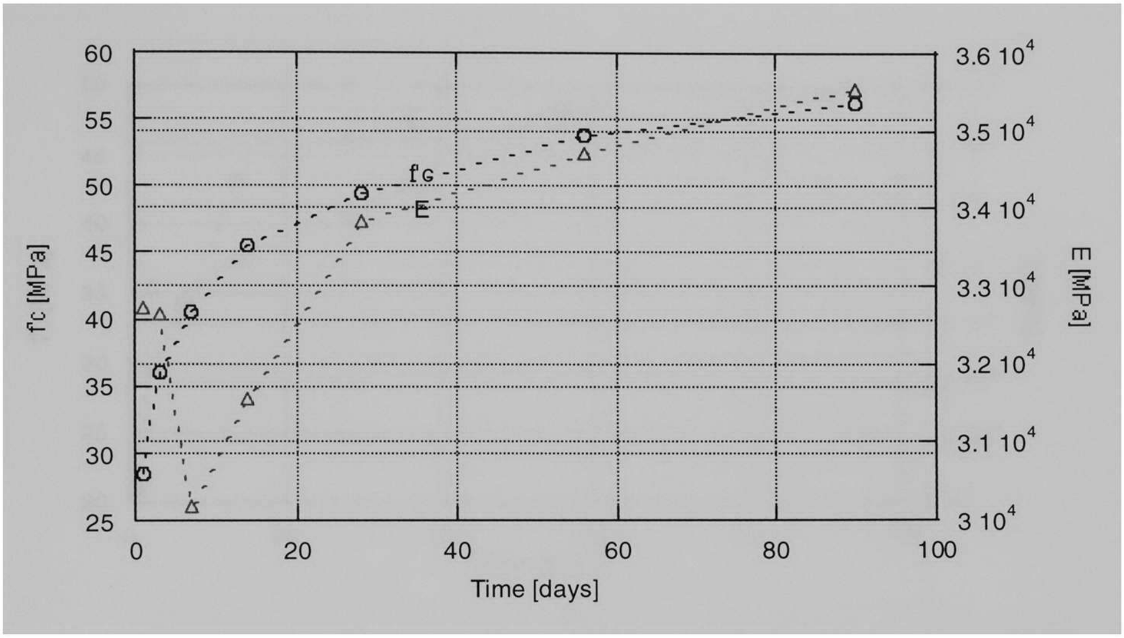


Figure 4.9 Comparison of 'f_c' and 'E' for SCC1 mix (N. Suksawang et. al., 2006)

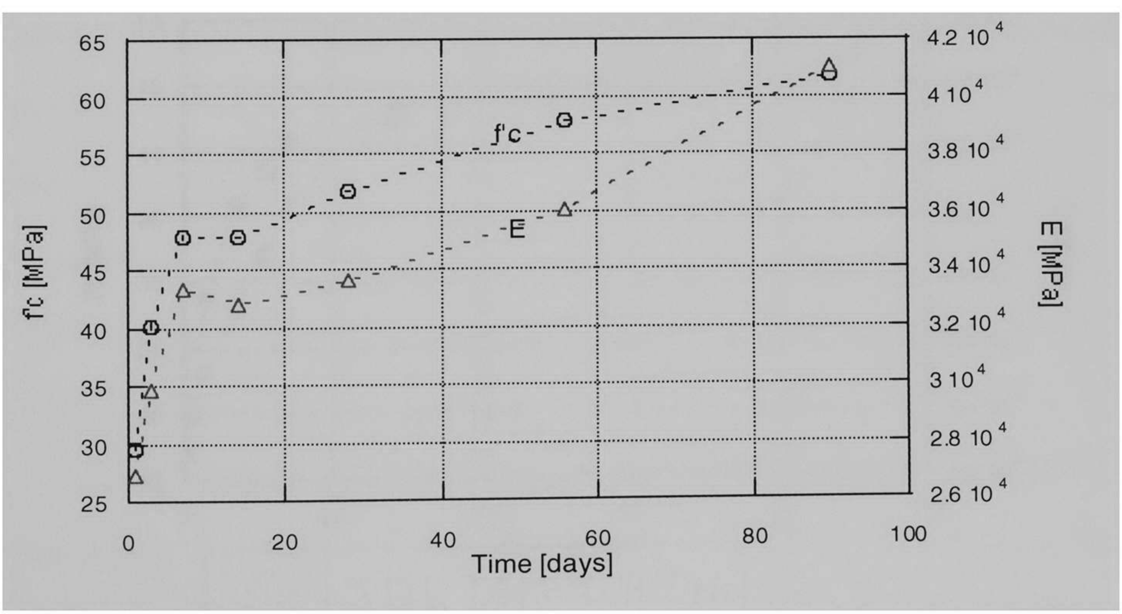


Figure 4.10 Graph for SCC 2 mix (N. Suksawang et. al., 2006)

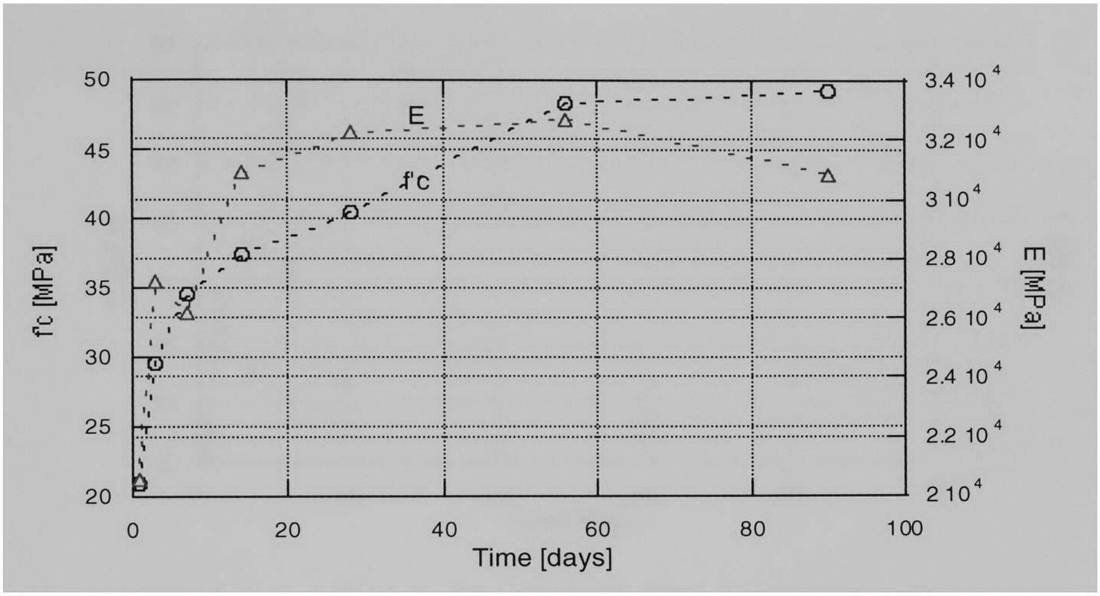


Figure 4.11 Comparison of 'f_c' and 'E' for SCC 3 mix (N. Suksawang et. al., 2006)

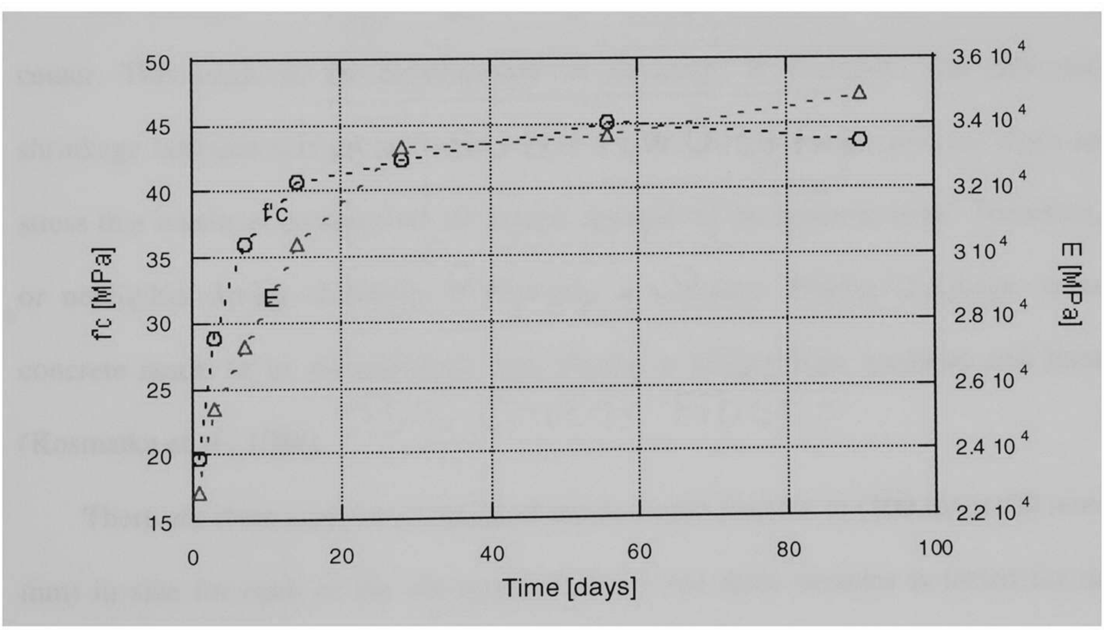


Figure 4.12 Comparison of 'f_c' and 'E' for SCC4 mix (N. Suksawang et. al., 2006)

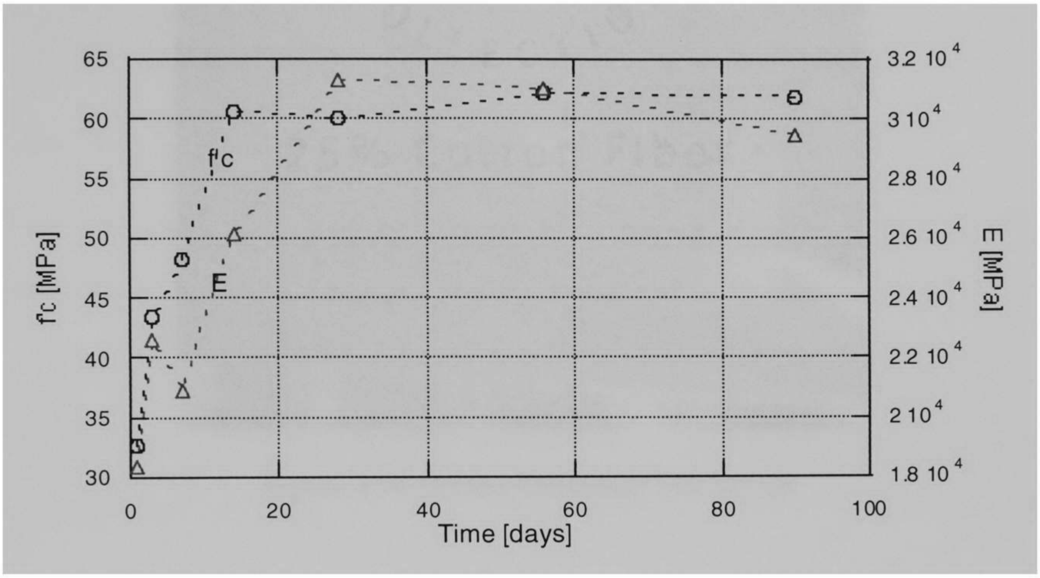


Figure 4.13 Graph for SCC 5 mix (N. Suksawang et. al., 2006

4.7 Drying Shrinkage Test

The surface of concrete loses moisture faster than that of the concrete near the center. This leads to the development of shrinkage in concrete. The difference of shrinkage between surface and near center in concrete can cause cracking when tensile stress that results is greater than the tensile strength of the concrete itself. Therefore, less or negligible drying shrinkage is expected in concrete. Drying shrinkage occurs as concrete reacts to its surroundings, specifically to temperature, moisture and humidity (Kosmatka et al., 1988).

There are three samples of standard prism 4 in×4 in×11.2 in (100 mm×100 mm×285 mm) in size for each of the six mixes. Each of the three samples is tested for drying shrinkage for 7, 10, 14, 21 and 28 days and an average value is taken for each batch.

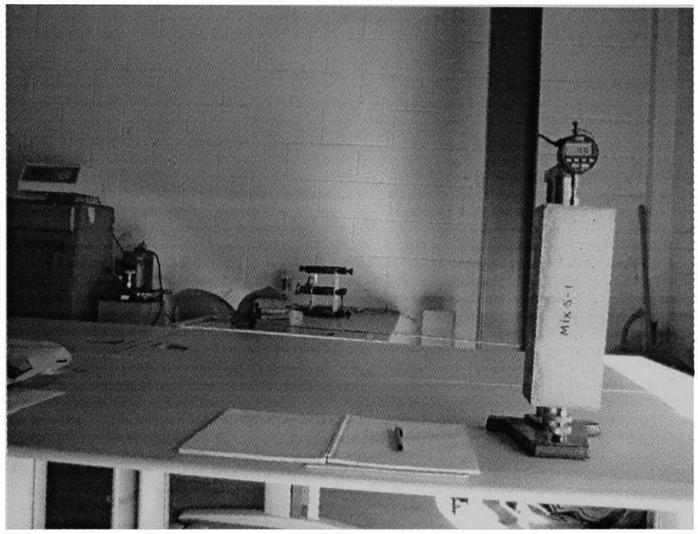


Figure 4.14 Drying Shrinkage Test Set up

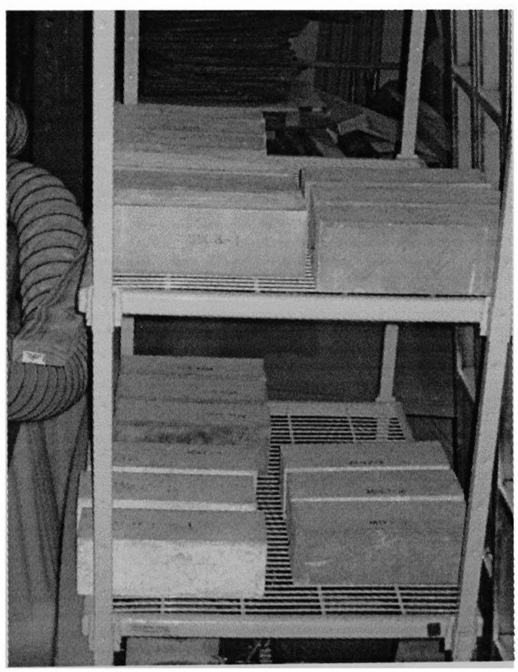


Figure 4.15 Samples for Drying Shrinkage Test

The samples were allowed to dry in a normal laboratory temperature and humidity. For uniform drying purpose, a special open air type of shelve was used as shown in Figure 4.15.

CHAPTER 5

TEST RESULTS

5.1 Compressive Strength

The compressive strength of hardened concrete was obtained in accordance with the ASTM C39 standards. The tests were performed at 7 and 28 days. The results are summarized in Table 5.1 (APPENDICES).

The test results show that the mix SCC 1 produced the highest 28 days compressive strength 8,547 psi (59 MPa) among the selected six mix models. However, mix SCC 6 has highest 7 days compressive strength 7,395 psi (51 MPa). It indicates that the use of pozzolanic materials in SCC not necessarily increase the compressive strength in concrete; but a small amount (3 percent) of silica fume in ordinary cement has a best performance in attaining initial strength. For reference, the combination of pozzolanic materials i.e. new fillers has been provided in Table 4.2, page 29.

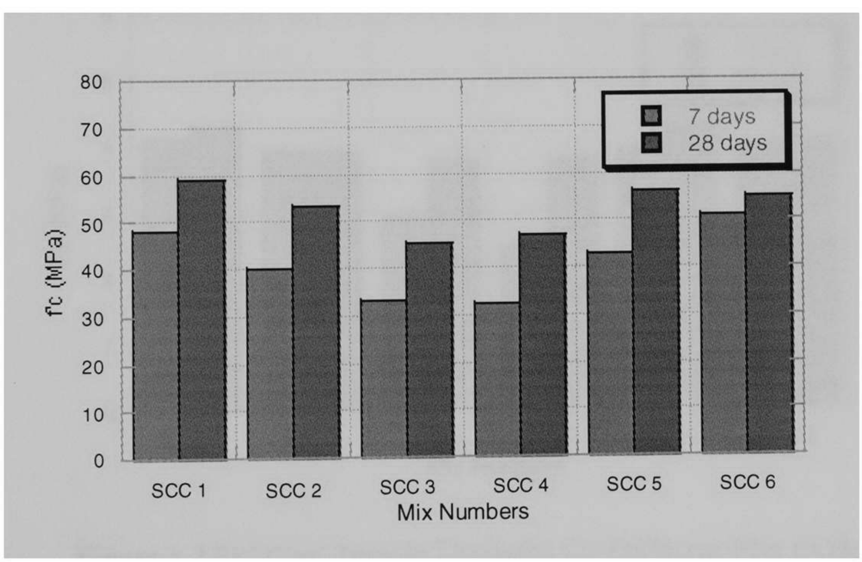


Figure 5.1 Compressive Strengths for Different Mix Models

5.2 Splitting Tensile Strength

It was performed in accordance with ASTM C 496 standards for all mixes. The cylinders for experimentation were 6 in×8 in (150 mm× 300 mm).Tests were conducted at 7 and 28 days with two cylinders for each test. The results are included in Table 5.2 (APPENDICES).

The best 28 day splitting tensile strength was obtained with the SCC 1 and SCC 5 mix producing same values as 620 to 630 psi (4.3 MPa). It shows that only 100% OPC or 97% OPC with 3% SF are the best combinations of the mix. Also, these two mixes have almost the same splitting tensile strength with the 7 days and 28 days test results (with only about 5% difference). However, all the 28 days test results are slightly lower or higher than 4 MPa.

Diagram 5.3 and 5.4 shows the variation of strengths with the two testing sample. The variation has been shown in both strength and percentage difference of the strengths.

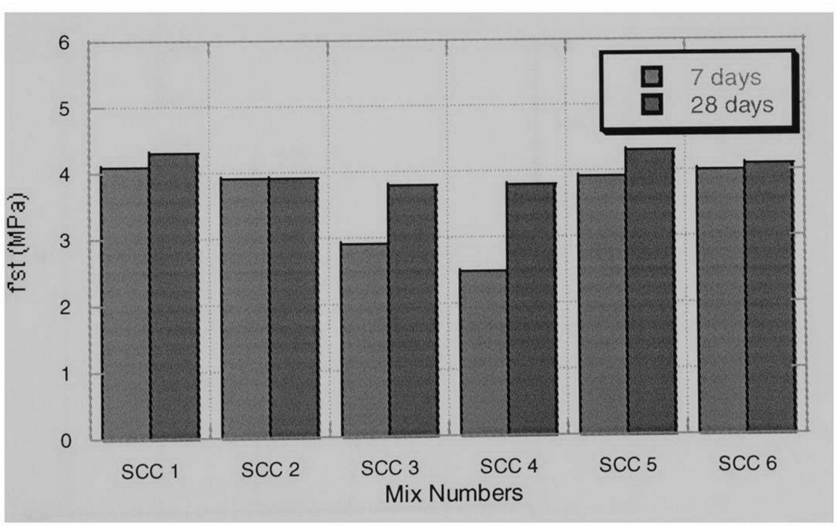


Figure 5.2 Splitting Tensile Strengths for Different Mix models

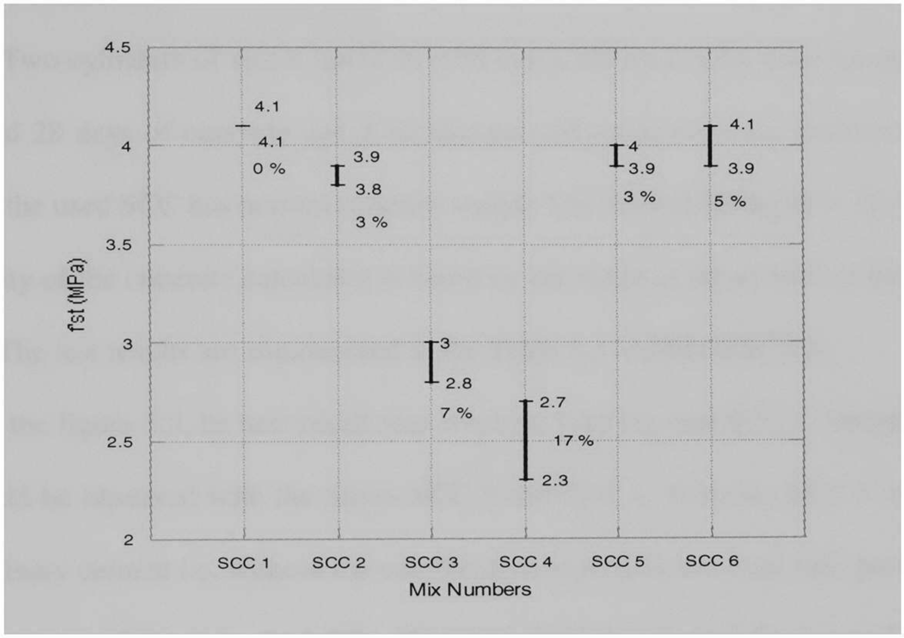


Figure 5.3 Seven day Tensile Test Results with Two Samples

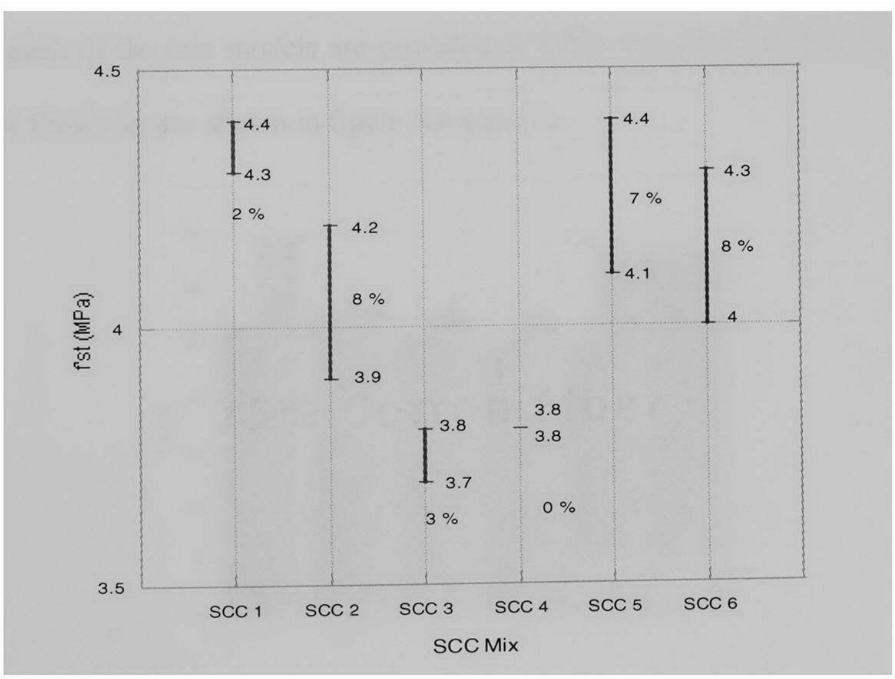


Figure 5.4 Twenty Eight day Tensile Test Results with Two Samples

5.3 Modulus of Elasticity

The elastic modulus tests were conducted in accordance with the ASTM C 469 standard. Two cylinders of size 6 in×12 in (150 mm ×300 mm) were used for each test at 7 days and 28 days of concrete age. Calculations and predictions are performed on the basis that the used SCC has normal concrete weight 150 lb/cft(2400 kg/m^3). The modulus of Elasticity of the concrete calculated is based on the strain at about 40% of the ultimate strength. The test results are summarized in the Table 5.3 (APPENDICES).

