EXPERIMENTAL EVALUATION OF THE MODULUS OF ELASTICITY OF SELF-CONSOLIDATING CONCRETE

by
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ABSTRACT

Self-consolidating concrete represents one of the most important advances for the concrete industry. Due to the rapid growth of the use of this new concrete technology, it is evident that research focused on its mechanical properties compared with conventional concrete is requested in order to fulfill design requirements and codes. Self-consolidating concrete modulus of elasticity property, using materials commercially available in Puerto Rico, is evaluated in this thesis to determine whether it is actually lower than that of conventional concrete or not. Other properties such as compressive strength, segregation tendency and slump flow were also examined.

Forty self-consolidating concrete mixtures were made under laboratory conditions varying different water-to-cement ratios, coarse-to-total aggregate ratios, and total aggregate volume content. Self-consolidating concrete modulus of elasticity appears to have the same value as that obtained in conventional concrete mixtures, as long as both type of concrete have similar aggregate volume content. Expressions given by ACI code to compute modulus of elasticity continues being acceptable to predict self-consolidating concrete modulus of elasticity.

RESUMEN

La tecnología de concreto autocompactante representa uno de los avances más importantes para la industria del concreto en los últimos años. Debido al rápido crecimiento en el uso de este tipo de concreto, es de vital importancia llevar a cabo investigaciones relevantes a sus propiedades mecánicas para corroborar los requisitos de diseño estipulados en los códigos. En esta tesis se evaluará el modulo de elasticidad de distintas mezclas de concreto autocompactante, usando materiales comercialmente disponibles en Puerto Rico para determinar si es menor al del concreto convencional. Otras propiedades, como resistencia a la compresión y la tendencia a la segregación también serán evaluadas.

Cuarenta mezclas de hormigón autocompactante fueron elaboradas en laboratorio, variando diferentes relaciones agua-cemento, relaciones agregado grueso-agregado total, y el contenido total de agregado en volumen. Los valores obtenidos de módulos de elasticidad tienden a tener los mismos valores que las muestras de hormigón convencional, siempre y cuando ambos tipos de concreto tienen volúmenes de agregados similares. Las expresiones dadas por el código ACI para calcular el módulo de elasticidad del concreto siguen produciendo resultados aceptables para el módulo de elasticidad de concreto autocompactante.

To my parents, Mercedes and Miguel; and my sister Maria Carolina.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL INFORMATION

This chapter explains the motivation for this research, and the proposed objectives to carry it out. Factors affecting self consolidating concrete modulus of elasticity are the main focus for this thesis.

Self consolidating concrete (SCC) refers to a highly flowable, nonsegregating type of concrete that flows due to its own weight through congested reinforcement without needing vibration for compaction. Since its inception in Japan in the late 1980s, it has become a very active research topic, and its development also represents one of the most important advances in concrete technology.

This type of concrete can be advantageous where vibration compaction is difficult because of heavy reinforcement or unfavorably shaped elements. Savings in labor costs can also be achieved since the amount of skilled workers required in the vibration operations is lower. The combination of high fluidity and segregation resistance results in consolidation due only to the concrete’s self weight.

In general, SCC is concrete made with conventional concrete materials, in some cases, with a viscosity-modifying admixture (VMA), and different material proportions.

1.2 MOTIVATION

Concrete is the most used material in the construction industry; therefore studying its mechanical properties and discovering new technologies in order to improve its performance are research topics of interest for the construction industry and design engineers.

Self-consolidating concrete (SCC) represents one of the most outstanding advances in concrete technology in recent decades. SCC is a concrete with the ability to compact itself only by means of its own weight without the requirement of vibration. It is able to fill reinforcement spaces and voids, even in highly reinforced concrete members and it flows without segregation.

The use of SCC offers many benefits to the work environment. These features are manifested by reducing labor, shortening of construction time, eliminating of vibration process and noise hazards. Another advantage is the ability to be cast in heavily reinforced elements and structures with a complicated geometry. The basic components of SCC are practically the same as those used in conventional concrete; however, in order to obtain the characteristics properties of SCC, a higher amount of fine materials and the incorporation of chemical admixtures are needed.

Due to the rapid growth of the use of this new concrete technology, it is evident that research focused on its mechanical properties compared with conventional concrete is necessary in order to fulfill design requirements and codes. Concrete mechanical properties such as modulus of elasticity and compressive strength are constantly used by structural engineers in the design of all civil engineering infrastructures.