In the figure 5.5, he best result was obtained with the mix SCC 1. Second highest result could be observed with the mixes SCC 5 and SCC 6. It means SCC 1 which was 100% ordinary cement i.e. without the combination of pozzolanic materials, produced the highest modulus of elasticity 34.2 GPa. However, SCC 5 with 10% fly ash and 3% silica fume could also give higher values as 32.7 and 32.9 MPa. Besides, SCC 6 with 3% silica fume alone had highest 7 days modulus of elasticity. For reference, the compositions of fillers for each of the mix models are provided in Table 4.2, page 29. The variations of modulus of Elasticity are shown in figure 5.6 and 5.7.

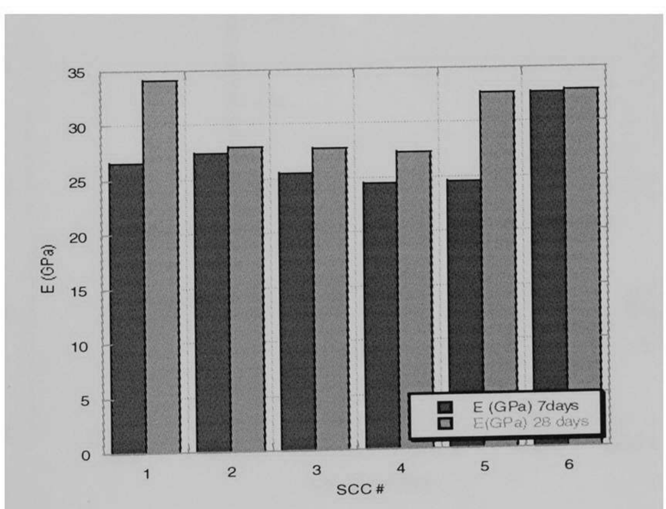


Figure 5.5 Modulus of Elasticity for Different Mix Models

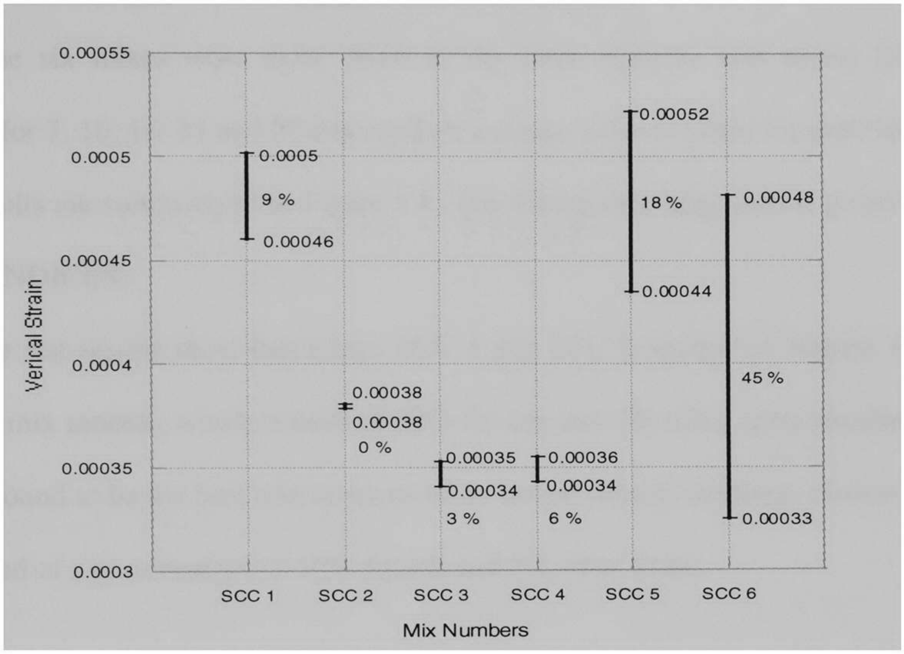


Figure 5.6 Seven days Test Results of Linear Strain for Modulus of Elasticity

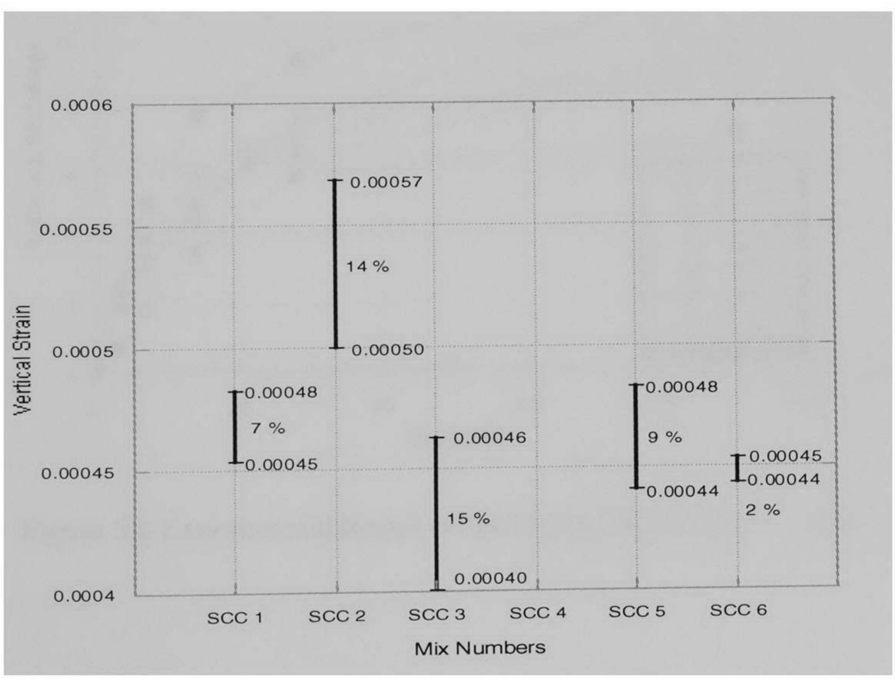


Figure 5.4 28 days Test Results of Linear Strain for Modulus of Elasticity

5.4 Drying Shrinkage

Three samples of standard size 4 in×4 in×11.2 in (100 mm×100 mm×285 mm) for each of the six mixes were used. Each of the three samples was tested for drying shrinkage for 7, 10, 14, 21 and 28 days and an average value is taken for each batch. The testing results are summarized in Figure 5.4. The drying shrinkage data is given in Table 5.4 (APPENDICES).

The test results show that mixes SCC 4 and SCC 6 attains the highest shrinkage than other mix models, which consist of 30% fly ash and 3% silica fume simultaneously. SCC 5 is found to be the best mix in terms of its lowest drying shrinkage character which is composed of a combination of 10% fly ash and 3% silica fume.

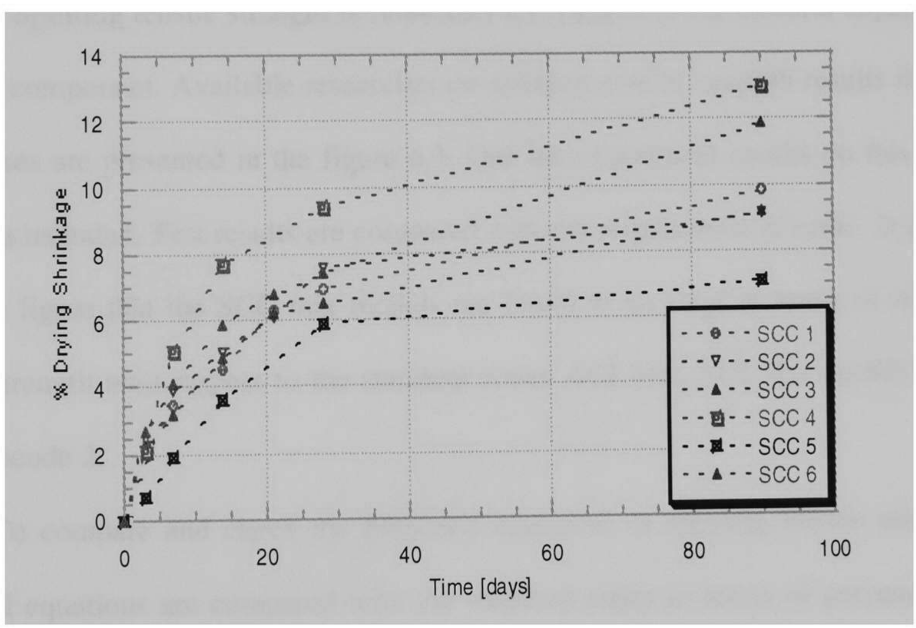


Figure 5.8 Experimental Result of the Drying Shrinkage vs. Time

CHAPTER 6

MODEL COMPARISONS

A comprehensive study of ultimate loads from various mix designs was done for self-consolidating concrete. The summary of the experimental results are compared with the available research to investigate the suitability of materials, established statistical models and its mechanical properties.

6.1 Splitting Tensile Strength

Highest compressive strength not necessarily means the highest splitting tensile strength. Splitting tensile strength is important as it indicates the flexural capacity of the concrete component. Available researches on splitting tensile strength results for various SCC mixes are presented in the figure 6.1. Our lab experiment results on this test have also been included. Test results are compared with the requirement of code. It is obvious from the figure that the SCC mix models are found to be ideal in terms of its splitting tensile strength with respect to the standard codes ACI 318, ACI 363 AASHTO/LRFD and Eurocode 2.

To compare and check the proposed equations of splitting tensile strength, the proposed equations are compared with the standard codes in terms of percentage error. Percentage error is obtained by dividing the standard deviation (SD) by the mean value of the corresponding code. Where SD is mathematically expressed as:

$$SD = \sqrt{\frac{(fst - fst_{code})^2}{n-1}}$$

Percentage error with respect to the given equation or code= (SD/mean) ×100

Where n= degree of freedom

The increased number of data corresponds to higher degree of freedom, which tends to increase the accuracy of the result. We have a total of 102 data for splitting tensile strength. The aim of our study here is to propose a best equation in terms of least percentage error with respect to the given code or equation. Three codes as explained earlier and two linear best fit equations, regular and forced through were chosen for determining the best equation for the splitting tensile strength of SCC. Regular linear curve is based on slope and intercept of the equation, whereas the forced through zero curves passes through the origin without intercept value.

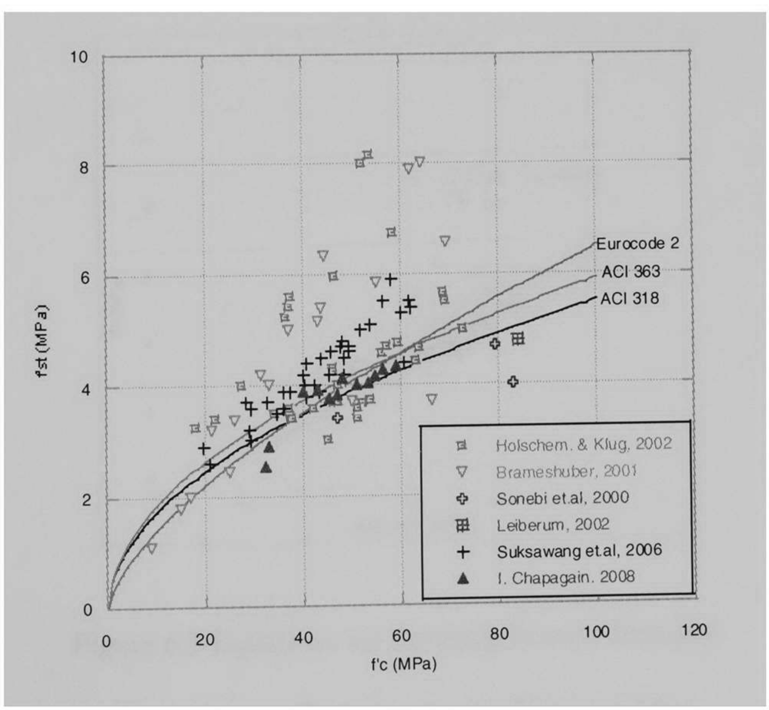


Figure 6.1 Comparison of Splitting Test Results with the Available Research and Codes

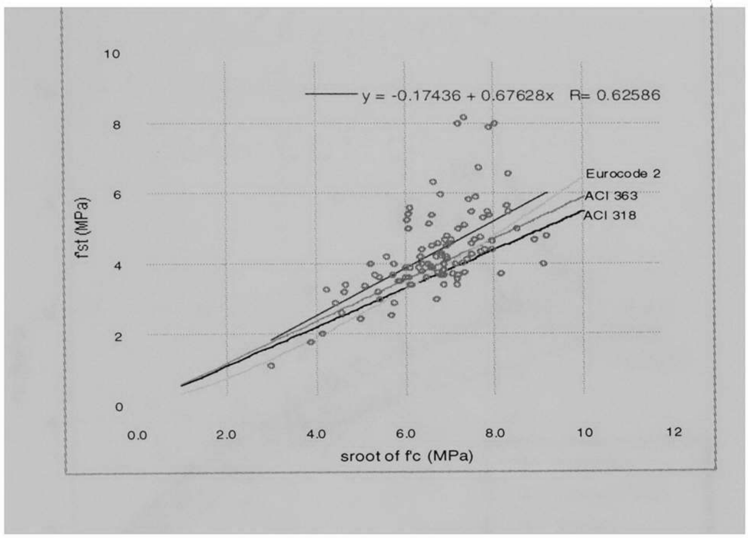


Figure 6.2 Equations for Splitting Tensile Strength
(Using Linear Best Fit: Regular)

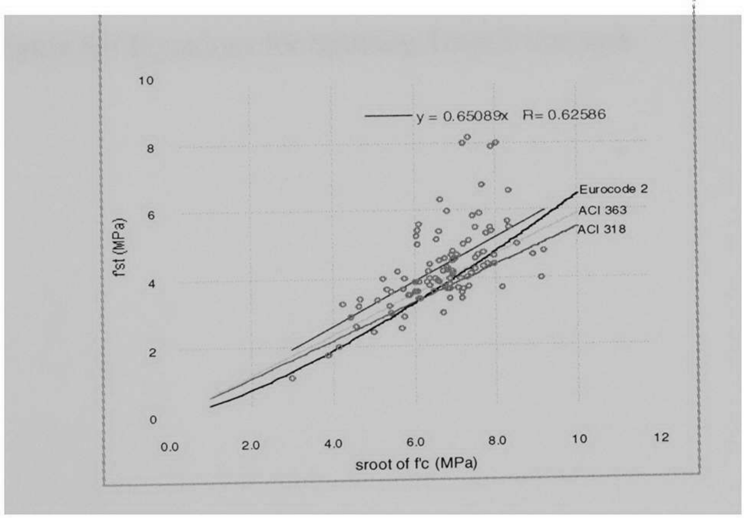


Figure 6.3 Equations for Splitting Tensile Strength

(Using Linear Best Fit: Forced Through Zero)

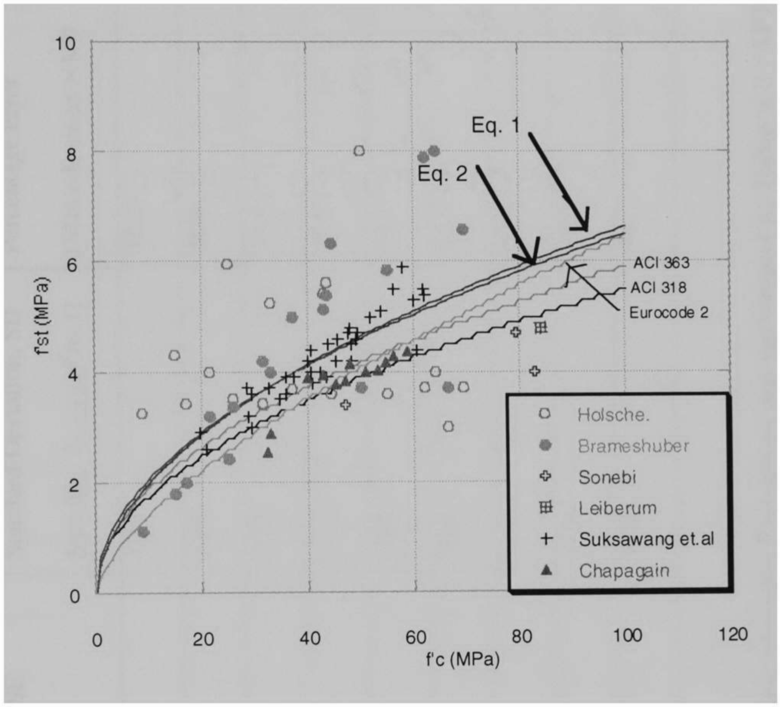


Figure 6.4 Equations for Splitting Tensile Strength

Table 6.1 Selection of Best Equation for Splitting Tensile Strength

S/N	Comparison	f_{st} Mean (code)	Sum of Squared Error, SSE $(f_{st} - f_{st\ ACI\ 318})^2$	Standard Deviation, SD Sqrt $[(f_{st} - f_{st\ ACI\ 318})^2/n-1]$	Percentage Error (SD/code mean)×100	Remarks
1	f_{st} wrt ACI 318 code	3.67	141.16	1.18	32.2	
2	f_{st} wrt ACI 363 code	3.94	110.9	1.05	26.6	
3	f_{st} wrt Eurocode 2	3.79	125.64	1.12	29.4	
4	Eq. 1 wrt ACI 318 code	3.67	51.87	0.72	19.5	
5	Eq. 2 wrt ACI 318 code	3.67	46.75	0.68	18.5	
6	Eq. 1 wrt ACI 363 code	3.94	19.99	0.44	11.3	
7	Eq. 2 wrt ACI 363 code	3.94	16.83	0.41	10.4	Best Equation
8	Eq. 1 wrt Eurocode 2	3.79	34.17	0.58	15.3	
9	Eq. 2 wrt Eurocode 2	3.79	31.30	0.56	14.7	

Note: Calculations of Percentage Error for the Splitting Tensile Strength Equations are performed in Table 6.2 (APPENDICES)

E= Modulus of Elasticity

wrt = with respect to

6.2 Modulus of Elasticity

Lesser the creep in concrete, the higher is the modulus of elasticity. Creep is undesirable as it tends to promote deflection in structural component. The research and data are limited and there is no specific mix proposed for the highest modulus of elasticity. Although the majority of the researchers suggest that modulus of elasticity is considerably increased with the addition of coarse aggregate in the mix, the fundamental concept of SCC is to limit coarse aggregate to get better consistency and flowability. Therefore, alternate mixes should be investigated independently to draw more conclusive statistical value of modulus of elasticity in SCC.

We have 129 data record for modulus of elasticity. The aim of the research is not only to compare the data and codes, but also to find the best curve for modulus of elasticity of SCC. To determine the best proposed equation for modulus of elasticity (E), the selected codes and the linear equations are compared with the available data in terms of its percentage error. Percentage error is obtained by dividing the standard deviation (SD) by the mean value of the equation of code. Where SD is mathematically expressed as:

$$SD = \sqrt{\frac{(E - E_{code})^2}{n-1}}$$

Percentage error with respect to the given equation= (SD/mean) $\times 100$

Where n= degree of freedom

The higher number of data corresponds to higher degree of freedom, which tends to increase the accuracy of the result.

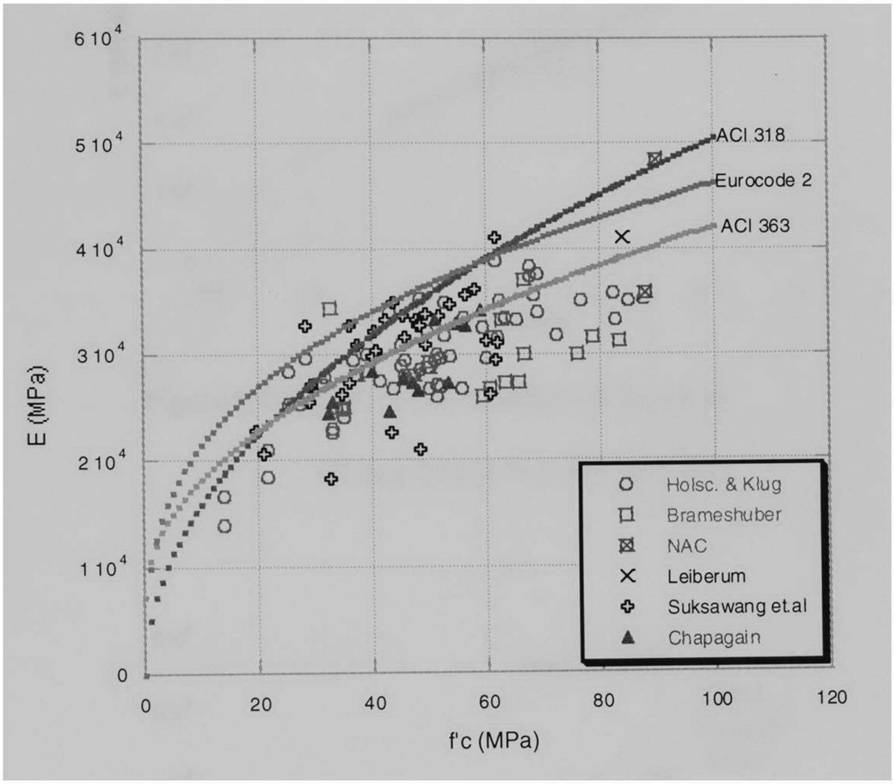


Figure 6.5 Comparison of Modulus of Elasticity Test Results with the Codes

Where, Holsc. & Klug = K. Holschemacher & Y. Klug, 1990

Brameshuber = Brameshuber, 2001

NAC = North American Conference on SCC, Nov 2002

Lieberum = Lieberum, 2002

Suksawang et.al. = N. Suksawang et.al., 2006

Chapagan= Indra P. Chapagain, 2008

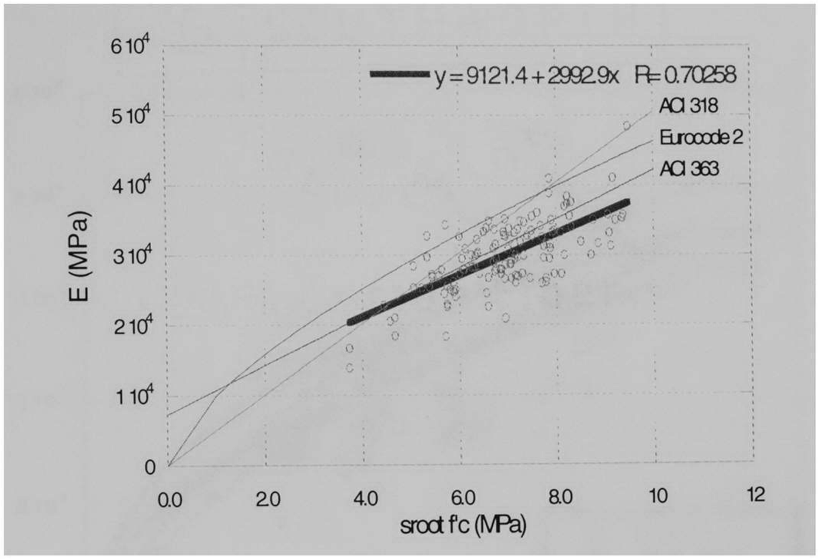


Figure 6.6 Equations for Modulus of Elasticity

(Using Linear Best Fit: Regular)

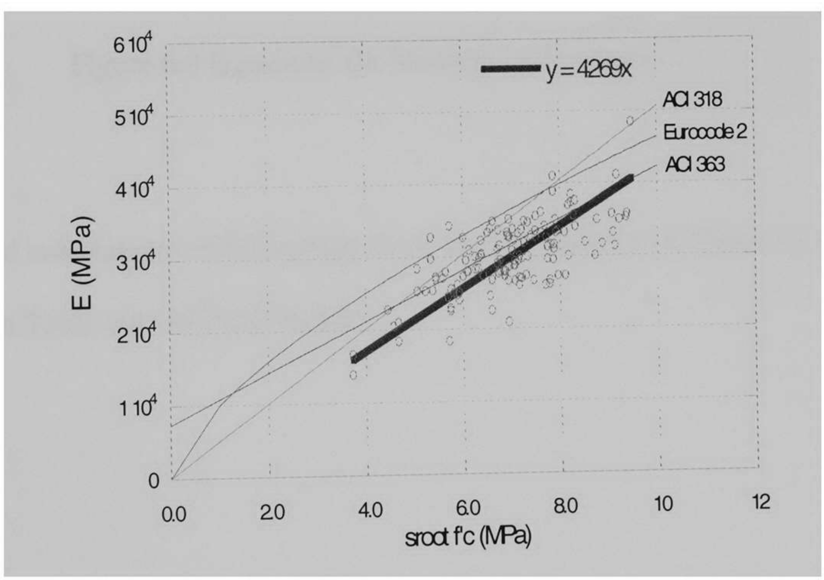


Figure 6.7 Equations for Modulus of Elasticity

(Using Linear Best Fit: Forced Through Zero)

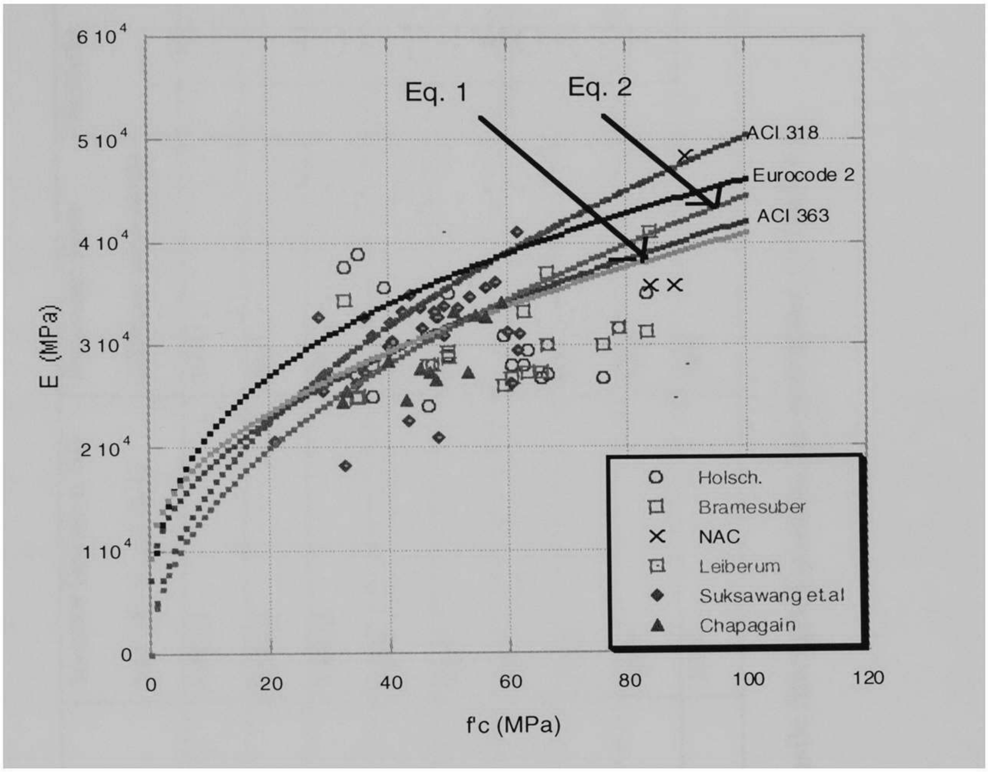


Figure 6.8 Equations for Modulus of Elasticity

Note: Partial calculations of Percentage Error for the Modulus of Elasticity are performed in Table 6.4 (APPENDICES)

Table 6.3 Selection of Best Equation for Modulus of Elasticity

S/N	Comparison	E Mean (code)	Sum of Squared Error, SSE $(E - E_{code})^2$	Standard Deviation, SD Sqrt $[(E - E_{code})^2/n-1]$	Percentage Error (SD/code mean)×100	Remarks
1	E wrt ACI 318 code	35137	6288543947	6982.0	19.9	
2	E wrt ACI 363 code	31538	3538031142	5237.0	16.6	
3	E wrt Eurocode 2	36224	6763816164	7241.0	20	
4	Eq. 1 wrt ACI 318 code	35137	2435956809	4345	12.4	
5	Eq. 2 wrt ACI 318 code	35137	2214842802	4143	8.5	
6	Eq. 1 wrt ACI 363 code	31538	22340541	416	1.3	Best Equation
7	Eq. 2 wrt ACI 363 code	31538	199285113	1243	3.9	
8	Eq. 1 wrt Eurocode 2	36224	3021625862	4840	13.4	
9	Eq. 2 wrt Eurocode 2	36224	3612285578	5292	14.6	

Note: Partial calculations of Percentage Error for the Splitting Tensile Strength Equations are performed in Table 6.4 (APPENDICES)

E = Modulus of Elasticity

wrt = with respect to

CHAPTER 7

CONCLUSIONS

The goals of the research were to access the material from a mechanical and durability (shrinkage) standpoint with the optimized mix design models and access the performance through a series of laboratory tests. The plastic and hardened concrete properties were thoroughly examined through spread test that conforms to ASTM C-1611 standard and material testing of concrete samples. Three SCC mix designs were strategically selected to bound the different proportioning methods: (1) a design based on controlled coarse to fine aggregate ratios, (2) a design based on the use of chemical admixtures and (3) a design based on the use of pozzolanic materials. A baseline comparison is made with the existing research of SCC.

The mix was prepared with the locally available aggregates and the cement was replaced by pozzolanic materials in different proportions. An experimental study was carried out to investigate the nature of compressive strength, tensile splitting strength, modulus of elasticity and drying shrinkage in concrete. The results demonstrate a better performance of concrete in its mechanical properties while proving to be economical as well. The obtained results were compared with the results of the existing research and ACI 318, ACI 363 and Eurocode 2.

After carefully performing the research and experimentation, the following conclusions were drawn:

(1) The local aggregates (ASTM# 57 FDOT and commercial sand) that were used in the tests were excellent to provide better compressive strength and modulus of elasticity with the SCC (Figure 6.4).

(2) Type of aggregate do not significantly affect on modulus of elasticity of self-consolidating concrete. For example, in the research of Suksawang et.al the granites were used as aggregates, but in this study soft limestone (ASTM#57 FDOT) were used and the difference of highest modulus of elasticity was only 3%.

(3) An optimum amount of superplasticizer 14 oz/cft (14 kg/m^3) was investigated with several trials for all the strategically selected mixes with a target slump flow of 22 to 28 in (560 mm to 700 mm) according to ASTM C-143.

(4) A dosage of 14 oz/cft (14 kg/m^3) of superplasticizer, 0.39 w/b ratio and 19 mm maximum size of aggregate produced satisfactory SCC with a good fluidity satisfying the requirement of targeted slump flow for all the selected mix models.

(5) The lowest and highest compressive strength results of the established mixes were 6,564 and 8,547 psi (45 MPa to 59 MPa) in comparison to the design strength of 8000 psi (55 MPa). The results of the compressive and splitting tensile strengths of the SCC mix models were compared with the requirement of codes ACI 318, ACI 363 and Eurocode 2 (Figure 5.1).

(6) To reduce the drying shrinkage in concrete, a small percent (3%) of silica fume with fly ash could be added (Figure 5.4).

(7) The addition of silica fume in SCC leads to the rapid initial strength gain in concrete (Figure 5.1).

(8) There is a decrease of modulus of elasticity with the increase of fly ash up to 20%, but 3% silica fume with fly ash considerably increased it. No significant difference was observed between SCC with different fly ash percentages above 20% (Figure 5.3).

(9) The test result of modulus of elasticity of SCC was found to be satisfactory in comparison to the available research and corresponds to the codes ACI 318, ACI 363 and Eurocode 2 (Figure 6.4).

(10) The best proposed equation for splitting tensile strength of SCC was determined as the equation produced by the linear curve passing through the zero (Figure 6.2 and 6.30 . Similarly, for the modulus of elasticity, the best equation was obtained with the regular linier curve (Figure 6.6 and 6.7).

An attempt was made to develop some trial mixes that could be used as economical tools for the optimum design of pozzolanic materials based SCC mixtures. Concrete with the cohesion, stability and flowability alone with great filling capacity opens up many possibilities for many different applications. It is important to note that the proposed research was conducted on a particular mix design models. The conclusions drawn in the research are based on the mix studied.

Future research should include an investigation of the optimized mixture designs incorporating the pozzolanic materials. The optimized mixture design should enhance both durability and mechanical properties of SCC. It should specifically continue to focus on the comparison of the use of fly ash, silica fume and blast furnace slag. Water and chloride permeability test along with shrinkage test should also be included to cover up

the durability test. The selected mixes should be tested in a laboratory setting to determine if they are indeed viable.

LIST OF REFERENCES

ACI Committee 234 (1995), Guide for the Use of Silica Fume in Concrete, *ACI Materials Journal*, Vol. 7, pp.437-440.

Aitcin, P.C. (2001), "High Performance Concrete," (in French), 1st Ed., Paris, France, Eyrolles; pp.683.

Asaga. K. and Roy (1980), D.M., Rheological Properties of Cement Mixes: IV. 'Effect of Superplasticizers on Viscocity and Yield Stress'. *Cement and Concrete Research.* pp. 287-295.

ASTM C 39 (1997), "Standard test method for compressive strength measurement in concrete", Annual Book of ASTM Standards, vol. 04.05, American Society for Testing and Materials, Philadelphia.

ASTM C 426 (1993). "Standard Test Method for Drying Shrinkage of Concrete Block", Annual Book of ASTM Standards, vol. 4.01, American Society for Testing and Materials, Philadelphia.

ASTM C 469 (2002b). "Standard Test Method for Static Modulus of Elasticity and Poisson's ratio of Concrete in Compression." , ASTM, Philadelphia.

ASTM C 496 (1992). "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", vol. 04.02. American Society for Testing and Materials, Philadelphia.

Bayasi, Z., and Soroushian, P. (January, 1988), 'High Fly Ash Concrete,' Fly Ash Applications to Concrete, Symposium, Michigan State University, pp. 1.7-15.7.

Bayasi, Z., and Soroushian, P. (1989), "Optimum Use of Pozzolanic Materials in steel Fiber Reinforced Concrete," Transportation Research Record 1226: International Symposium on Recent Developments in Concrete Fiber Composites, Washington D.C., pp.25-30.

Bayast, Z., Fuessle, R., Taylor, M., and Helenek, H. (Feb, 1990), "Silica Fume Effects on the Permeability and Microstructure of Concrete," Bradley University, pp. 54.

Beitzel Herald (2001), 'Influence of mixing procedure of the production of SCC', v.67 No.1, pp12-13.

Bouzoubaa, N., Lachemi M. (2001), Self-Compacting Concrete Incorporating High Volumes of Class F Fly Ash: Preliminary Results, Cement and Concrete Research, Vol. 31, No. 3, pp. 413-420.

CARBO C., L.FERNANDEZ LUCO, S. MORENO, AND R. TORRENT (2003), 'Self-Consolidating Concrete: Design and Performance. *North American Conference on the design and use of self-consolidating concrete.*

Ozyildirim C. (2003), 'Evaluation of Self-Consolidating Concrete' pp. 15.

Daimon, M. and Roy D.M. (1978), Rheological Properties of Cement Mixes: I. Method, Preliminary Experiments, and Absorption Studies. *Cement and Concrete Research*, pp.753-764.

Daimon, M. and Roy, D. M. (1979). Rheological Properties of Cement Mixes: II. Zeta Potential and Preliminary Viscocity Studies. *Cement and Concrete Research*, pp.103-110.

Dehn[1] Frank, Klaus Holschemacher[2], Dirk weiBe[3] (2000), 'Time Development of Material Properties and Bond Behavior'.
Portland Cements Association (1979), Design and Control of Concrete Mixtures, pp. 139-295.

Domone P.L. (2005), 'Self-compacting Concrete: An Analysis of 11 Years of Case Studies'.

EFNARC (February, 2002), "Specifications and Guidelines for Self-Compacting Concrete", UK (www.efnarc.org), pp. 1-32.

Gaimster, R., and Foord, C. (April, 2000), "Self-Compacting Concrete," Concrete, vol. 34, pp 23-25.

Goodier C. (Winter 2002/2003), 'Design and use of SCC' vol 6 No. 4.

Gunnar Rise (2001), Concrete Precasting Plant and Technology: 'Self Compacting Concrete', vol.67 No.1, pp.83-85.

Hayakawa, M., Matsuaoka, Y., and Shindoh, T. (1993), Development and Application of Superworkable Concrete. *RILEM International Workshop on Special Concretes: Workability and Mixing.*

Ho, D.W.S., Sheinn A.M.M., Ng C.C. and C.T. Tam (2003), 'The Use of Quarry Dust for SCC Applications', *Cement and Concrete Research*, vol. 32, No. 4, pp. 505 – 511.

Hogson D., Schindler A.K., Brown D.A., Mary group Gardiner, (2005), 'Self-consolidating Concrete for use in Drilled Shaft Applications'.

Holschemacher K., Klug Y. (2002), 'A Database for the Evaluation of Hardened Properties of SCC.' Annual Civil Engineering Report No.7, pp. 123-134.

Huang, J.W. (1990), "Engineering Properties of Silica Fume Concrete and Mortar," M.S. Thesis, Bradley University, Department of Civil Engineering and Construction, pp.108.

Khayat, K.H. (May-June,1999), "Workability, Testing and Performance of Self Consolidated Concrete", ACI Materials Journal, V.96 No.3, pp. 346-352.

Khayat, K.H., Assaad, J., Daczko J. (March- April 2004), "Comparison of Field-oriented Test Methods to Access Dynamic Stability of Self-Consolidating Concrete", *ACI Materials Journal*, V. 101, No. 2, pp. 168-176.

Kosmatka, S. H. and Panarese W.C. (1988). Design and Control of Concrete Mixtures, Skokie, IL: *Portland cements Association.*

Krieg, W. (October, 2003), "Self-Compacting Concrete: Definition, Development, and Applications", A Technical Paper Presented in the meeting of the ACI, Saudi Arabia Chapter, Eastern Province.

Lamond, J. (1983), "Twenty Five Years Experience Using Fly Ash in Concrete," *ACI Publication SP 79*: Fly Ash, Silica Fume, Slag and other Natural By-Products in Concrete, vol. 1, pp 47-69.

Mehta, P. (1986), "Concrete Structure, Properties and Materials," Prentice-Hall, Inc, pp. 1 to 169.

Mindess, S. and Young, J.F. (1981), "Concrete," Prentice-Hall, Inc., Eaglewood Cliffs, NJ, pp. 671.

Mullarky, J.I. and Vanikar, S.; 'Opportunities and Challenges for SCC in Highway Structures', *First North American Conference on the Design and Use of Self-Consolidating Concrete*, pp185-190.

Nagataki, S. and Fujiwara, H. (1995), 'Self-Compacting Property of Highly Flowable Concrete. *ACI* SP 154, Las Vegas, pp. 301-314.