There is not much research available to determine how SCC's modulus of elasticity compares with that of conventional concrete. However; as it is known that the modulus of elasticity of concrete depends on the proportion of the Young's modulus of the individual components and their percentages by volume. Thus, it is expected that the modulus of elasticity of concrete increases for high contents of aggregates of high rigidity. Then, a relative small modulus of elasticity might be expected for SCC, because of the high content of ultra fine materials used in some SCC applications, which carries out a corresponding decrease in the coarse aggregate.

Some authors have pointed out the importance of the determination of the elastic modulus. The knowledge of this parameter is very important from a design point of view when the deformations of the different structural elements of a structure have to be calculated. Then, an expected lower modulus of elasticity for SCC is of concern for structural designers since structural deflections, which depend of this parameter and serviceability of structures, might be affected.

Therefore, it is important to determine if the equations given by codes to estimate the modulus of elasticity of conventional concrete are correct and safe for structures built with SCC or if there are mixture proportions or concrete components which could improve the expected lower modulus of elasticity in SCC and make it similar to conventional concrete modulus.

According to ACI 318-05[1] , the modulus of elasticity of concrete shall be permitted to be taken as a function of the unit weight of concrete and the compressive strength as it will be discussed in the literature review. However, the expression given by ACI 318-05[1] to compute the modulus of elasticity is normally used for conventional concrete and its applicability should be checked for self consolidating concrete to know if the same expression is still valid for this kind of concrete.

In Puerto Rico, SCC have begun to be used in the recent years in many applications by the concrete industry; then, the knowledge of the mechanical properties, such as compressive strength and modulus of elasticity using materials commercially available in Puerto Rico is required.

1.3 OBJECTIVES

1.3.1 General Objective:

This research project pretends to study experimentally the modulus of elasticity in self consolidating concrete, and the factors that influence it to find out how it compares with that of conventional concrete.

1.3.2 Specific Objectives:

- Evaluate the effect of various SCC mixture proportions on its modulus of elasticity, and compare it to that of conventional concrete elaborated with materials commercially available in Puerto Rico.
- Determine if the equations given by design codes to compute modulus of elasticity are applicable for SCC.
- Determine if total aggregate content can improve SCC modulus of elasticity in case of getting a lower modulus compared to that of conventional concrete.

- Evaluate fresh properties and compressive strength in SCC with the parameters used to evaluate modulus of elasticity.

1.4 ORGANIZATION OF THIS REPORT

This thesis is divided in six chapters. The introductory chapter contains the objective and motivation of this research as it was already described before. The following chapters contain the following information:

- Chapter 2 contains general SCC background information such as origin, advantages, materials and composition. Description of SCC mechanical properties found in the literature is also described.
- Chapter 3 contains the literature review of the thesis. Previous research regarding this thesis research is described.
- Chapter 4 contains the methodology used to carry out the experimental program proposed. Mixtures proportions, materials, laboratory tests and the mechanism used to determine modulus of elasticity are explained.
- Chapter 5 contains the discussion and analysis of all the data obtained in the experimental program.
- Chapter 6 contains the conclusion made from the analysis results, and recommendations for future work.

CHAPTER 2

BASIC CONCEPTS OF SELF-CONSOLIDATING CONCRETE

2.1 INTRODUCTION

This chapter's objective is to provide relevant background information regarding self consolidating concrete such as origin, advantages, composition and mechanical properties. A brief explanation about concrete modulus of elasticity definition, which is the main focus of this research, is also shown.

2.2 ORIGIN AND DEVELOPMENT OF SCC

Self-consolidating concrete was first developed in the late 1980s to achieve durable concrete structures. The creation of durable concrete structures requires adequate compaction by skilled workers. However, the gradual reduction in the number of skilled workers in Japan's construction has led to a similar reduction in the quality of construction work [2]. Then, one solution to achieve durable concrete structures independent of construction work is the employment of self compacting concrete. The necessity of this type of concrete was proposed by Okamura in 1986 [2].

SCC was later used to facilitate construction operations and reduce construction time. It has been used to cast sections with highly congested reinforcement and areas that present restricted access to placement and consolidation. SCC has recently been used in concrete repair applications in Canada and Switzerland, including the repair of bridge abutments, tunnel sections and retaining walls, where it ensured adequate filling of restricted areas and provided high surface quality [3].

The use of SCC in North America has grown dramatically, especially in the precast industry, where it has been used in regular production at precast plants in the United States since 2000. The majority of such concrete has been used to produce precast elements for parking garage structures and architectural panels [3].

2.3 ADVANTAGES

Workability is perhaps the most beneficial reason for using SCC. Conventional concrete is best used in open reinforcement and spacious formwork and it simply cannot flow through compact reinforcement as well as SCC can. Using conventional concrete in dense reinforcement can lead to several sections of formwork having voids or being not filled with concrete, large aggregate concentration and inconsistent reliability due to variable vibration application skills at the job site [4]. Several other secondary benefits of SCC include elimination of vibration noise, better quality surface finishes, faster placement, and increased construction productivity [4].

SCC is not necessarily more expensive than conventional concrete. Although the amount of cement and admixtures, which are the most expensive concrete constituents, required to produced SCC are higher; savings can be made in other areas besides material cost such as speed of placement, decreasing the construction time and labor cost.

2.4 COMPOSITION OF SELF CONSOLIDATING CONCRETE

The basic components for the mix composition of SCC are the same as in conventional concrete. However, to obtain the requested properties of fresh concrete, the SCC needs a higher proportion of ultrafine materials and the incorporation of chemical admixtures, in particularly an effective superplasticizer [5]. Ordinary and approved filler materials such as fly ash, limestone powder, blast furnace slag, silica fume and quartzite powder can be used in SCC mixture design too.

A comparison of mix proportioning between self consolidating concrete and conventional concrete can be seen in Figure 2-1.

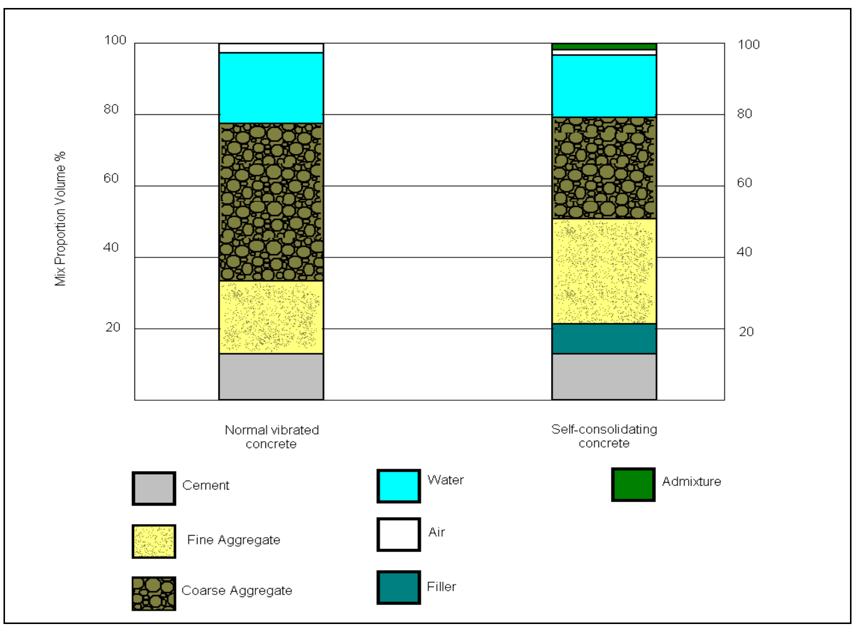

Figure 2-1 Comparison of mix proportioning between self consolidating concrete and conventional concrete,(adapted from Guerra 2006, [6])

For both concrete types, the cement and water content is similar; however a decrease in coarse aggregate content with a corresponding increase in fillers (silica fume, fly ash, furnace slag) and sand is required in SCC in order to ensure high flowability without segregation.

According to Fran De Larrard [7], SCC can be proportioned in several ways; however, in general two main technologies have been developed. In the first technology a superplasticizer is used in combination with a large quantity of fine materials. The second technology is based on the addition of a superplasticizer and a viscosity-modifying agent (VMA).

For mixtures based on the second technology, the yield strength; which is the amount stress required to initiate plastic deformation in a material, is controlled by the superplasticizer, while the plastic viscosity and segregation resistance is controlled by VMA. These viscosity agents can play the same role as that of fine particles in the first technology [7].