Nawy Edward G., 'Reinforced Concrete, A Fundamental Approach', *ACI 318-05 Code.*

New Self-Compacting Concrete for Pre-cast Elements (2001), TR-6-03, vol. 67, No3, pp.100-108.

Okamura H. and Ouchi M. (January, 1989), Self-Compacting Concrete, Proceedings of the first International RILEM Symposium.

Ozawa K., Maekawa K., Kunishima M. and Okamura H. (1989); Development of High performance concrete based on the durability design of concrete structures, Proceeding of

the second East-Asia and Pacific Conference on Structural Engineering and Construction, vol. 1, pp. 445-450.

Okamura H. (1997), "Self-Compacting High-performance Concrete," *Concrete International*, Vol. 19, No.7, pp.50-54.

Okamura, H. and Ouchi, M. (April 2003), "Self-compacting Concrete", *Journal of Advanced Concrete Technology*, vol. 1, No. 1, pp. 5-15.

Ouchi M., Nakamura S., Osterson T., Hallberg S., and Lwin M. (2003), 'Applications of Self-Compacting · Concrete in Japan, Europe and the United States..' ISHPC.

Ozyildirim C., Lane D.S. (June, 2003) Final Report on 'Evaluation of Self-Consolidating Concrete' pp.1-15.

Petersson O. (October, 1997), 'Final Report on Preliminary Mix Design', Swedish Cement and Concrete Research Institute, pp. 1-27.

Popovics, S. (January-February 1982), "Strength Relationships for Fly Ash Concrete," *ACI Journal*, Vol. 79, No.1, pp. 39-43.

Ravina, D. (April 1984), "Slump loss of Fly Ash Concrete," *Concrete International*, Detroit MI, Vol. 6, Vol. 4, pp. 35-39.

SHI CAIJUN, YANZHONG WU, YIXING SHAO, 'Comparison of two Design Approaches for SCC', Conference notes, First North American Conference on the Design and Use of Self-Consolidating Concrete, pp. 313.

Specification and Guidelines for SCC (Feb 2002), EFNARC.

Kosmatka, S.H. and Panarese, W.C. (2002), 'Design and Control of Concrete Mixtures'.

Sturrup, V.P., Hooton, R.D. and Clendenning, T.G. (1993), "Durability of Fly Ash Concrete," *ACI Publication* SP 79: Fly Ash, Silica Fume, Slag and Other Mineral By-Products in Concrete, vol.1, pp. 71-86.

Subramanian, S. and Chattopadhyay, D. (Jan 2002), 'Experiments for Mix Proportioning of Self Compacting Concrete', *Indian Concrete Journal* vol. 76 No. 1, pp. 13-20.

Suksawan N., Nassif H.H. and Hussain S. N. (2006), "Evaluation of Mechanical Properties for Self-Consolidating, Normal, and High Performance Concrete."

The European Guidelines for Self-Compacting Concrete, 'Specification, Production and Use' (May, 2005).

Uchikawa, H., Hanehara, S., and Sawaki, D. (January, 1997); 'The Role of Steric Repulsive Force in the Dispersion of Cement Particles in Fresh Paste Prepared with Organic Admixture. *Cement and Concrete Research*, vol. 27. No.1. pp. 37-50.

US Department of Transportation, Federal Highway Administration (July, 1986) 'Fly Ash Facts for Highway Engineers', pp. 47.

Xie, Y., Liu B., Yin J. and Zhou S. (2002), 'Optimum Mix Parameters of High-Strength Self-Compacting Concrete with Ultra pulverized Fly Ash. *Cement and Concrete Research*, vol. 32, No. 3, pp. 477-480.

Zhu W., Gibbs J. C. and Bartos P. J.M. (2000), 'Uniformity of in-situ Properties of SCC in Full Scale Structural Elements'.

APPENDICES

Table 3.2 The Physical and Chemical properties of Portland cement

CHEMICAL		
Item	Spec. Limit	Test Result
SiO_2(%)	20.0 min	21.3
Al_2O_3 (%)	6.0 max	4.6
Fe_2O_3 (%)	6.0 max	3.4
CaO(%)	NA	63.2
MgO(%)	6.0 max	2.2
SO_3(%)	3.0 max	2.7
Loss on ignition (%)	3.0 max	1.2
Na_2O(%)	NA	0.19
K_2O(%)	NA	0.50
Insoluble Residue (%)	0.75 max	0.27
C_3S	NA	52
C_2S	NA	22
C_3A	8 max	6
C_4AF	NA	10
$C_4AF+2(C_3A)$	NA	22

PHYSICAL		
Item	Spec. Limit	Test Result
Air content of mortar (volume %)	12 max	8
Fineness (m^2/kg) (Air permeability)	280 min	377
Autoclave expansion (%)	0.80 max	0.04
Compressive Strength (MPa)	min	
1 Day	NA	
3 Days	7.0	23.4
7 Days	12.0	29.8
28 Days	NA	
Time of Setting (minutes)		
Initial (Vicat's apparatus)	Not less than 45 and not more than 375	124

NA= Not applicable.

Table 4.3 General Physical and Chemical Properties of Silica Fume

Compound	Quantity (%)	
	Fly Ash (Class F)	Portland Cement
SiO_2	50-55	20-25
Al_2O_3	20-27	2-5
Fe_2O3	5-10	1-5
CaO	5-10	60-65
MgO	0.5-2	1-4
SO_3	0-2	2-5

Table 5.1 Compressive Strength Test Results

Target Strength: 8000 psi (55 MPa)
SCC Cylinder Size: 4 in×8 in (100 mm×100 mm)

	Mix 1		Mix 2		Mix 3	
Comp. Test	7 d	28 d	7 d	28 d	7 d	28 d
P_1 [lb]	89.22×10^3	103.7×10^3	70.8×10^3	101.3×10^3	62.51×10^3	83.11×10^3
P_2 [lb]	83.22×10^3	111.04×10^3	73.56×10^3	86.19×10^3	58.4×10^3	80.73×10^3
P_3 [lb]	90.57×10^3	107.49×10^3	73.99×10^3	104.3×10^3	59.89×10^3	83.64×10^3
P_{ave}[lb]	87.67×10^3	107.41×10^3	72.8×10^3	97.27×10^3	60.27×10^3	82.49×10^3
f'_c [psi]	6,976.50	8,547.40	5,793	7,740	4,796	6,564
f'c [MPa]	48.1	58.9	39.9	53.4	33	25.3

	Mix 4		Mix 5		Mix 6	
Comp. Test	7 d	28 d	7 d	28 d	7 d	28 d
P_1 [lb]	61.87×10^3	94.83×10^3	79.21×10^3	107.11×10^3	97.73×10^3	109.81×10^3
P_2 [lb]	57.91×10^3	81.11×10^3	74.21×10^3	107.01×10^3	90.78×10^3	100.55×10^3
P_3 [lb]	57.19×10^3	81.29×10^3	81.86×10^3	93.70×10^3	90.3×10^3	89.25×10^3
P_{ave}[lb]	58.99×10^3	85.74×10^3	78.43×10^3	102.6×10^3	92.93×10^3	99.87×10^3
f'_c [psi]	4,694	6,823	6,241	8,165	7,395	7,947
f'c[MPa]	32.4	47	43	56.3	51	54.8

Table 5.2 Splitting Tensile Strength Test Results

Sample size: 6 in×12 in (150 mm × 300 mm) cylinder

Number of Samples: 2

	Mix 1		Mix 2		Mix 3	
T. Strength	7d	28d	7d	28d	7d	28d
P_1 [lb]	67.91×10^3	71.15×10^3	62.6×10^3	63.45×10^3	46.01×10^3	61.02×10^3
P_2 [lb]	67.5×10^3	71.55×10^3	64.65×10^3	68.72×10^3	48.7×10^3	62.39×10^3
P_{av} [lb]	67.71×10^3	71.35×10^3	63.625×10^3	64.41×10^3	47.4×10^3	61.71×10^3
T [psi]	598.64	630.9	562.5	569.6	419.1	545.6
T [MPa]	4.1	4.3	3.9	3.9	2.9	3.8

	Mix 4		Mix 5		Mix 6	
T. Strength	7d	28d	7d	28d	7d	28d
P_1 [lb]	38.53×10^3	62.65×10^3	63.21×10^3	72.51×10^3	66.98×10^3	70.94×10^3
P_2 [lb]	44.79×10^3	62.8×10^3	65.38×10^3	67.72×10^3	64.20×10^3	65.18×10^3
P_{av} [lb]	41.66×10^3	62.73×10^3	64.295×10^3	70.115×10^3	65.59×10^3	68.06×10^3
T [psi]	368.3	554.6	568.5	620	579.9	601.8
T[MPa]	2.5	3.8	3.9	4.3	4	4.1

$T = 2P/\pi LD$

T= Splitting Tensile Strength
L= Length of cylinder
D= Diameter of cylinder

Table 5.3 Modulus of Elasticity Test Results

Mix: 1
Sample Size: 6 in×12 in (cyl.)
Concrete Age: 7d

$F_{av} = 87.67\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 6976.5$ psi

$F'_{av} = f_{av} \times [\pi\ (6^2)/4] = 197257.5$ lb

$0.4\times F'_{av} = 78,903$ lb

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	4	0	4	0.5	4	3	0	3	0	3
10,000	8	1	8.5	1.5	8.25	8	0.5	7	0.5	7.5
20,000	17	3	19	3	18	17	2	16	2	16.5
30,000	28	5	30.5	5	29.25	28	4.5	25	4	26.5
40,000	38	6.5	41	6.5	39.5	37.5	5.5	34	5	35.75
50,000	48	11	51	8	49.5	47.5	6.5	43	6.5	45.25
60,000	58	11.5	62	10	60	57.5	8.5	52.5	9	55
70,000	69	12	73	11.5	71	69	10	61	11	65
80,000	80	14	83	13.5	81.5	80.5	13	69	12.5	74.75

Dial V= Dial gauge **v**ertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$
$= [(R_{v(ave)}\times0.0001")/(2\times8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	f_c [psi]
5,000	28	8084062	4.00	3.00	3.50	0.0000	176.84
10,000	28	7185833	8.25	7.50	7.88	0.0000	353.68
20,000	28	6560978	18.00	16.50	17.25	0.0001	707.36
30,000	28	6090235	29.25	26.50	27.88	0.0002	1061.03
40,000	28	6016046	39.50	35.75	37.63	0.0002	1414.71
50,000	28	5972394	49.50	45.25	47.38	0.0003	1768.39
60,000	28	5904880	60.00	55.00	57.50	0.0004	2122.07
70,000	28	5825280	71.00	65.00	68.00	0.0004	2475.74
80,000	28	5794655	81.50	74.75	78.13	0.0005	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for $f'_c \geq$ 6000 psi):

$E= [40{,}000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c [psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74
12956084	0.0002	2829.42

Mix: 2
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 7d

Calculation: $F_{av} = 72.8\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 5{,}793$ psi

$F'_{av} = f_{av} \times [\pi\,(6^2)/4] = 163800$ lb

$0.4\times F'_{av} = 65{,}520$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	3.5	0.5	4	0	3.75	3	0.5			3
10,000	8	1	9.5	0.5	8.75	7	1			7
20,000	17	2	18.5	2	17.75	16	3			16
30,000	25	3	28.5	3.5	26.75	26	4.5			26
40,000	35	5	37	5	36	34.5	6			34.5
50,000	44.5	6	47	6.5	45.75	44.5	8			44.5
60,000	54	8	57	8	55.5	55	9.5			55
70,000	64	9.5	66.5	9.5	65.25	65	11.5			65

Dial V = Dial gauge **v**ertical
Dial H = Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times0.0001")/(2\times8")]$

$E \quad = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	f'_c [psi]
5,000	28	8,383,471	3.75	3	3.38	0.0000	176.84
10,000	28	7,185,833	8.75	7	7.88	0.0000	353.68
20,000	28	6,706,777	17.75	16	16.88	0.0001	707.36
30,000	28	6,436,599	26.75	26	26.38	0.0002	1061.03
40,000	28	6,421,382	36.00	34.5	35.25	0.0002	1414.71
50,000	28	6,270,186	45.75	44.5	45.13	0.0003	1768.39
60,000	28	6,145,350	55.50	55	55.25	0.0003	2122.07
70,000	28	6,225,839	62.25	65	63.63	0.0004	2475.74

Rv= Reading in vertical dial gauge
Rh= Reading in horiz. dial gauge

ACI CODE(for $f'_c \leq 6000$ psi):

$E = 33 * w_c^{1.5} * (\sqrt{f'_c})$ psi

E [psi]	ε [Strain]	f'_c [psi]
4286826	0.0000	176.84
6062487	0.0001	353.68
8573651	0.0001	707.36
10500536	0.0001	1061.03
12124974	0.0001	1414.71
13556133	0.0001	1768.39
14850000	0.0001	2122.07
16039833	0.0002	2475.74

Mix: 3
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 7d

Calculation: $F_{av} = 60.27\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 4,796$ psi

$F'_{av} = f_{av} \times [\pi (6^2)/4] = 135603.7$ lb

$0.4\times F'_{av} = 54,241.5$ lb

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	**$R_{v1(ave)}$**	Dial V	Dial H	Dial V	Dial H	**$R_{v2(ave)}$**
5,000	5	0	4	0.5	4.5	4	0.5	4.5	0.5	4.25
10,000	9.5	0.5	9.5	1.5	9.5	8.5	1	10	1	9.25
20,000	19	2	20	3	19.5	17.5	2	20	2.5	18.75
30,000	29	4	30	4.5	29.5	28	3.5	31	4	29.5
40,000	39.5	5.5	41	7	40.25	37.5	5	41	5.5	39.25
50,000	51	8	53	8	52	48.5	7	51.5	7	50
60,000	62	10	63	10	62.5	59	9	62	9	60.5

Dial V= Dial gauge **v**ertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Average **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times0.0001")/(2\times8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	f'_c [psi]
5,000	28.274	6,467,249	4.50	4.25	4.375	2.7E-05	176.84
10,000	28.274	6,036,099	9.50	9.25	9.375	5.9E-05	353.68
20,000	28.274	5,917,745	19.50	18.75	19.125	0.00012	707.36
30,000	28.274	5,754,756	29.50	29.50	29.5	0.00018	1061.03
40,000	28.274	5,694,433	40.25	39.25	39.75	0.00025	1414.71
50,000	28.274	5,547,885	52.00	50.00	51	0.00032	1768.39
60,000	28.274	5,520,823	62.50	60.50	61.5	0.00038	2122.07

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for $f'_c \leq 6000$ psi):

$E = 33 * w_c^{1.5} * (\sqrt{f'_c})$ psi

E [psi]	ε [Strain]	f'_c [psi]
4286826	0.00004	176.84
6062487	0.00006	353.68
8573651	0.00008	707.36
10500536	0.00010	1061.03
12124974	0.00012	1414.71
13556133	0.00013	1768.39
14850000	0.00014	2122.07

Mix: 4
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 7d

Calculation: $F_{av} = 58.99\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 4{,}694$ psi

$F'_a = f_{av} \times [\pi\,(6^2)/4] = 132{,}719.7$ lb

$0.4\times F'_{av} = 53{,}088$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	4	0	4	0.5	4	3	0.5	5	0	4
10,000	9	0.5	10	1.5	9.5	8	2	9	1	8.5
20,000	20	2	21	2.5	20.5	18	5	20	1.5	19
30,000	30	4	31.5	4	30.75	30	6	31	2.5	30.5
40,000	41	5.5	41.5	6	41.25	40	7.25	41.5	4	40.75
50,000	53	7.5	53.5	8.5	53.25	51	9.5	52	6	51.5
60,000	64.5	9	65	10	64.75	61	11.5	64	7.5	62.5

Dial V = Dial gauge vertical
Dial H = Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times0.0001")/(2\times8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28	7073554	4.00	4.00	4.00	0.0000	176.84
10,000	28	6287604	9.50	8.50	9.00	0.0001	353.68
20,000	28	5730474	20.50	19.00	19.75	0.0001	707.36
30,000	28	5543357	30.75	30.50	30.63	0.0002	1061.03
40,000	28	5520823	41.25	40.75	41.00	0.0003	1414.71
50,000	28	5402237	53.25	51.50	52.38	0.0003	1768.39
60,000	28	5336434	64.75	62.50	63.63	0.0004	2122.07

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for $f'_c \geq 6000$ psi):
$E = [40{,}000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c [psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07

Mix: 5
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 7d

Calculation: $F_{av} = 78.43\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 6{,}211$ psi

$F'_{av} = f_{av} \times [\pi (6^2)/4] = 176{,}467.5$ lb

$0.4\times F'_{av} = 70{,}587$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	3.5	1	6	1	4.75	5	0	4.5	0.5	4.75
10,000	8.5	1.5	10.5	2	9.5	11	0.5	21.5	1	16.25
20,000	18	3.5	20	4	19	22	1	35	1.5	28.5
30,000	26	5	29	5.5	27.5	31.5	3	47.5	3	39.5
40,000	37.5	7	39.5	7.5	38.5	43	5	60	4.5	51.5
50,000	47.5	9	49.5	9	48.5	52	6	72	6	62
60,000	58	10	60	11	59	63.5	8	83	7.5	73.25
70,000	69	12.5	69	13	69	82	10	84	9	83

Dial V= Dial gauge **v**ertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times 0.0001")/(2\times 8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	f_c [psi]
5,000	28	5956677	4.75	4.75	4.75	0.0000	176.84
10,000	28	4395218	9.50	16.25	12.88	0.0001	353.68
20,000	28	4765342	19.00	28.50	23.75	0.0001	707.36
30,000	28	5067621	27.50	39.50	33.50	0.0002	1061.03
40,000	28	5030083	38.50	51.50	45.00	0.0003	1414.71
50,000	28	5121125	48.50	62.00	55.25	0.0003	1768.39
60,000	28	5134678	59.00	73.25	66.13	0.0004	2122.07
70,000	28	5212092	69.00	83.00	76.00	0.0005	2475.74

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for $f'_c \geq 6000$ psi):
$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c [psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74

Mix: 6
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 7d

Calculation: $F_{av} = 92.93\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 7,395$ psi

$F'_{av} = f_{av} \times [\pi (6^2)/4] = 209,092.5$ lb

$0.4\times F'_{av} = 83,637$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	0	1	0	0	0	3	0.5	3	0.5	3
10,000	1	1.5	1.5	1	1.25	7.5	1	8.5	1.5	8
20,000	6.5	3	7.5	2.5	7	16	3	16.5	3	16.25
30,000	12	4.5	14	4	13	24.5	3.5	25	5	24.75
40,000	18	6	20	6	19	34	6.5	34.5	6.5	34.25
50,000	24.5	7.5	25.5	7	25	43	8	44.5	8	43.75
60,000	32	9	33.5	9	32.75	54	10	55	9.5	54.5
70,000	40	11.5	41.5	10.5	40.75	64	12	64	11	64
80,000	48	12	50	12	49	74	14	73	13	73.5

Dial H = Dial gauge **h**orizontal
Dial V = Dial gauge **v**ertical
$R_{v(ave)}$ = **A**verage **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$
$= [(R_{v(ave)}\times0.0001")/(2\times8")]$
$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28	18862811	0.00	3.00	1.50	0.0000	176.84
10,000	28	12235337	1.25	8.00	4.63	0.0000	353.68
20,000	28	9735644	7.00	16.25	11.63	0.0001	707.36
30,000	28	8994188	13.00	24.75	18.88	0.0001	1061.03
40,000	28	8501548	19.00	34.25	26.63	0.0002	1414.71
50,000	28	8231045	25.00	43.75	34.38	0.0002	1768.39
60,000	28	7782936	32.75	54.50	43.63	0.0003	2122.07
70,000	28	7563132	40.75	64.00	52.38	0.0003	2475.74
80,000	28	7391142	49.00	73.50	61.25	0.0004	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for $f'_c \geq 6000$ psi):

$E = [40{,}000(\sqrt{f'_c}) + 10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c[psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74
12956084	0.0002	2829.42

Mix: 1
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 28d

Calculation: $F_{av} = 107.41\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 8{,}547.4$ psi

$F'_{av} = f_{av} \times [\pi\,(6^2)/4] = 241{,}672.5$ lb

$0.4\times F'_{av} = 96{,}669$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	**$R_{v1(ave)}$**	Dial V	Dial H	Dial V	Dial H	**$R_{v2(ave)}$**
5,000	3	0	2.5	0	2.75	6.5	0.5	3	1	4.75
10,000	7	1	6	0	6.5	7	1	6.5	1.5	6.75
20,000	14.5	2	12.5	1.5	13.5	15	2.5	14	3	14.5
30,000	22	3.5	19	3	20.5	23	4	22	4.5	22.5
40,000	29	5	26	4	27.5	31	5	39.5	6	35.25
50,000	35	7	33	6	34	39	7	37.5	7.5	38.25
60,000	43	8	40.5	7	41.75	47.5	9	45	9	46.25
70,000	50	9	56.5	8.5	53.25	55.5	10.5	53.5	11	54.5
80,000	58	11	63	10	60.5	64	12.5	62	12.5	63