SCC rheology is characterized by a low yield stress to ensure high deformability and moderate plastic viscosity to maintain homogeneous suspension of solids, hence reducing interparticle collision, segregation and flow blockage. SCC design procedures are in general based on the two technologies mentioned above; however scientific theories and practical experiences have been proposed for SCC mixture proportioning too [8], [9].

Other authors have also given some guidelines for SCC mixture proportions in function of the aggregate content, as it is illustrated in Table 2-1.

Table 2-1 Mixture proportion guidelines for self consolidating concrete (Aaron W. Saak [8])

AUTHOR	Vc/Vagg	Vf/Vagg	Vb/Vs	(Vb+Vf)/Vagg
Okamura	0.64	0.36	0.22	0.64
Yurgui, et al.	0.54	0.46	0.24	0.78
Ambrose, et al.	0.44	0.56	0.18	0.78

Where: Vc =Volume coarse aggregate, Vagg = Volume of total aggregate, Vf = Volume of fine aggregate, Vb = Volume of binder (solids), Vs= Volume of total solids (aggregate + binder).

ACI committee 237 [3] also reports guidelines for SCC mixture proportions, as seen in Table 2-2. Mortar fraction is defined as the product composed by cement, sand and water, while powder content includes all cementitious materials.

Table 2-2 Mixtures Proportions given by ACI 237 committee

Absolute volume of coarse aggregate	28 to 32%
Paste fraction (calculated on volume)	34 to 40%(total mixture volume)
Mortar Fraction (calculated on volume)	68 to 72%(total mixture volume)
Typical cement(powder content)	650 to 800 lb/yd^3(lower with a VMA)

2.5 MECHANIS FOR ACHIEVING SELF COMPACTABILITY

In this kind of concrete, the method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar during mixing, transport, placement and when the concrete flows through the confined zone of reinforcing bars.

However, as expressed by El-Chabib and Nehdi [10], the required flowability of SCC is difficult to achieve without decreasing the viscosity of the mortar matrix, which reduces the ability of SCC to resist the segregation of large and dense coarse aggregate particles, as a solution to prevent this problem, the ability of SCC to resist segregation can be enhanced using a viscosity –modifying admixture (VMA) [10], which was mentioned previously.

Okamura and Ouchi [2] recommend the following method to achieve self compactability:

- Limited aggregate content
- Low water-powder ratio
- Use of superplasticizer

Research has found that the energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal is effective in avoiding this kind of blockage [2].

Highly viscous paste is also required to avoid the blockage of coarse aggregate when concrete flow through obstacles. When concrete is deformed, paste with a high viscosity also prevents localized increased in internal stress due to the approach of coarse aggregate particles. High deformability can be achieved only by the employment of the superplasticizer, keeping the water-powder ratio to a very low value [2].

2.5.1 Admixtures used in SCC

As admixtures plays an important role in the mechanism for achieving self compactability, a brief description of high range water-reducing admixtures (superplasticizer) and viscosity modifying admixtures is mentioned.

2.5.1.1 Superplasticizer

Also called “high range water-reducing admixtures”, superplasticizers are frequently used to modify a low slump concrete such that it becomes a high slump concrete [4]. Due to the highly workability nature of SCC they are necessary to increase the flow in the mixture.

Some superplasticizers can retard final set by one to almost four hours which is not convenient. The admixture can be combined with an accelerating admixture to counteract the retarding tendencies or even to provide some net acceleration of setting. When water-reducing admixtures are used in concrete mixtures, some increases in compressive strength can be expected. Probably, this reflects the development of a uniform microstructure when the cement is dispersed. The reduction of the water-cement ratio and the creation of a more uniform pore structure means that the permeability of concrete can be reduced by the use of superplasticizers, along with a general improvement on its durability [6].

2.5.1.2 Viscosity Modifying Admixture (VMA)

Viscosity modifying admixtures are used to increase the viscosity of the cementitious material within a concrete mixture while maintaining adequate cohesion. Viscosity-modifying admixtures are added in concrete used in places with extreme congestions due to reinforcement configurations or unusual geometry forms, where fluid but cohesive concrete is required in order to resist bleeding and segregation [4].

2.6 FILLERS USED IN SCC

Although, the only cementitious material that will be used in this research will be Portland cement, a description of the most common fillers or supplementary cementitious materials used in SCC is presented as reference.