Dial V= Dial gauge **v**ertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times 0.0001")/(2\times 8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28	7545124	2.75	4.75	3.75	0.0000	176.84
10,000	28	8541650	6.50	6.75	6.63	0.0000	353.68
20,000	28	8084062	13.50	14.50	14.00	0.0001	707.36
30,000	28	7896060	20.50	22.50	21.50	0.0001	1061.03
40,000	28	7214461	27.50	35.25	31.38	0.0002	1414.71
50,000	28	7832309	34.00	38.25	36.13	0.0002	1768.39
60,000	28	7716604	41.75	46.25	44.00	0.0003	2122.07
70,000	28	7352557	53.25	54.50	53.88	0.0003	2475.74
80,000	28	7331295	60.50	63.00	61.75	0.0004	2829.42

ACI CODE(for 12,000 psi>f'_c> 6000 psi):

$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c [psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74
12956084	0.0002	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

Mix: 2
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 28d

Calculation: $F_{av} = 97.267\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 7{,}740$ psi

$F'_{av} = f_{av} \times [\pi\,(6^2)/4] = 218{,}850.75$ lb

$0.4\times F'_{av} = 87{,}540$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	**$R_{v1(ave)}$**	Dial V	Dial H	Dial V	Dial H	**$R_{v2(ave)}$**
5,000	3.5	1	4.5	0.5	4	3	0	3	0.5	3
10,000	8	2	9	1.5	8.5	8	1	8.5	1	8.25
20,000	18	3.5	18	3	18	17.5	2.5	19	3	18.25
30,000	26.5	5	27	4.5	26.75	26.5	4	28.5	4.5	27.5
40,000	36	6.5	36.5	6	36.25	37	5.5	39.5	6	38.25
50,000	45.5	8	46	7	45.75	47	7	50	7.5	48.5
60,000	54.5	9.5	54.5	8.5	54.5	58	8.5	60	9	59
70,000	64	11.5	64	10.5	64	68.5	10	69.5	10	69
80,000	71	13	73	12	72	80	12	80	12	80

Dial V= Dial gauge vertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times0.0001")/(2\times8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28	8084062	4.00	3.00	3.50	0.0000	176.84
10,000	28	6756828	8.50	8.25	8.38	0.0001	353.68
20,000	28	6244241	18.00	18.25	18.13	0.0001	707.36
30,000	28	6258628	26.75	27.50	27.13	0.0002	1061.03
40,000	28	6076610	36.25	38.25	37.25	0.0002	1414.71
50,000	28	6004078	45.75	48.50	47.13	0.0003	1768.39
60,000	28	5982918	54.50	59.00	56.75	0.0004	2122.07
70,000	28	5956677	64.00	69.00	66.50	0.0004	2475.74
80,000	28	5956677	72.00	80.00	76.00	0.0005	2829.42

ACI CODE(for 12,000 psi>f'_c> 6000 psi):

$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c [psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74
12956084	0.0002	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horizontal dial gauge

Mix: 3
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 28d

Calculation: $F_{av} = 82.49\times10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 6{,}564$ psi

$F'_{av} = f_{av} \times [\pi (6^2)/4] = 185{,}592.7$ lb

$0.4\times F'_{av} = 74{,}237$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	4.5	0	3	0	3.75	2.5	0	3.5	0.5	3
10,000	9	1	8	1	8.5	6	0.5	8	1.5	7
20,000	18.5	2.5	18	3	18.25	12	2	16.5	3	14.25
30,000	28.5	4.5	28.5	5	28.5	20.5	4	24.5	4.5	22.5
40,000	38.5	6.5	39	7	38.75	30	5.5	33.5	6.5	31.75
50,000	49	8	49	9	49	39.5	7.5	43	8	41.25
60,000	59.5	10	59.5	11	59.5	49.5	9	51.5	9.5	50.5
70,000	69	12	69.5	12.5	69.25	59.5	11	60.5	11.5	60
80,000	81	14	80	15	80.5	68.5	12.5	71	13	69.75

Dial V= Dial gauge **v**ertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)}\times0.0001")/(2\times8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28	8383471	3.75	3.00	3.38	0.0000	176.84
10,000	28	7301733	8.50	7.00	7.75	0.0000	353.68
20,000	28	6964730	18.25	14.25	16.25	0.0001	707.36
30,000	28	6657463	28.50	22.50	25.50	0.0002	1061.03
40,000	28	6421382	38.75	31.75	35.25	0.0002	1414.71
50,000	28	6270186	49.00	41.25	45.13	0.0003	1768.39
60,000	28	6173283	59.50	50.50	55.00	0.0003	2122.07
70,000	28	6129501	69.25	60.00	64.63	0.0004	2475.74
80,000	28	6026056	80.50	69.75	75.13	0.0005	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for 12,000 psi>f'_c> 6000 psi):

$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c [psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74
12956084	0.0002	2829.42

Mix: 4
Sample Size: 6 in×12 in
(cyl.)
Concrete Age: 28d

Calculation: $F_{av} = 85.74 \times 10^3$ lb

$f_{av} = F_{av}/[\pi(4^2)/4] = 6{,}823$ psi

$F'_{av} = f_{av} \times [\pi\,(6^2)/4] = 192922.5$ lb

$0.4 \times F'_{av} = 77{,}169$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	1	0								
10,000	6	0.5								
20,000	15	1								
30,000	24	1.5								
40,000	33	3								
50,000	43	4.5								
60,000	54	5								
70,000	65	7.5								
80,000	74	8								

Dial V= Dial gauge **v**ertical
Dial H= Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)} \times 0.0001")/(2\times 8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28	14147108			2	1.3E-05	176.84
10,000	28	9431405			6	3.8E-05	353.68
20,000	28	7545124			15	9.4E-05	707.36
30,000	28	7073554			24	0.00015	1061.03
40,000	28	6859204			33	0.00021	1414.71
50,000	28	6580050			43	0.00027	1768.39
60,000	28	6287604			54	0.00034	2122.07
70,000	28	6094139			65	0.00041	2475.74
80,000	28	6117668			74	0.00046	2829.42

ACI CODE(for 12,000 psi>f'_c> 6000 psi):

$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c[psi]
4028147	0.0000	176.84
5260838	0.0001	353.68
7004126	0.0001	707.36
8341798	0.0001	1061.03
9469508	0.0001	1414.71
10463040	0.0002	1768.39
11361262	0.0002	2122.07
12187262	0.0002	2475.74
12956084	0.0002	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horiz. dial gauge

Mix: 5
Sample Size: 6 in×12 in (cyl.)
Concrete Age: 28d

Calculation: $F_{av} = 102.64 \times 10^3$ (lb)

$f_{av} = F_{av}/[\pi(4^2)/4] = 8{,}168$ psi

$F'_{av} = f_{av} \times [\pi (6^2)/4] = 230{,}940$ lb

$0.4\times F'_{av} = 92{,}376$ [lb]

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	**$R_{v1(ave)}$**	Dial V	Dial H	Dial V	Dial H	**$R_{v2(ave)}$**
5,000	0	0.5	0	0	0	3.5	0	2.5	0	3
10,000	1	0.5	2	0.5	1.5	8	0	6.5	0.5	7.25
20,000	8	1	10	2	9	16	1	16	2	16
30,000	16	2.5	27.5	3.5	21.75	24.5	3	23	3.5	23.75
40,000	24	3.5	35	5	29.5	34	4	32.5	5	33.25
50,000	32	5	32	6.5	32	41	6	40	6.5	40.5
60,000	40	6.5	40.5	8	40.25	50	7	49	8	49.5
70,000	49	8	48.5	10	48.75	59	9	56.5	9	57.75

Dial V = Dial gauge **v**ertical
Dial H = Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$
$= [(R_{v(ave)} \times 0.0001")/(2\times 8")]$
$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28.27	18862811	0.00	3.00	1.5	0.0000	176.84
10,000	28.27	12934499	1.50	7.25	4.375	0.0000	353.68
20,000	28.27	9054149	9.00	16.00	12.5	0.0001	707.36
30,000	28.27	7462211	21.75	23.75	22.75	0.0001	1061.03
40,000	28.27	7214461	29.50	33.25	31.375	0.0002	1414.71
50,000	28.27	7805301	32.00	40.50	36.25	0.0002	1768.39
60,000	28.27	7566141	40.25	49.50	44.875	0.0003	2122.07
70,000	28.27	7438855	48.75	57.75	53.25	0.0003	2475.74
80,000	28.27	#REF!	#REF!	#REF!	#REF!	#REF!	2829.42

R_v = Reading in vert. dial gauge

R_h = Reading in horiz. dial gauge

ACI CODE(for 12,000 psi>f'_c> 6000 psi):

$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c[psi]
1611840	0.0001	176.84
1843663	0.0002	353.68
2171512	0.0003	707.36
2423079	0.0004	1061.03
2635159	0.0005	1414.71
2822006	0.0006	1768.39
2990929	0.0007	2122.07
3146269	0.0008	2475.74
3290856	0.0009	2829.42

Mix: 6
Sample Size: 6 in ×12 in (cyl.)
Concrete Age: 28d

Calculation: $F_{av} = 99.87 \times 10^3$ (lb)

$f_{av} = F_{av}/[\pi(4^2)/4] = 7,947$ (psi)

$F'_{av} = f_{av} \times [\pi (6^2)/4] = 224,708$ (lb)

$0.4\times F'_{av} = 89,883$ (lb)

Load [lb]	Sample 1		Sample 1 (Repeated)			Sample 2		Sample 2 (Repeated)		
	Dial V	Dial H	Dial V	Dial H	$R_{v1(ave)}$	Dial V	Dial H	Dial V	Dial H	$R_{v2(ave)}$
5,000	2.5	0	3	0	2.75	4	0	3.5	0	3.75
10,000	6.5	0	7.5	1	7	8	0	8	1	8
20,000	14.5	1	16	2.5	15.25	16	2	15	2.5	15.5
30,000	22	2	23.5	4	22.75	24	3	23.5	4	23.75
40,000	30	3.5	31.5	6	30.75	32.5	4.5	32.5	6	32.5
50,000	37.5	4.5	39.5	7.5	38.5	41	6	40.5	7.5	40.75
60,000	45	6	47	9.5	46	49	7.5	49	9.5	49
70,000	54	7.5	55	10.5	54.5	58	8.5	56.5	10.5	57.25
80,000	62	9	63.5	12	62.75	66	10.5	64	12	65

Dial V = Dial gauge **v**ertical
Dial H = Dial gauge **h**orizontal
$R_{v(ave)}$ = Av. **r**eading in **v**ertical dial gauge

$\varepsilon v_{(ave)} = \Delta L_{(ave)}/2L$

$= [(R_{v(ave)} \times 0.0001")/(2\times 8")]$

$E = f_c/\varepsilon_{v,ave}$

EXPERIMENTAL DATA:

P [lb]	$A=\pi 6^2/4$	E [psi]	R_{v1}	R_{v2}	$R_{v(ave)}$	$\varepsilon_{v(ave)}$	fc [psi]
5,000	28.27	1.149E-07	2.75	3.75	3.25	0.0000	176.84
10,000	28.27	1.325E-07	7.00	8.00	7.5	0.0000	353.68
20,000	28.27	1.358E-07	15.25	15.50	15.375	0.0001	707.36
30,000	28.27	1.37E-07	22.75	23.75	23.25	0.0001	1061.03
40,000	28.27	1.397E-07	30.75	32.50	31.625	0.0002	1414.71
50,000	28.27	1.4E-07	38.50	40.75	39.625	0.0002	1768.39
60,000	28.27	1.399E-07	46.00	49.00	47.5	0.0003	2122.07
70,000	28.27	1.411E-07	54.50	57.25	55.875	0.0003	2475.74
80,000	28.27	1.411E-07	62.75	65.00	63.875	0.0004	2829.42

ACI CODE(for 12,000 psi>f'_c> 6000 psi):

$E= [40,000(\sqrt{f'_c})+10^6][(w_c/145)^{1.5}]$ psi

E [psi]	ε [Strain]	f'_c[psi]
1611840	0.0001	176.84
1843663	0.0002	353.68
2171512	0.0003	707.36
2423079	0.0004	1061.03
2635159	0.0005	1414.71
2822006	0.0006	1768.39
2990929	0.0007	2122.07
3146269	0.0008	2475.74
3290856	0.0009	2829.42

R_v = Reading in vertical dial gauge

R_h = Reading in horizon. dial gauge

Table 5.4 Drying Shrinkage Test Results

Mix: 1

Date	Sample 1	Rod 1	Sample 2	Rod 2	Sample 3	Rod 3
29-Jan	0.2243	0.1406	0.1618	0.1406	0.1781	0.1405
1-Feb	0.2263	0.1437	0.1708	0.1506	0.1894	0.1529
5-Feb	0.1671	0.0848	0.1043	0.085	0.1206	0.0847
12-Feb	0.1673	0.0852	0.1044	0.0856	0.1208	0.0862
	0.1681	0.086	0.104	0.0851	0.1215	0.0858
19-Feb	0.1686	0.0871	0.1042	0.0858	0.1215	0.0867
	0.1674	0.0869	0.1043	0.0866	0.1205	0.0864
26-Feb	0.165	0.0843	0.102	0.0841	0.1182	0.0844
	0.1648	0.0841	0.1017	0.0843	0.1189	0.0842
28-Apr	0.1471	0.0682	0.0849	0.0682	0.1012	0.0682
	0.1471	0.0682	0.0849	0.0682	0.1012	0.0682

Time (days)	Sample 1	Sample 2	Sample 3	Av. Value	% Drying Shrinkage
0	0.0837	0.0212	0.0376	0.0475	0
3	0.0826	0.0202	0.0365	0.0464	2.2
7	0.0823	0.0193	0.0359	0.0458	3.5
14	0.0821	0.0189	0.0352	0.0454	4.5
21	0.0810	0.0181	0.0345	0.0445	6.3
28	0.0807	0.0177	0.0343	0.0442	6.9
90	0.0789	0.0167	0.0330	0.0429	9.8

Mix : 2

Date	Sample 1	Rod 1	Sample 2	Rod 2	Sample 3	Rod 3
31-Jan	0.2407	0.1403	0.138	0.1547	0.2315	0.1577
3-Feb						
7-Feb	0.1844	0.0859	0.0664	0.0857	0.1579	0.0857
	0.1842	0.0857	0.0663	0.0857	0.1578	0.0856
14-Feb	0.1847	0.0864	0.0658	0.0862	0.1576	0.0862
	0.1836	0.086	0.0665	0.0858	0.1577	0.086
21-Feb	0.1835	0.0865	0.0654	0.0864	0.1582	0.0866
	0.1834	0.0864	0.0664	0.0866	0.1576	0.0863
28-Feb	0.1805	0.0849	0.0637	0.0846	0.1549	0.0845
	0.1807	0.085	0.0638	0.0843	0.1554	0.0845
30-Apr	0.1633	0.0681	0.0464	0.0681	0.1378	0.0681
	0.1633	0.0681	0.0464	0.0681	0.1378	0.0681

Time(days)	Sample 1	Sample 2	Sample 3	Av. Value	% Drying Shrinkage
0	0.1004	-0.0167	0.0738	0.0525	0
3					
7	0.0985	-0.0194	0.0722	0.0505	3.9
14	0.0980	-0.0199	0.0716	0.0499	5.0
21	0.0970	-0.0206	0.0715	0.0493	6.1
28	0.0957	-0.0207	0.0707	0.0485	7.6
90	0.0952	-0.0217	0.0697	0.0477	9.1

Mix: 3

Date	Sample 1	Rod 1	Sample 2	Rod 2	Sample 3	Rod 3
2-Feb	0.1923	0.1467	0.2293	0.1512	0.1938	0.1444
5-Feb	0.1283	0.0849	0.1622	0.0847	0.1335	0.0852
9-Feb	0.1287	0.086	0.1618	0.0854	0.1335	0.0855
	0.1288	0.0856	0.1623	0.0855	0.1334	0.0854
16-Feb	0.1283	0.0872	0.1615	0.086	0.1334	0.0866
	0.1285	0.0867	0.1623	0.0858	0.1341	0.0865
23-Feb	0.1278	0.0857	0.1607	0.0856	0.1321	0.0854
	0.1272	0.0866	0.1605	0.0858	0.1311	0.0855
1-Mar	0.1264	0.0854	0.1594	0.0845	0.1301	0.0844
	0.126	0.0851	0.1591	0.0844	0.13	0.0835
2-May	0.1077	0.0682	0.1414	0.0682	0.1127	0.0682
	0.1077	0.0682	0.1414	0.0682	0.1127	0.0682

Time (days)	Sample 1	Sample 2	Sample 3	Av. Value	% Drying Shrinkage
0	0.0456	0.0781	0.0494	0.0577	0.0
3	0.0434	0.0775	0.0483	0.0564	2.3
7	0.0430	0.0766	0.0480	0.0559	3.2
14	0.0415	0.0760	0.0472	0.0549	4.9
21	0.0414	0.0749	0.0462	0.0541	6.2
28	0.0410	0.0748	0.0461	0.0540	6.5
90	0.0395	0.0732	0.0445	0.0524	9.2

Mix : 4

Date	Sample 1	Rod 1	Sample 2	Rod 2	Sample 3	Rod 3
6-Feb	0.1546	0.0855	0.0612	0.0854	0.1521	0.0853
9-Feb	0.1537	0.0856	0.0611	0.0854	0.1506	0.0851
	0.1531	0.0848	0.0605	0.0856	0.1514	0.0853
13-Feb	0.1519	0.084	0.0589	0.0849	0.1498	0.0852
	0.1519	0.0843	0.0587	0.0855	0.1497	0.0849
20-Feb	0.1538	0.0874	0.0594	0.0869	0.1508	0.0868
	0.1536	0.0872	0.0602	0.0869	0.1499	0.0862
27-Feb						
5-Mar	0.1504	0.0844	0.0566	0.0845	0.1477	0.0844
	0.1506	0.0846	0.057	0.0845	0.1467	0.0842
6-May	0.1329	0.0682	0.0391	0.0682	0.1298	0.0682
	0.1329	0.0682	0.0391	0.0682	0.1298	0.0682

Time(days)	Sample 1	Sample 2	Sample 3	Av. Value	% Drying Shrinkage
0	0.0691	-0.0242	0.0668	0.0372	0
3	0.0682	-0.0247	0.0658	0.0364	2.1
7	0.0678	-0.0264	0.0647	0.0354	5.1
14	0.0664	-0.0271	0.0639	0.0344	7.7
21					
28	0.0660	-0.0277	0.0629	0.0337	9.4
90	0.0647	-0.0291	0.0616	0.0324	13.0

Mix : 5

Date	Sample 1	Rod 1	Sample 2	Rod 2	Sample 3	Rod 3
11-Feb	0.1409	0.0861	0.1306	0.0851	0.1413	0.0858
	0.1412	0.0856	0.1306	0.0862	0.1415	0.0858
14-Feb	0.1406	0.0855	0.1299	0.0865	0.1405	0.0856
	0.1408	0.0857	0.1301	0.0845	0.1415	0.0863
18-Feb	0.1411	0.0869	0.1307	0.0864	0.141	0.0865
	0.1407	0.0859	0.1306	0.0867	0.1406	0.0866
25-Feb	0.137	0.0845	0.1276	0.0842	0.1367	0.084
	0.1381	0.0833	0.1277	0.0842	0.1375	0.084
3-Mar						
10-Mar	0.0639	0.0121	0.0545	0.0116	0.0635	0.0117
	0.0637	0.0119	0.054	0.0115	0.0643	0.0119
11-May	0.1199	0.0683	0.1096	0.0682	0.1199	0.0682
	0.1199	0.0683	0.1096	0.0682	0.1199	0.0682

Time(days)	Sample 1	Sample 2	Sample 3	Av. Value	% Drying Shrinkage
0	0.0552	0.0450	0.0556	0.0519	0
3	0.0551	0.0445	0.0551	0.0516	0.7
7	0.0545	0.0441	0.0543	0.0510	1.9
14	0.0537	0.0435	0.0531	0.0501	3.6
21					
28	0.0518	0.0427	0.0521	0.0489	5.9
90	0.0516	0.0414	0.0517	0.0482	7.1

Mix : 6

Date	Sample 1	Rod 1	Sample 2	Rod 2	Sample 3	Rod 3
14-Feb	0.1162	0.0871	0.0731	0.0861	0.1579	0.0853
	0.1159	0.0869	0.0723	0.0866	0.1585	0.0866
17-Feb	0.1149	0.0864	0.0719	0.0861	0.1566	0.0857
	0.1149	0.0861	0.0721	0.0863	0.1567	0.0859
21-Feb	0.1149	0.0869	0.072	0.0862	0.1569	0.0864
	0.1149	0.0864	0.072	0.0865	0.1564	0.0866
28-Feb	0.1122	0.0844	0.0699	0.0802	0.1548	0.0846
	0.1121	0.0843	0.0699	0.0801	0.1543	0.0844
6-Mar	0.0401	0.0119	0.0002	0.0118	0.0813	0.0118
	0.0392	0.012	0.0001	0.0116	0.0815	0.0117
13-Mar	0.0402	0.0126	0.0001	0.0157	0.0821	0.0125
	0.0399	0.0129	0	0.0158	0.0822	0.0126
14-May	0.0946	0.0688	0.052	0.0688	0.1371	0.0689
	0.0946	0.0688	0.052	0.0688	0.1371	0.0689

Time(days)	Sample 1	Sample 2	Sample 3	Av. Value	% Drying Shrinkage
0	0.0291	-0.0137	0.0723	0.0292	0
3	0.0287	-0.0142	0.0709	0.0284	2.7
7	0.0283	-0.0144	0.0702	0.0280	4.1
14	0.0278	-0.0154	0.0701	0.0275	5.9
21	0.0277	-0.0157	0.0697	0.0272	6.8
28	0.0273	-0.0157	0.0696	0.0271	7.4
90	0.0258	-0.0168	0.0682	0.0257	11.9

Table 6.2 Calculations of the Percentage Error for the Splitting Tensile Strength

f'_c [MPa]	f_{st} [MPa]	f_{st} = 0.55*sqrt(f'_c)	$f_{st\,1}$= 0.68*sqrt(f'_c)-0.17	$f_{st\,2}$= 0.65*sqrt(f'_c)	($f_{st\,1}$ - $f_{st\,ACI\,318}$)	($f_{st\,2}$ - $f_{st\,ACI\,318}$)	($f_{st\,1}$ - $f_{st\,ACI\,318})^2$	($f_{st\,2}$ - $f_{st\,ACI\,318})^2$
17.9	3.3	2.33	2.71	2.75	0.38	0.42	0.14	0.18
21.9	3.4	2.57	3.01	3.04	0.44	0.47	0.19	0.22
27.4	4.0	2.88	3.39	3.40	0.51	0.52	0.26	0.27
34.1	3.5	3.21	3.80	3.80	0.59	0.58	0.35	0.34
36.5	5.3	3.32	3.94	3.93	0.62	0.60	0.38	0.37
36.9	5.4	3.34	3.96	3.95	0.62	0.61	0.38	0.37
37.5	5.6	3.37	3.99	3.98	0.63	0.61	0.39	0.38
37.1	3.6	3.35	3.97	3.96	0.62	0.61	0.39	0.37
41.9	3.6	3.56	4.23	4.21	0.67	0.65	0.45	0.42
45.0	3.0	3.69	4.39	4.36	0.70	0.67	0.49	0.45
46.2	3.7	3.74	4.45	4.42	0.71	0.68	0.51	0.46
47.1	3.7	3.77	4.49	4.46	0.72	0.69	0.52	0.47
47.1	4.0	3.77	4.49	4.46	0.72	0.69	0.52	0.47
46.2	4.3	3.74	4.45	4.42	0.71	0.68	0.51	0.46
46.5	6.0	3.75	4.47	4.43	0.72	0.68	0.51	0.46
51.2	3.4	3.93	4.69	4.65	0.76	0.72	0.58	0.51
52.1	3.7	3.97	4.74	4.69	0.77	0.72	0.59	0.52
52.0	8.0	3.97	4.73	4.69	0.77	0.72	0.59	0.52
53.8	8.2	4.03	4.82	4.77	0.78	0.73	0.61	0.54
58.5	6.8	4.21	5.03	4.97	0.82	0.76	0.68	0.59
68.8	5.7	4.56	5.47	5.39	0.91	0.83	0.82	0.69
69.1	5.5	4.57	5.48	5.40	0.91	0.83	0.83	0.69
37.4	3.4	3.36	3.99	3.97	0.62	0.61	0.39	0.37
37.7	3.4	3.37	4.00	3.99	0.63	0.61	0.39	0.38
72.6	5.0	4.69	5.63	5.54	0.94	0.85	0.88	0.73
46.2	4.3	3.74	4.45	4.42	0.71	0.68	0.51	0.46
51.2	3.6	3.93	4.69	4.65	0.76	0.72	0.58	0.51
53.8	3.8	4.03	4.82	4.77	0.78	0.73	0.61	0.54

56.2	4.6	4.12	4.93	4.87	0.80	0.75	0.65	0.56
57.1	4.7	4.15	4.97	4.91	0.81	0.76	0.66	0.57
59.4	4.8	4.24	5.07	5.01	0.83	0.77	0.69	0.59
63.1	4.4	4.37	5.23	5.16	0.86	0.79	0.74	0.63
63.5	4.7	4.38	5.25	5.18	0.87	0.80	0.75	0.64
8.9	1.1	1.64	1.86	1.94	0.22	0.30	0.05	0.09
17.1	2.0	2.27	2.64	2.69	0.37	0.41	0.14	0.17
21.4	3.2	2.54	2.98	3.01	0.43	0.46	0.19	0.21
26.0	3.4	2.80	3.30	3.31	0.49	0.51	0.24	0.26
33.0	4.0	3.16	3.74	3.73	0.58	0.57	0.33	0.33
42.9	5.1	3.60	4.28	4.26	0.68	0.65	0.46	0.43
43.6	5.4	3.63	4.32	4.29	0.69	0.66	0.47	0.44
44.3	6.3	3.66	4.36	4.33	0.70	0.67	0.48	0.44
55.0	5.9	4.08	4.87	4.82	0.79	0.74	0.63	0.55
66.4	3.7	4.48	5.37	5.30	0.89	0.81	0.79	0.66
69.3	6.6	4.58	5.49	5.41	0.91	0.83	0.83	0.69
62.1	7.9	4.34	5.19	5.12	0.85	0.79	0.73	0.62
64.3	8.0	4.41	5.28	5.21	0.87	0.80	0.76	0.64
15.0	1.8	2.13	2.46	2.52	0.33	0.39	0.11	0.15
25.0	2.4	2.75	3.23	3.25	0.48	0.50	0.23	0.25
31.4	4.2	3.08	3.64	3.64	0.56	0.56	0.31	0.31
37.1	5.0	3.35	3.97	3.96	0.62	0.61	0.39	0.37
50.0	3.7	3.89	4.64	4.60	0.75	0.71	0.56	0.50
47.0	3.4	3.77	4.49	4.46	0.72	0.69	0.52	0.47
79.5	4.7	4.90	5.89	5.80	0.99	0.89	0.98	0.79
83.0	4.0	5.01	6.03	5.92	1.01	0.91	1.03	0.83
84.0	4.8	5.04	6.06	5.96	1.02	0.92	1.04	0.84
28.5	3.7	2.94	3.46	3.47	0.52	0.53	0.27	0.29
36.0	3.9	3.30	3.91	3.90	0.61	0.60	0.37	0.36
40.6	4.4	3.50	4.16	4.14	0.66	0.64	0.43	0.41

45.6	4.6	3.71	4.42	4.39	0.71	0.68	0.50	0.46
49.4	4.7	3.87	4.61	4.57	0.74	0.70	0.55	0.49
53.8	5.1	4.03	4.82	4.77	0.78	0.73	0.61	0.54
56.3	5.5	4.13	4.93	4.88	0.81	0.75	0.65	0.56
29.5	3.6	2.99	3.52	3.53	0.54	0.54	0.29	0.30
40.1	4.2	3.48	4.14	4.12	0.65	0.63	0.43	0.40
47.8	4.7	3.80	4.53	4.49	0.73	0.69	0.53	0.48
47.9	4.8	3.81	4.54	4.50	0.73	0.69	0.53	0.48
51.8	5.0	3.96	4.72	4.68	0.77	0.72	0.59	0.52
57.9	5.9	4.19	5.00	4.95	0.82	0.76	0.67	0.58
61.8	5.5	4.32	5.18	5.11	0.85	0.79	0.73	0.62
20.9	2.6	2.51	2.94	2.97	0.42	0.46	0.18	0.21
29.5	3.0	2.99	3.52	3.53	0.54	0.54	0.29	0.30
34.6	3.5	3.24	3.83	3.82	0.59	0.59	0.35	0.35
37.5	3.9	3.37	3.99	3.98	0.63	0.61	0.39	0.38
40.5	4.0	3.50	4.16	4.14	0.66	0.64	0.43	0.41
48.3	4.5	3.82	4.56	4.52	0.73	0.69	0.54	0.48
49.2	4.6	3.86	4.60	4.56	0.74	0.70	0.55	0.49
19.8	2.9	2.45	2.86	2.89	0.41	0.44	0.17	0.20
28.9	3.2	2.96	3.49	3.49	0.53	0.54	0.28	0.29
36.0	3.6	3.30	3.91	3.90	0.61	0.60	0.37	0.36
40.8	3.8	3.51	4.17	4.15	0.66	0.64	0.44	0.41
42.4	4.0	3.58	4.26	4.23	0.68	0.65	0.46	0.42
45.2	4.2	3.70	4.40	4.37	0.70	0.67	0.50	0.45
43.7	4.5	3.64	4.33	4.30	0.69	0.66	0.48	0.44
32.6	3.7	3.14	3.71	3.71	0.57	0.57	0.33	0.33
43.5	3.9	3.63	4.31	4.29	0.69	0.66	0.47	0.44
48.2	4.2	3.82	4.55	4.51	0.73	0.69	0.54	0.48
60.6	4.4	4.28	5.12	5.06	0.84	0.78	0.71	0.61
60.0	5.3	4.26	5.10	5.03	0.84	0.77	0.70	0.60

62.1	5.4	4.33	5.19	5.12	0.85	0.79	0.73	0.62
61.8	5.5	4.32	5.18	5.11	0.85	0.79	0.73	0.62
48.1	4.1	3.81	4.55	4.51	0.73	0.69	0.54	0.48
58.9	4.3	4.22	5.05	4.99	0.83	0.77	0.69	0.59
39.9	3.9	3.48	4.13	4.11	0.65	0.63	0.42	0.40
53.4	4.0	4.02	4.80	4.75	0.78	0.73	0.61	0.53
33.1	2.9	3.16	3.74	3.74	0.58	0.58	0.33	0.33
45.3	3.8	3.70	4.40	4.37	0.70	0.67	0.50	0.45
32.4	2.5	3.13	3.70	3.70	0.57	0.57	0.32	0.32
47.0	3.8	3.77	4.49	4.46	0.72	0.69	0.52	0.47
43.0	3.9	3.61	4.29	4.26	0.68	0.66	0.47	0.43
56.3	4.3	4.13	4.93	4.88	0.81	0.75	0.65	0.56
51.0	4.0	3.93	4.69	4.64	0.76	0.71	0.57	0.51
54.8	4.1	4.07	4.86	4.81	0.79	0.74	0.63	0.55
	Mean $f_{st\,ACI\,318}$	**3.67**		**Error Range max**	**1.02**	**0.92**	**51.87**	**46.75**
				min	**0.22**	**0.30**		

SD for proposed eq. 1= sqrt(51.87/n-1)= sqrt(51.87/101) = 0.72

SD for proposed eq. 2= sqrt(46.75/n-1)= sqrt(46.75/ 101)= 0.68

SD= Standard Deviation

Percentage Error with respect to proposed **eq. 1 (ACI 318)**= (0.72/3.67)*100= **19.6 %**

Percentage Error with respect to proposed **eq. 2 (ACI 318)**= (0.68/3.67)*100= **18.5 %**

f'_c [MPa]	f_{st} [MPa]	$f_{st} = 0.59*sqrt(f'_c)$	$f_{st\,1} = 0.68*sqrt(f'_c)-0.17$	$f_{st\,2} = 0.65*sqrt(f'_c)$	$(f_{st\,1} - f_{st\,ACI\,363})$	$(f_{st\,2} - f_{st\,ACI\,363})$	$(f_{st\,1} - f_{st\,ACI\,363})^2$	$(f_{st\,2} - f_{st\,ACI\,363})^2$
17.9	3.3	2.50	2.71	2.75	0.21	0.25	0.04	0.06
21.9	3.4	2.76	3.01	3.04	0.25	0.28	0.06	0.08
27.4	4.0	3.09	3.39	3.40	0.30	0.31	0.09	0.10
34.1	3.5	3.45	3.80	3.80	0.36	0.35	0.13	0.12
36.5	5.3	3.56	3.94	3.93	0.37	0.36	0.14	0.13
36.9	5.4	3.58	3.96	3.95	0.38	0.36	0.14	0.13
37.5	5.6	3.61	3.99	3.98	0.38	0.37	0.15	0.14
37.1	3.6	3.59	3.97	3.96	0.38	0.37	0.14	0.13
41.9	3.6	3.82	4.23	4.21	0.41	0.39	0.17	0.15
45.0	3.0	3.96	4.39	4.36	0.43	0.40	0.19	0.16
46.2	3.7	4.01	4.45	4.42	0.44	0.41	0.20	0.17
47.1	3.7	4.05	4.49	4.46	0.45	0.41	0.20	0.17
47.1	4.0	4.05	4.49	4.46	0.45	0.41	0.20	0.17
46.2	4.3	4.01	4.45	4.42	0.44	0.41	0.20	0.17
46.5	6.0	4.02	4.47	4.43	0.44	0.41	0.20	0.17
51.2	3.4	4.22	4.69	4.65	0.47	0.43	0.22	0.18
52.1	3.7	4.26	4.74	4.69	0.48	0.43	0.23	0.19
52.0	8.0	4.25	4.73	4.69	0.48	0.43	0.23	0.19
53.8	8.2	4.33	4.82	4.77	0.49	0.44	0.24	0.19
58.5	6.8	4.51	5.03	4.97	0.52	0.46	0.27	0.21
68.8	5.7	4.89	5.47	5.39	0.58	0.50	0.33	0.25
69.1	5.5	4.91	5.48	5.40	0.58	0.50	0.33	0.25
37.4	3.4	3.61	3.99	3.97	0.38	0.37	0.14	0.13
37.7	3.4	3.62	4.00	3.99	0.38	0.37	0.15	0.14
72.6	5.0	5.03	5.63	5.54	0.60	0.51	0.36	0.26
46.2	4.3	4.01	4.45	4.42	0.44	0.41	0.20	0.17
51.2	3.6	4.22	4.69	4.65	0.47	0.43	0.22	0.18
53.8	3.8	4.33	4.82	4.77	0.49	0.44	0.24	0.19

56.2	4.6	4.42	4.93	4.87	0.50	0.45	0.25	0.20
57.1	4.7	4.46	4.97	4.91	0.51	0.45	0.26	0.21
59.4	4.8	4.55	5.07	5.01	0.52	0.46	0.27	0.21
63.1	4.4	4.69	5.23	5.16	0.54	0.48	0.30	0.23
63.5	4.7	4.70	5.25	5.18	0.55	0.48	0.30	0.23
8.9	1.1	1.76	1.86	1.94	0.10	0.18	0.01	0.03
17.1	2.0	2.44	2.64	2.69	0.20	0.25	0.04	0.06
21.4	3.2	2.73	2.98	3.01	0.25	0.28	0.06	0.08
26.0	3.4	3.01	3.30	3.31	0.29	0.31	0.08	0.09
33.0	4.0	3.39	3.74	3.73	0.35	0.34	0.12	0.12
42.9	5.1	3.86	4.28	4.26	0.42	0.39	0.18	0.15
43.6	5.4	3.89	4.32	4.29	0.42	0.40	0.18	0.16
44.3	6.3	3.93	4.36	4.33	0.43	0.40	0.18	0.16
55.0	5.9	4.38	4.87	4.82	0.50	0.44	0.25	0.20
66.4	3.7	4.81	5.37	5.30	0.56	0.49	0.32	0.24
69.3	6.6	4.91	5.49	5.41	0.58	0.50	0.34	0.25
62.1	7.9	4.65	5.19	5.12	0.54	0.47	0.29	0.22
64.3	8.0	4.73	5.28	5.21	0.55	0.48	0.30	0.23
15.0	1.8	2.29	2.46	2.52	0.18	0.23	0.03	0.05
25.0	2.4	2.95	3.23	3.25	0.28	0.30	0.08	0.09
31.4	4.2	3.31	3.64	3.64	0.33	0.34	0.11	0.11
37.1	5.0	3.60	3.97	3.96	0.38	0.37	0.14	0.13
50.0	3.7	4.17	4.64	4.60	0.47	0.42	0.22	0.18
47.0	3.4	4.04	4.49	4.46	0.45	0.41	0.20	0.17
79.5	4.7	5.26	5.89	5.80	0.63	0.53	0.40	0.29
83.0	4.0	5.38	6.03	5.92	0.65	0.55	0.42	0.30
84.0	4.8	5.41	6.06	5.96	0.65	0.55	0.43	0.30
28.5	3.7	3.15	3.46	3.47	0.31	0.32	0.10	0.10
36.0	3.9	3.54	3.91	3.90	0.37	0.36	0.14	0.13
40.6	4.4	3.76	4.16	4.14	0.40	0.38	0.16	0.15

45.6	4.6	3.98	4.42	4.39	0.44	0.41	0.19	0.16
49.4	4.7	4.15	4.61	4.57	0.46	0.42	0.21	0.18
53.8	5.1	4.33	4.82	4.77	0.49	0.44	0.24	0.19
56.3	5.5	4.43	4.93	4.88	0.51	0.45	0.26	0.20
29.5	3.6	3.20	3.52	3.53	0.32	0.33	0.10	0.11
40.1	4.2	3.74	4.14	4.12	0.40	0.38	0.16	0.14
47.8	4.7	4.08	4.53	4.49	0.45	0.41	0.20	0.17
47.9	4.8	4.08	4.54	4.50	0.45	0.42	0.21	0.17
51.8	5.0	4.25	4.72	4.68	0.48	0.43	0.23	0.19
57.9	5.9	4.49	5.00	4.95	0.51	0.46	0.27	0.21
61.8	5.5	4.64	5.18	5.11	0.54	0.47	0.29	0.22
20.9	2.6	2.70	2.94	2.97	0.24	0.27	0.06	0.08
29.5	3.0	3.20	3.52	3.53	0.32	0.33	0.10	0.11
34 6	3.5	3.47	3.83	3.82	0.36	0.35	0.13	0.12
37.5	3.9	3.61	3.99	3.98	0.38	0.37	0.15	0.14
40.5	4.0	3.75	4.16	4.14	0.40	0.38	0.16	0.15
48.3	4.5	4.10	4.56	4.52	0.46	0.42	0.21	0.17
49.2	4.6	4.14	4.60	4.56	0.46	0.42	0.21	0.18
19.8	2.9	2.63	2.86	2.89	0.23	0.27	0.05	0.07
28.9	3.2	3.17	3.49	3.49	0.31	0.32	0.10	0.10
36.0	3.6	3.54	3.91	3.90	0.37	0.36	0.14	0.13
40.8	3.8	3.77	4.17	4.15	0.40	0.38	0.16	0.15
42.4	4.0	3.84	4.26	4.23	0.42	0.39	0.17	0.15
45 2	4.2	3.97	4.40	4.37	0.44	0.40	0.19	0.16
43.7	4.5	3.90	4.33	4.30	0.42	0.40	0.18	0.16
32.6	3.7	3.37	3.71	3.71	0.34	0.34	0.12	0.12
43.5	3.9	3.89	4.31	4.29	0.42	0.40	0.18	0.16
48.2	4.2	4.10	4.55	4.51	0.45	0.42	0.21	0.17
60.6	4.4	4.59	5.12	5.06	0.53	0.47	0.28	0.22
60.0	5.3	4.57	5.10	5.03	0.53	0.46	0.28	0.22

62.1	5.4	4.65	5.19	5.12	0.54	0.47	0.29	0.22
61.8	5.5	4.64	5.18	5.11	0.54	0.47	0.29	0.22
48.1	4.1	4.09	4.55	4.51	0.45	0.42	0.21	0.17
58.9	4.3	4.53	5.05	4.99	0.52	0.46	0.27	0.21
39.9	3.9	3.73	4.13	4.11	0.40	0.38	0.16	0.14
53.4	4.0	4.31	4.80	4.75	0.49	0.44	0.24	0.19
33.1	2.9	3.39	3.74	3.74	0.35	0.35	0.12	0.12
45.3	3.8	3.97	4.40	4.37	0.44	0.40	0.19	0.16
32.4	2.5	3.36	3.70	3.70	0.34	0.34	0.12	0.12
47.0	3.8	4.05	4.49	4.46	0.45	0.41	0.20	0.17
43.0	3.9	3.87	4.29	4.26	0.42	0.39	0.18	0.15
56.3	4.3	4.43	4.93	4.88	0.51	0.45	0.26	0.20
51.0	4.0	4.21	4.69	4.64	0.47	0.43	0.22	0.18
54.8	4.1	4.37	4.86	4.81	0.50	0.44	0.25	0.20
	Mean $f_{st\ ACI\ 363}$	**3.94**		**Error Range max**	**0.65**	**0.55**	**19.99**	**16.83**
				min	**0.10**	**0.18**		

SD for proposed eq. 1= sqrt(19.99/n-1)= sqrt(19.99/101) = 0.44
SD for proposed eq. 2= sqrt(16.83/n-1)= sqrt(16.83/ 101)= 0.41
SD= Standard Deviation

Percentage Error with respect to proposed **eq. 1(ACI 363)** = (0.44/3.94)*100= **11.2 %**
Percentage Error with respect to proposed **eq. 2(ACI 363)** = (0.41/3.94)*100= **10.4 %**

f'_c [MPa]	f_{st} [MPa]	$f_{st} = 0.30(f'_c)^{2/3}$	$f_{st\,1} = 0.68*sqrt(f'_c)-0.17$	$f_{st\,2} = 0.65*sqrt(f'_c)$	$(f_{st\,1} - f_{st\,Eurocode\,2})$	$(f_{st\,2} - f_{st\,Eurocode\,2})$	$(f_{st\,1} - f_{st\,Eurocode\,2})^2$	$(f_{st\,2} - f_{st\,Eurocode\,2})^2$
17.9	3.3	2.05	2.71	2.75	0.65	0.70	0.43	0.49
21.9	3.4	2.35	3.01	3.04	0.66	0.69	0.44	0.48
27.4	4.0	2.73	3.39	3.40	0.66	0.68	0.44	0.46
34.1	3.5	3.15	3.80	3.80	0.65	0.64	0.42	0.41
36.5	5.3	3.30	3.94	3.93	0.64	0.63	0.41	0.39
36.9	5.4	3.33	3.96	3.95	0.64	0.62	0.40	0.39
37.5	5.6	3.36	3.99	3.98	0.63	0.62	0.40	0.38
37.1	3.6	3.33	3.97	3.96	0.63	0.62	0.40	0.39
41.9	3.6	3.62	4.23	4.21	0.61	0.59	0.38	0.35
45.0	3.0	3.80	4.39	4.36	0.60	0.56	0.36	0.32
46.2	3.7	3.86	4.45	4.42	0.59	0.56	0.35	0.31
47.1	3.7	3.91	4.49	4.46	0.58	0.55	0.34	0.30
47.1	4.0	3.91	4.49	4.46	0.58	0.55	0.34	0.30
46.2	4.3	3.86	4.45	4.42	0.59	0.56	0.35	0.31
46.5	6.0	3.88	4.47	4.43	0.59	0.55	0.35	0.31
51.2	3.4	4.13	4.69	4.65	0.56	0.51	0.31	0.26
52.1	3.7	4.18	4.74	4.69	0.55	0.51	0.31	0.26
52.0	8.0	4.18	4.73	4.69	0.55	0.51	0.31	0.26
53.8	8.2	4.28	4.82	4.77	0.54	0.49	0.29	0.24
58.5	6.8	4.52	5.03	4.97	0.51	0.45	0.26	0.20
68.8	5.7	5.04	5.47	5.39	0.43	0.35	0.19	0.13
69.1	5.5	5.05	5.48	5.40	0.43	0.35	0.19	0.12
37.4	3.4	3.35	3.99	3.97	0.63	0.62	0.40	0.38
37.7	3.4	3.37	4.00	3.99	0.63	0.62	0.40	0.38
72.6	5.0	5.22	5.63	5.54	0.40	0.32	0.16	0.10
46.2	4.3	3.86	4.45	4.42	0.59	0.56	0.35	0.31
51.2	3.6	4.14	4.69	4.65	0.56	0.51	0.31	0.26
53.8	3.8	4.28	4.82	4.77	0.54	0.49	0.29	0.24

56.2	4.6	4.40	4.93	4.87	0.53	0.47	0.28	0.22
57.1	4.7	4.45	4.97	4.91	0.52	0.46	0.27	0.21
59.4	4.8	4.57	5.07	5.01	0.50	0.44	0.25	0.20
63.1	4.4	4.75	5.23	5.16	0.48	0.41	0.23	0.17
63.5	4.7	4.78	5.25	5.18	0.47	0.40	0.22	0.16
8.9	1.1	1.29	1.86	1.94	0.57	0.65	0.33	0.42
17.1	2.0	1.99	2.64	2.69	0.65	0.70	0.42	0.49
21.4	3.2	2.31	2.98	3.01	0.66	0.69	0.44	0.48
26.0	3.4	2.63	3.30	3.31	0.66	0.68	0.44	0.46
33.0	4.0	3.09	3.74	3.73	0.65	0.65	0.42	0.42
42.9	5.1	3.67	4.28	4.26	0.61	0.58	0.37	0.34
43.6	5.4	3.71	4.32	4.29	0.60	0.58	0.36	0.33
44.3	6.3	3.76	4.36	4.33	0.60	0.57	0.36	0.33
55.0	5.9	4.34	4.87	4.82	0.53	0.48	0.29	0.23
66.4	3.7	4.92	5.37	5.30	0.45	0.38	0.20	0.14
69.3	6.6	5.06	5.49	5.41	0.43	0.35	0.18	0.12
62.1	7.9	4.71	5.19	5.12	0.48	0.42	0.23	0.17
64.3	8.0	4.81	5.28	5.21	0.47	0.40	0.22	0.16
15.0	1.8	1.82	2.46	2.52	0.64	0.69	0.41	0.48
25.0	2.4	2.56	3.23	3.25	0.67	0.69	0.44	0.47
31.4	4.2	2.99	3.64	3.64	0.65	0.66	0.43	0.43
37.1	5.0	3.34	3.97	3.96	0.63	0.62	0.40	0.39
50.0	3.7	4.07	4.64	4.60	0.57	0.52	0.32	0.28
47.0	3.4	3.91	4.49	4.46	0.58	0.55	0.34	0.30
79.5	4.7	5.55	5.89	5.80	0.35	0.25	0.12	0.06
83.0	4.0	5.71	6.03	5.92	0.32	0.21	0.10	0.05
84.0	4.8	5.75	6.06	5.96	0.31	0.20	0.10	0.04
28.5	3.7	2.80	3.46	3.47	0.66	0.67	0.44	0.45
36.0	3.9	3.27	3.91	3.90	0.64	0.63	0.41	0.40
40.6	4.4	3.54	4.16	4.14	0.62	0.60	0.38	0.36

45.6	4.6	3.83	4.42	4.39	0.59	0.56	0.35	0.31
49.4	4.7	4.04	4.61	4.57	0.57	0.53	0.33	0.28
53.8	5.1	4.28	4.82	4.77	0.54	0.49	0.29	0.24
56.3	5.5	4.41	4.93	4.88	0.53	0.47	0.28	0.22
29.5	3.6	2.86	3.52	3.53	0.66	0.67	0.43	0.44
40.1	4.2	3.51	4.14	4.12	0.62	0.60	0.39	0.36
47.8	4.7	3.95	4.53	4.49	0.58	0.54	0.34	0.29
47.9	4.8	3.96	4.54	4.50	0.58	0.54	0.34	0.29
51.8	5.0	4.17	4.72	4.68	0.56	0.51	0.31	0.26
57.9	5.9	4.49	5.00	4.95	0.51	0.46	0.26	0.21
61.8	5.5	4.69	5.18	5.11	0.49	0.42	0.24	0.18
20.9	2.6	2.28	2.94	2.97	0.66	0.70	0.44	0.48
29.5	3.0	2.86	3.52	3.53	0.66	0.67	0.43	0.44
34.6	3.5	3.19	3.83	3.82	0.64	0.64	0.42	0.41
37.5	3.9	3.36	3.99	3.98	0.63	0.62	0.40	0.38
40.5	4.0	3.54	4.16	4.14	0.62	0.60	0.38	0.36
48.3	4.5	3.98	4.56	4.52	0.58	0.54	0.33	0.29
49.2	4.6	4.03	4.60	4.56	0.57	0.53	0.33	0.28
19.8	2.9	2.20	2.86	2.89	0.66	0.70	0.44	0.49
28.9	3.2	2.83	3.49	3.49	0.66	0.67	0.44	0.45
36.0	3.6	3.27	3.91	3.90	0.64	0.63	0.41	0.40
40.8	3.8	3.56	4.17	4.15	0.62	0.60	0.38	0.36
42.4	4.0	3.65	4.26	4.23	0.61	0.58	0.37	0.34
45.2	4.2	3.81	4.40	4.37	0.60	0.56	0.35	0.32
43.7	4.5	3.72	4.33	4.30	0.60	0.57	0.36	0.33
32.6	3.7	3.06	3.71	3.71	0.65	0.65	0.42	0.42
43.5	3.9	3.71	4.31	4.29	0.60	0.58	0.37	0.33
48.2	4.2	3.97	4.55	4.51	0.58	0.54	0.33	0.29
60.6	4.4	4.63	5.12	5.06	0.50	0.43	0.25	0.19
60.0	5.3	4.60	5.10	5.03	0.50	0.44	0.25	0.19

62.1	5.4	4.70	5.19	5.12	0.48	0.42	0.23	0.17
61.8	5.5	4.69	5.18	5.11	0.49	0.42	0.24	0.18
48.1	4.1	3.97	4.55	4.51	0.58	0.54	0.33	0.29
58.9	4.3	4.54	5.05	4.99	0.51	0.45	0.26	0.20
39.9	3.9	3.51	4.13	4.11	0.62	0.60	0.39	0.36
53.4	4.0	4.25	4.80	4.75	0.55	0.50	0.30	0.25
33.1	2.9	3.09	3.74	3.74	0.65	0.65	0.42	0.42
45.3	3.8	3.81	4.40	4.37	0.59	0.56	0.35	0.32
32.4	2.5	3.05	3.70	3.70	0.65	0.65	0.42	0.42
47.0	3.8	3.91	4.49	4.46	0.58	0.55	0.34	0.30
43.0	3.9	3.68	4.29	4.26	0.61	0.58	0.37	0.34
56.3	4.3	4.41	4.93	4.88	0.53	0.47	0.28	0.22
51.0	4.0	4.13	4.69	4.64	0.56	0.52	0.31	0.27
54.8	4.1	4.33	4.86	4.81	0.54	0.48	0.29	0.23
	Mean $f_{st\ ACI\ 36}$	**3.79**		**Error Range max**	**0.67**	**0.70**	**34.17**	**31.30**
				min	**0.31**	**0.20**		

SD for eq. 1= sqrt(34.17/n-1)= sqrt(34.17/101) = 0.58

SD for eq. 1= sqrt(31.3/n-1)= sqrt(31.3/ 101) = 0.56

SD= Standard Deviation

Percentage Error with respect to proposed **eq. 1 (Eurocode 2)**= (0.44/3.79)*100= **11.6 %**

Percentage Error with respect to proposed **eq. 2 (Eurocode 2)**= (0.41/3.79)*100= **10.8 %**

Table 6.4 Calculation of Percentage Error for the Modulus of Elasticity

f_c' (MPa)	E (MPa)	$E_{ACI\ 318}$	$E_{eq.\ 1}$	$E_{eq.\ 2}$	$E_{eq.1} - E_{ACI\ 318}$	$E_{eq.2} - E_{ACI\ 318}$	$(E_{eq.1} - E_{ACI\ 318})^2$	$(E_{eq.2} - E_{ACI\ 318})^2$
84	41100	46337	38399	40949	-7937	-5388	63001590	29030400
31.2	27100	28240	27101	24956	-1139	-3284	1297535	10782720
33.8	25000	29393	27821	25975	-1572	-3418	2472048	11681280
35	24000	29910	28144	26432	-1767	-3478	3120781	12096000
37	28000	30753	28670	27177	-2083	-3576	4339491	12787200
45	29000	33915	30644	29971	-3271	-3944	10699510	15552000
45	31000	33915	30644	29971	-3271	-3944	10699510	15552000
45.8	28000	34215	30831	30237	-3384	-3979	11449837	15828480
45.8	29500	34215	30831	30237	-3384	-3979	11449837	15828480
47	28000	34660	31109	30630	-3551	-4030	12609995	16243200
50	26700	35750	31789	31593	-3960	-4157	15683008	17280000
51.2	27100	36176	32056	31969	-4120	-4207	16977519	17694720
51.2	30000	36176	32056	31969	-4120	-4207	16977519	17694720
55.6	26700	37698	33006	33315	-4692	-4384	22017539	19215360
61	31600	39487	34123	34895	-5364	-4591	28773190	21081600
62.5	35000	39969	34424	35322	-5545	-4648	30750764	21600000
61.7	38900	39713	34264	35095	-5449	-4618	29690867	21323520
68.5	35600	41844	35594	36978	-6250	-4866	39056702	23673600
69	37600	41996	35689	37113	-6307	-4883	39775733	23846400
76.7	35000	44277	37114	39129	-7164	-5149	51319975	26507520
85	35000	46612	38571	41192	-8041	-5420	64652210	29376000
36.7	29500	30628	28592	27067	-2036	-3561	4146168	12683520
65.5	33300	40917	35016	36159	-5901	-4758	34827347	22636800

69.1	34000	42027	35708	37140	-6318	-4887	39920012	23880960
82.7	33200	45977	38175	40631	-7802	-5346	60873278	28581120
82.3	35800	45865	38105	40532	-7760	-5333	60222457	28442880
87.6	35300	47319	39013	41817	-8306	-5502	68997032	30274560
39.1	30000	31614	29207	27938	-2406	-3676	5791077	13512960
49.7	28700	35642	31722	31498	-3920	-4144	15365052	17176320
51	29400	36105	32011	31907	-4094	-4198	16759278	17625600
52	29700	36458	32231	32218	-4226	-4239	17860242	17971200
53.8	29900	37083	32622	32771	-4461	-4312	19901961	18593280
56	33500	37834	33091	33434	-4743	-4399	22497334	19353600
59.4	32600	38965	33797	34434	-5168	-4531	26710636	20528640
63.3	33500	40224	34583	35547	-5641	-4677	31822309	21876480
13.9	13900	18849	21238	16657	2389	-2192	5705464	4803840
13.9	16700	18849	21238	16657	2389	-2192	5705464	4803840
21.8	18400	23606	24207	20861	602	-2745	362219	7534080
21.8	21000	23606	24207	20861	602	-2745	362219	7534080
25.5	25300	25530	25409	22562	-121	-2969	14691	8812800
27.3	25300	26416	25962	23344	-454	-3072	206053	9434880
25.5	28400	25530	25409	22562	-121	-2969	14691	8812800
28.5	29700	26990	26321	23852	-670	-3138	448475	9849600
31.8	27900	28510	27269	25195	-1241	-3315	1539123	10990080
33	22600	29043	27602	25666	-1441	-3377	2075963	11404800
33	22900	29043	27602	25666	-1441	-3377	2075963	11404800
41.2	27400	32451	29730	28678	-2721	-3773	7405010	14238720
43.6	26800	33383	30312	29501	-3071	-3882	9432631	15068160
43	33900	33153	30168	29298	-2985	-3855	8908257	14860800
48.2	28600	35100	31384	31019	-3716	-4081	13810349	16657920
48.2	35200	35100	31384	31019	-3716	-4081	13810349	16657920
49.7	32200	35642	31722	31498	-3920	-4144	15365052	17176320
51.2	26100	36176	32056	31969	-4120	-4207	16977519	17694720
52	27000	36458	32231	32218	-4226	-4239	17860242	17971200

52.7	31900	36702	32384	32434	-4318	-4268	18645228	18213120
52.7	34900	36702	32384	32434	-4318	-4268	18645228	18213120
60	29600	39162	33920	34608	-5242	-4554	27478309	20736000
62.1	31600	39841	34344	35208	-5497	-4633	30219345	21461760
67.6	37400	41568	35422	36734	-6146	-4833	37772466	23362560
67.6	38400	41568	35422	36734	-6146	-4833	37772466	23362560
72.4	31900	43018	36328	38016	-6691	-5002	44767052	25021440
34.6	24700	29739	28037	26281	-1702	-3458	2897426	11957760
37.3	28000	30877	28747	27287	-2130	-3590	4536411	12890880
46.7	28000	34550	31040	30532	-3509	-4017	12316127	16139520
47.3	28000	34771	31178	30728	-3593	-4043	12906375	16346880
50	29300	35750	31789	31593	-3960	-4157	15683008	17280000
59.3	26000	38933	33777	34405	-5156	-4527	26583376	20494080
60.7	26700	39389	34062	34809	-5328	-4580	28382723	20977920
63.3	27300	40224	34583	35547	-5641	-4677	31822309	21876480
62.7	33300	40033	34464	35378	-5569	-4655	31017567	21669120
65.7	27300	40980	35055	36215	-5925	-4765	35104667	22705920
66.7	30000	41290	35249	36489	-6042	-4801	36501337	23051520
66.7	37000	41290	35249	36489	-6042	-4801	36501337	23051520
76	30000	44075	36987	38950	-7088	-5125	50235782	26265600
78.7	31700	44851	37472	39636	-7379	-5215	54453514	27198720
83.3	31300	46143	38279	40778	-7865	-5365	61853094	28788480
35	25000	29910	28144	26432	-1767	-3478	3120781	12096000
39.3	28300	31694	29258	28009	-2437	-3685	5937996	13582080
32.7	34300	28911	27520	25549	-1391	-3362	1935200	11301120
50	28700	35750	31789	31593	-3960	-4157	15683008	17280000
88	35780	47427	39080	41912	-8347	-5515	69672131	30412800
90	48380	47963	39415	42386	-8548	-5577	73073536	31104000
49.4	33824	35534	31655	31402	-3879	-4132	15049407	17072640
51.8	33647	36387	32188	32156	-4200	-4231	17638108	17902080

40.5	32210	32175	29557	28433	-2617	-3741	6849784	13996800
42.4	33336	32921	30023	29093	-2897	-3828	8395364	14653440
60	31271	39162	33920	34608	-5242	-4554	27478309	20736000
40.6	30192	32214	29582	28468	-2632	-3746	6928066	14031360
47.8	33299	34954	31293	30890	-3661	-4064	13405859	16519680
34.6	26124	29739	28037	26281	-1702	-3458	2897426	11957760
36	27303	30334	28409	26807	-1926	-3527	3709315	12441600
48.2	20893	35100	31384	31019	-3716	-4081	13810349	16657920
28.5	32723	26990	26321	23852	-670	-3138	448475	9849600
29.5	26916	27460	26614	24267	-846	-3193	715766	10195200
20.9	20565	23113	23900	20426	787	-2688	619092	7223040
19.8	22848	22497	23515	19881	1018	-2616	1037146	6842880
32.6	18332	28866	27492	25510	-1374	-3357	1889238	11266560
36	32634	30334	28409	26807	-1926	-3527	3709315	12441600
40.1	29871	32015	29458	28293	-2557	-3723	6540160	13858560
29.5	27193	27460	26614	24267	-846	-3193	715766	10195200
28.9	25407	27179	26438	24019	-741	-3160	548469	9987840
43.5	22572	33345	30288	29468	-3057	-3877	9344448	15033600
45.6	31547	34140	30785	30171	-3356	-3970	11260495	15759360
47.9	32802	34991	31316	30922	-3675	-4069	13506575	16554240
37.5	30910	30960	28799	27360	-2161	-3600	4669666	12960000
40.8	30395	32294	29632	28538	-2662	-3755	7085670	14100480
60.6	26146	39357	34042	34781	-5315	-4576	28252946	20943360
53.8	34716	37083	32622	32771	-4461	-4312	19901961	18593280
57.9	36077	38470	33488	33997	-4982	-4473	24822632	20010240
48.3	32649	35137	31407	31051	-3730	-4086	13912145	16692480
45.2	33636	33990	30691	30038	-3299	-3952	10885324	15621120
62.1	31018	39841	34344	35208	-5497	-4633	30219345	21461760
56.3	35540	37935	33154	33524	-4781	-4411	22859435	19457280
61.8	40998	39745	34284	35123	-5461	-4621	29822709	21358080

49.2	30856	35462	31610	31339	-3852	-4124	14840270	17003520
43.7	34888	33422	30336	29535	-3086	-3886	9521126	15102720
61.8	29489	39745	34284	35123	-5461	-4621	29822709	21358080
58.93	50280	38812	33701	34299	-5110	-4513	26117089	20366990
53.37	40288	36933	32528	32639	-4405	-4295	19402135	18443094
45.26	40728	34012	30704	30057	-3307	-3955	10938684	15640888
47.04	40147	34676	31119	30644	-3557	-4032	12652264	16258040
56.3	48117	37935	33154	33524	-4781	-4411	22859435	19457280
54.8	48328	37426	32836	33074	-4590	-4352	21068398	18938880
48.10	39061	35064	31361	30987	-3703	-4077	13710126	16623805
39.94	41723	31952	29418	28237	-2534	-3715	6418912	13803727
33.07	37517	29073	27621	25692	-1452	-3381	2108113	11428047
32.36	36010	28762	27427	25417	-1335	-3344	1782687	11184998
43.03	36087	33164	30175	29308	-2989	-3856	8934370	14871234
50.99	48787	36101	32009	31903	-4092	-4198	16744848	17621019
	Mean	**35137**	**Error Range**	**Max**	**2389**	**-2192**	**2435956809**	**2214842802**
				Min	**-8548**	**-5577**		

SD with respect to proposed eq. 1= sqrt(2435956809/n-1)= sqrt(2435956809/129) = 4345
SD with respect to proposed eq. 2= sqrt(2214842802/n-1)= sqrt(2214842802/129) = 4143
SD= Standard deviation

Percentage error with respect to eq. 1= (4345/35137)*100 = **12.4**
Percentage error with respect to eq. 2= (4143/35137)*100 = **8.5**

f_c' (MPa)	E (MPa)	$E_{ACI\ 363}$	$E_{eq.\ 1}$	$E_{eq.\ 2}$	$E_{eq\cdot 1} - E_{ACI\ 363}$	$E_{eq.2} - E_{ACI\ 363}$	$(E_{eq.1} - E_{ACI\ 363})^2$	$(E_{eq.2} - E_{ACI\ 363})^2$
84	41100	39276	38399	40949	-876	1673	767895	2799168
31.2	27100	26772	27101	24956	329	-1816	108164	3296867
33.8	25000	27569	27821	25975	252	-1593	63550	2538999
35	24000	27926	28144	26432	218	-1494	47370	2231174
37	28000	28508	28670	27177	162	-1331	26090	1772227
45	29000	30693	30644	29971	-49	-722	2407	520778
45	31000	30693	30644	29971	-49	-722	2407	520778
45.8	28000	30900	30831	30237	-69	-664	4767	440613
45.8	29500	30900	30831	30237	-69	-664	4767	440613
47	28000	31208	31109	30630	-99	-578	9742	334007
50	26700	31961	31789	31593	-171	-368	29320	135406
51.2	27100	32255	32056	31969	-200	-286	39853	81660
51.2	30000	32255	32056	31969	-200	-286	39853	81660
55.6	26700	33307	33006	33315	-301	8	90612	60
61	31600	34543	34123	34895	-420	352	176492	124246
62.5	35000	34876	34424	35322	-452	446	204525	198481
61.7	38900	34699	34264	35095	-435	396	189359	156846
68.5	35600	36171	35594	36978	-577	807	333026	651088
69	37600	36277	35689	37113	-587	836	344845	699377
76.7	35000	37853	37114	39129	-739	1276	546360	1628404
85	35000	39466	38571	41192	-895	1726	800327	2979376
36.7	29500	28422	28592	27067	170	-1355	28847	1836932
65.5	33300	35531	35016	36159	-515	628	265616	394731

69.1	34000	36298	35708	37140	-589	842	347229	709221
82.7	33200	39027	38175	40631	-852	1604	726457	2571781
82.3	35800	38950	38105	40532	-845	1582	713874	2503406
87.6	35300	39954	39013	41817	-942	1862	886851	3468851
39.1	30000	29103	29207	27938	104	-1165	10859	1357983
49.7	28700	31886	31722	31498	-164	-389	26922	151074
51	29400	32206	32011	31907	-195	-299	37994	89639
52	29700	32450	32231	32218	-218	-231	47690	53587
53.8	29900	32882	32622	32771	-260	-111	67623	12293
56	33500	33401	33091	33434	-310	34	96120	1144
59.4	32600	34183	33797	34434	-385	252	148528	63497
63.3	33500	35052	34583	35547	-469	495	220173	244699
13.9	13900	20284	21238	16657	954	-3626	910625	13148679
13.9	16700	20284	21238	16657	954	-3626	910625	13148679
21.8	18400	23570	24207	20861	638	-2709	406423	7339553
21.8	21000	23570	24207	20861	638	-2709	406423	7339553
25.5	25300	24900	25409	22562	509	-2338	259420	5466700
27.3	25300	25512	25962	23344	450	-2167	202813	4697392
25.5	28400	24900	25409	22562	509	-2338	259420	5466700
28.5	29700	25909	26321	23852	412	-2057	169826	4229706
31.8	27900	26959	27269	25195	311	-1764	96650	3110386
33	22600	27327	27602	25666	275	-1661	75842	2758538
33	22900	27327	27602	25666	275	-1661	75842	2758538
41.2	27400	29682	29730	28678	48	-1004	2343	1007613
43.6	26800	30326	30312	29501	-14	-824	186	679240
43	33900	30166	30168	29298	2	-869	3	754460
48.2	28600	31512	31384	31019	-128	-493	16380	243215
48.2	35200	31512	31384	31019	-128	-493	16380	243215
49.7	32200	31886	31722	31498	-164	-389	26922	151074
51.2	26100	32255	32056	31969	-200	-286	39853	81660
52	27000	32450	32231	32218	-218	-231	47690	53587

52.7	31900	32619	32384	32434	-235	-184	55069	33981
52.7	34900	32619	32384	32434	-235	-184	55069	33981
60	29600	34318	33920	34608	-398	290	158775	84002
62.1	31600	34788	34344	35208	-444	421	196882	177085
67.6	37400	35981	35422	36734	-559	754	312164	568110
67.6	38400	35981	35422	36734	-559	754	312164	568110
72.4	31900	36983	36328	38016	-655	1033	429435	1067837
34.6	24700	27808	28037	26281	229	-1527	52469	2330984
37.3	28000	28594	28747	27287	153	-1307	23482	1708938
46.7	28000	31132	31040	30532	-91	-599	8340	359152
47.3	28000	31284	31178	30728	-106	-557	11248	309850
50	29300	31961	31789	31593	-171	-368	29320	135406
59.3	26000	34160	33777	34405	-383	246	146848	60349
60.7	26700	34476	34062	34809	-414	334	171094	111384
63.3	27300	35052	34583	35547	-469	495	220173	244699
62.7	33300	34920	34464	35378	-457	458	208393	209609
65.7	27300	35574	35055	36215	-520	640	269918	409997
66.7	30000	35789	35249	36489	-540	700	291845	490289
66.7	37000	35789	35249	36489	-540	700	291845	490289
76	30000	37713	36987	38950	-726	1237	526604	1530288
78.7	31700	38249	37472	39636	-777	1387	604287	1922838
83.3	31300	39142	38279	40778	-863	1636	745479	2675752
35	25000	27926	28144	26432	218	-1494	47370	2231174
39.3	28300	29159	29258	28009	99	-1150	9767	1321943
32.7	34300	27235	27520	25549	284	-1686	80773	2843922
50	28700	31961	31789	31593	-171	-368	29320	135406
88	35780	40029	39080	41912	-949	1883	900438	3546778
90	48380	40399	39415	42386	-985	1987	969445	3946603
49.4	33824	31812	31655	31402	-157	-409	24619	167651
51.8	33647	32401	32188	32156	-214	-245	45671	60033

40.5	32210	29491	29557	28433	67	-1057	4468	1117616
42.4	33336	30006	30023	29093	17	-913	295	834197
60	31271	34318	33920	34608	-398	290	158775	84002
40.6	30192	29518	29582	28468	64	-1050	4122	1101494
47.8	33299	31411	31293	30890	-118	-521	13987	271759
34.6	26124	27808	28037	26281	229	-1527	52469	2330984
36	27303	28219	28409	26807	189	-1412	35869	1993509
48.2	20893	31512	31384	31019	-128	-493	16380	243215
28.5	32723	25909	26321	23852	412	-2057	169826	4229706
29.5	26916	26233	26614	24267	381	-1966	145037	3865649
20.9	20565	23230	23900	20426	670	-2804	449310	7862918
19.8	22848	22804	23515	19881	711	-2923	506033	8543543
32.6	18332	27205	27492	25510	287	-1695	82456	2872760
36	32634	28219	28409	26807	189	-1412	35869	1993509
40.1	29871	29380	29458	28293	77	-1088	5999	1183484
29.5	27193	26233	26614	24267	381	-1966	145037	3865649
28.9	25407	26039	26438	24019	400	-2020	159624	4081360
43.5	22572	30299	30288	29468	-11	-832	123	691467
45.6	31547	30849	30785	30171	-64	-678	4104	459962
47.9	32802	31436	31316	30922	-121	-514	14568	264463
37.5	30910	28651	28799	27360	148	-1291	21825	1667523
40.8	30395	29573	29632	28538	59	-1034	3472	1069658
60.6	26146	34453	34042	34781	-411	327	169310	107247
53.8	34716	32882	32622	32771	-260	-111	67623	12293
57.9	36077	33840	33488	33997	-352	157	124199	24502
48.3	32649	31537	31407	31051	-130	-486	17006	236344
45.2	33636	30745	30691	30038	-54	-707	2924	500041
62.1	31018	34788	34344	35208	-444	421	196882	177085
56.3	35540	33471	33154	33524	-317	53	100345	2845
61.8	40998	34721	34284	35123	-437	402	191229	161797

49.2	30856	31762	31610	31339	-152	-423	23137	179212
43.7	34888	30352	30336	29535	-16	-817	262	667136
61.8	29489	34721	34284	35123	-437	402	191229	161797
58.93	50280	34076	33701	34299	-375	222	140742	49440
53.37	40288	32778	32528	32639	-250	-140	62525	19546
45.26	40728	30760	30704	30057	-56	-703	3081	494196
47.04	40147	31219	31119	30644	-100	-575	9952	330489
56.3	48117	33471	33154	33524	-317	53	100345	2845
54.8	48328	33119	32836	33074	-283	-45	80027	2002
48.10	39061	31487	31361	30987	-126	-500	15773	250101
39.94	41723	29337	29418	28237	82	-1100	6671	1210227
33.07	37517	27347	27621	25692	273	-1655	74761	2739625
32.36	36010	27133	27427	25417	294	-1715	86508	2941575
43.03	36087	30174	30175	29308	1	-866	1	750568
50.99	48787	32203	32009	31903	-195	-300	37873	90181
	Mean	**31538**	**Error Range**	**Max**	**954**	**1987**	**22340541**	**199285113**
				Min	**-985**	**-3626**		

SD with respect to proposed eq. 1= sqrt(22340541/n-1)= sqrt(22340541/129) = 416

SD with respect to proposed eq. 2= sqrt(199285113/n-1)= sqrt(199285113/129) = 1243

SD= Standard deviation

Percentage error with respect to eq. 1= (416/31538)*100 = **1.3**

Percentage error with respect to eq. 2= (1243/31538)*100 = **3.9**

f_c' (MPa)	E (MPa)	$E_{Eurocode\ 2}$	$E_{eq.\ 1}$	$E_{eq.\ 2}$	$E_{eq.1} - E_{Eurocode\ 2}$	$E_{eq.2} - E_{Eurocode\ 2}$	$(E_{eq.1} - E_{Eurocode\ 2})^2$	$(E_{eq.2} - E_{Eurocode\ 2})^2$
84	41100	43705	38399	40949	-5306	-2756	28150584	7597437
31.2	27100	31416	27101	24956	-4316	-6460	18624803	41734929
33.8	25000	32266	27821	25975	-4445	-6291	19759888	39573202
35	24000	32643	28144	26432	-4500	-6211	20247329	38577270
37	28000	33254	28670	27177	-4584	-6077	21011821	36925555
45	29000	35496	30644	29971	-4852	-5524	23539457	30518328
45	31000	35496	30644	29971	-4852	-5524	23539457	30518328
45.8	28000	35705	30831	30237	-4873	-5468	23750712	29901339
45.8	29500	35705	30831	30237	-4873	-5468	23750712	29901339
47	28000	36014	31109	30630	-4905	-5384	24054887	28985389
50	26700	36764	31789	31593	-4975	-5172	24751938	26748303
51.2	27100	37056	32056	31969	-5001	-5087	25006757	25875600
51.2	30000	37056	32056	31969	-5001	-5087	25006757	25875600
55.6	26700	38089	33006	33315	-5083	-4774	25833363	22790130
61	31600	39284	34123	34895	-5161	-4389	26639664	19261287
62.5	35000	39603	34424	35322	-5179	-4282	26827092	18333216
61.7	38900	39434	34264	35095	-5170	-4339	26728997	18825328
68.5	35600	40832	35594	36978	-5238	-3854	27435709	14852754
69	37600	40931	35689	37113	-5242	-3818	27476949	14579590
76.7	35000	42400	37114	39129	-5287	-3271	27949558	10702604
85	35000	43878	38571	41192	-5307	-2686	28161803	7214987
36.7	29500	33164	28592	27067	-4572	-6097	20900842	37172466
65.5	33300	40227	35016	36159	-5211	-4068	27158478	16546382

69.1	34000	40951	35708	37140	-5243	-3811	27485032	14525270
82.7	33200	43478	38175	40631	-5304	-2848	28130414	8110020
82.3	35800	43408	38105	40532	-5303	-2876	28122909	8271246
87.6	35300	44321	39013	41817	-5308	-2504	28174183	6268628
39.1	30000	33871	29207	27938	-4664	-5934	21753778	35207925
49.7	28700	36691	31722	31498	-4969	-5193	24686148	26968496
51	29400	37008	32011	31907	-4997	-5101	24965202	26020146
52	29700	37248	32231	32218	-5017	-5030	25169392	25301080
53.8	29900	37673	32622	32771	-5051	-4902	25514912	24030192
56	33500	38180	33091	33434	-5089	-4745	25900594	22518819
59.4	32600	38937	33797	34434	-5140	-4503	26422852	20276443
63.3	33500	39772	34583	35547	-5189	-4225	26921009	17847662
13.9	13900	23994	21238	16657	-2757	-7337	7598881	53831340
13.9	16700	23994	21238	16657	-2757	-7337	7598881	53831340
21.8	18400	27878	24207	20861	-3670	-7017	13471516	49238721
21.8	21000	27878	24207	20861	-3670	-7017	13471516	49238721
25.5	25300	29373	25409	22562	-3964	-6812	15714692	46397976
27.3	25300	30049	25962	23344	-4087	-6704	16700935	44948609
25.5	28400	29373	25409	22562	-3964	-6812	15714692	46397976
28.5	29700	30483	26321	23852	-4162	-6631	17322901	43967557
31.8	27900	31617	27269	25195	-4347	-6422	18896689	41236269
33	22600	32009	27602	25666	-4407	-6343	19422402	40238271
33	22900	32009	27602	25666	-4407	-6343	19422402	40238271
41.2	27400	34467	29730	28678	-4737	-5789	22437606	33513019
43.6	26800	35124	30312	29501	-4812	-5622	23152864	31609765
43	33900	34962	30168	29298	-4794	-5664	22980402	32081898
48.2	28600	36318	31384	31019	-4934	-5299	24344308	28081297
48.2	35200	36318	31384	31019	-4934	-5299	24344308	28081297
49.7	32200	36691	31722	31498	-4969	-5193	24686148	26968496
51.2	26100	37056	32056	31969	-5001	-5087	25006757	25875600
52	27000	37248	32231	32218	-5017	-5030	25169392	25301080

52.7	31900	37415	32384	32434	-5031	-4980	25307069	24803233
52.7	34900	37415	32384	32434	-5031	-4980	25307069	24803233
60	29600	39068	33920	34608	-5148	-4460	26506247	19892724
62.1	31600	39519	34344	35208	-5175	-4310	26778572	18578454
67.6	37400	40653	35422	36734	-5230	-3918	27357969	15351013
67.6	38400	40653	35422	36734	-5230	-3918	27357969	15351013
72.4	31900	41593	36328	38016	-5265	-3576	27721985	12791297
34.6	24700	32518	28037	26281	-4482	-6238	20087309	38908945
37.3	28000	33343	28747	27287	-4596	-6056	21121528	36678993
46.7	28000	35937	31040	30532	-4897	-5405	23980248	29213282
47.3	28000	36090	31178	30728	-4912	-5363	24128604	28758237
50	29300	36764	31789	31593	-4975	-5172	24751938	26748303
59.3	26000	38916	33777	34405	-5139	-4510	26408705	20340749
60.7	26700	39219	34062	34809	-5158	-4410	26600362	19449653
63.3	27300	39772	34583	35547	-5189	-4225	26921009	17847662
62.7	33300	39646	34464	35378	-5182	-4267	26850959	18211212
65.7	27300	40268	35055	36215	-5213	-4053	27178596	16430565
66.7	30000	40471	35249	36489	-5223	-3982	27275625	15857705
66.7	37000	40471	35249	36489	-5223	-3982	27275625	15857705
76	30000	42271	36987	38950	-5284	-3321	27918406	11029467
78.7	31700	42766	37472	39636	-5294	-3130	28026599	9796851
83.3	31300	43583	38279	40778	-5305	-2806	28140519	7871278
35	25000	32643	28144	26432	-4500	-6211	20247329	38577270
39.3	28300	33929	29258	28009	-4671	-5920	21821346	35045445
32.7	34300	31912	27520	25549	-4392	-6363	19293193	40487779
50	28700	36764	31789	31593	-4975	-5172	24751938	26748303
88	35780	44388	39080	41912	-5308	-2476	28174005	6129169
90	48380	44722	39415	42386	-5307	-2336	28165124	5456300
49.4	33824	36617	31655	31402	-4962	-5214	24619510	27189485
51.8	33647	37200	32188	32156	-5013	-5044	25129267	25444158

40.5	32210	34271	29557	28433	-4713	-5837	22215878	34075155
42.4	33336	34798	30023	29093	-4775	-5706	22803760	32556541
60	31271	39068	33920	34608	-5148	-4460	26506247	19892724
40.6	30192	34299	29582	28468	-4717	-5830	22247928	33994669
47.8	33299	36217	31293	30890	-4924	-5327	24249440	28381317
34.6	26124	32518	28037	26281	-4482	-6238	20087309	38908945
36	27303	32951	28409	26807	-4543	-6144	20636877	37749840
48.2	20893	36318	31384	31019	-4934	-5299	24344308	28081297
28.5	32723	30483	26321	23852	-4162	-6631	17322901	43967557
29.5	26916	30835	26614	24267	-4221	-6568	17820442	43143739
20.9	20565	27489	23900	20426	-3589	-7063	12879071	49887913
19.8	22848	26998	23515	19881	-3483	-7117	12128841	50650867
32.6	18332	31879	27492	25510	-4387	-6370	19249797	40570953
36	32634	32951	28409	26807	-4543	-6144	20636877	37749840
40.1	29871	34158	29458	28293	-4700	-5865	22086417	34397683
29.5	27193	30835	26614	24267	-4221	-6568	17820442	43143739
28.9	25407	30625	26438	24019	-4186	-6606	17524142	43638605
43.5	22572	35097	30288	29468	-4809	-5629	23124407	31688276
45.6	31547	35653	30785	30171	-4868	-5482	23698542	30055117
47.9	32802	36242	31316	30922	-4927	-5320	24273306	28306185
37.5	30910	33403	28799	27360	-4604	-6043	21193967	36514821
40.8	30395	34355	29632	28538	-4724	-5817	22311652	33833876
60.6	26146	39198	34042	34781	-5156	-4417	26587125	19512645
53.8	34716	37673	32622	32771	-5051	-4902	25514912	24030192
57.9	36077	38607	33488	33997	-5119	-4610	26203063	21251563
48.3	32649	36343	31407	31051	-4936	-5292	24367778	28006505
45.2	33636	35548	30691	30038	-4857	-5510	23592918	30363614
62.1	31018	39519	34344	35208	-5175	-4310	26778572	18578454
56.3	35540	38248	33154	33524	-5094	-4724	25950194	22316363
61.8	40998	39455	34284	35123	-5171	-4332	26741490	18763456

49.2	30856	36567	31610	31339	-4957	-5229	24574608	27337251
43.7	34888	35151	30336	29535	-4815	-5615	23181207	31531326
61.8	29489	39455	34284	35123	-5171	-4332	26741490	18763456
58.93	50280	38835	33701	34299	-5134	-4536	26356066	20578090
53.37	40288	37571	32528	32639	-5043	-4933	25434028	24334222
45.26	40728	35563	30704	30057	-4859	-5506	23608127	30319424
47.04	40147	36025	31119	30644	-4906	-5381	24065495	28952829
56.3	48117	38248	33154	33524	-5094	-4724	25950194	22316363
54.8	48328	37905	32836	33074	-5069	-4831	25695081	23337415
48.10	39061	36293	31361	30987	-4932	-5306	24321044	28155211
39.94	41723	34112	29418	28237	-4694	-5876	22034502	34525870
33.07	37517	32031	27621	25692	-4410	-6339	19451172	40182333
32.36	36010	31802	27427	25417	-4376	-6385	19146733	40767244
43.03	36087	34970	30175	29308	-4795	-5662	22989180	32058080
50.99	48787	37005	32009	31903	-4996	-5102	24962435	26029739
	Mean	**36224**	**Error Range**	**Max**	**-2757**	**-2336**	**3021625862**	**3612285578**
				Min	**-5308**	**-7337**		

SD with respect to proposed eq. 1= sqrt(3021625862/n-1)= sqrt(3021625862/129) = 4840

SD with respect to proposed eq. 2= sqrt(3612285578/n-1)= sqrt(3612285578/129) = 5292

SD= Standard deviation

Percentage error with respect to eq. 1= (4840/36224)*100 = **13.4**

Percentage error with respect to eq. 2= (5292/36224)*100 = **14.6**