ACI committee 237 [3] indicates that combining finely divided powders such as furnace slag, silica fume and fly ash can enhance the filling ability, stability and mechanical properties of SCC mixtures.

2.6.1 Blast furnace slag

Slags are by-products of metallurgical processes, even from production of metals from ore or refinement of impure metals. The slag used in concrete comes from the blast furnace production of iron from ore and not from metals.

Commonly, slag can constitute from 30% to 45% by mass of the cementing material in the mixture. Due to its smooth surface characteristics and fineness, it increases pump ability, workability and reduces bleeding of cast concrete [6].

The use of slag will generally retard the setting time of concrete, which is advantageous in hot weather, because it allows more time to place and finish the concrete, but has a negative effect on the early strength [6].

2.6.2 Fly ash

Fly ash is a fine residue collected or precipitated from the exhaust gases of any industrial furnace. Since cement is the most expensive concrete constituent, the use of fly ash, can have beneficial effect in cost. However, other technical benefits can be achieved by using fly ash.

Fly ash particles are spherical with a smooth surface. Because of this fly ash may enhance the workability and slump flow of SCC. Slump flow values can be increased when the replacement rates are between 20 to 40% of Portland cement [3].

Fly ash is also used in concrete mixes in order to reduce the heat of hydration, permeability, and bleeding. The durability is improved by providing a better sulfate resistance.

The relative density or specific gravity of fly ash generally ranges between 1.9 and 2.8; therefore, for a given mass a larger volume can be incorporated into the SCC design, since its density is lower than that of common cement [3].

The main concern with the excessive use of fly ash is a decrease in the air entraining ability and early strength due the influence of residual carbon from the ash [6].

2.6.3 Silica fume

Silica fume consist of very fine spherical particles of silica produced as a by-product in the manufacture of ferrosilicon alloys [11]. The smoke that results from furnace operation is collected and sold as silica fume.

Silica fume can increase the stability of SCC mixtures. The stability is increased by silica fume ability to reduce the mobility within the concrete matrix. Silica fume is used in amounts of 5% to 10% by mass of the total cementitious material, in applications where high degree of impermeability and high compressive strength are needed in concrete [3].

2.7 FORMWORK ELEMENT CHARACTERISTICS

The highly fluid nature of SCC may lead to higher formwork pressure than conventional concrete, especially when the casting rate is high. According to ACI committee [3], forms or molds assembled to receive SCC come in different sizes and shapes. Formwork should be nonleaking and grout-tight when placing SCC, especially when the mixture has relatively low viscosity. The need to design the formwork is greater than conventional formwork so as to avoid honeycombs and surface defects.

2.8 SEGREGATION RESISTANCE

Segregation is defined as the separation of coarse aggregate particles from the mortar matrix during transporting, placement and setting of fresh concrete. It is mainly due to the difference in material densities and the relatively low viscosity of the mortar fraction considering the highly flowable nature of SCC [10].

One of the most important requirements for any self-flowing material is that the particles remain suspended while the material is at rest. It is equally important that the particles move with the matrix as a cohesive fluid during flow. Consequently, segregation of the aggregates must be avoided under both static (at rest) and dynamic (flowing) conditions [8].

A fresh SCC with poor segregation resistance can lead to a nonuniform distribution of coarse aggregates in the concrete skeleton, contributing to blockage of concrete flow, honeycombing and even nonuniform mechanical properties and durability in the hardened state. The ability of SCC to resist segregation can be enhanced using viscosity-modifying admixtures (VMA), and carefully manipulating the proportions of mixture ingredients.

2.9 MECHANICAL PROPERTIES

As SCC has become a greatly used material for the construction industry, studies related to its mechanical and fresh properties are issues of main interest for structural engineers and the concrete industry.

2.9.1 Compressive and tensile strength

Grube and Rickert [12], found that compressive strength and flexural tensile strength at 28 days for conventional and SCC have approximately the same values. Similar results are indicated by Holschemacher and Klung [5]; however, isolated cases showed that at the same water cement ratios slightly higher compressive strengths were reached for SCC, indicating that at the current time there is insufficient research to result in generalized conclusions with this fact [5].

On the other hand, as it is known all parameters which influence the characteristics of the cement matrix and of the interfacial transition zone are of decisive importance in respect of the tensile load bearing behavior. Hence it appears there is a tendency of higher tensile strength of SCC. The reason for this fact is given by the better microstructure, especially the smaller total porosity and the more even pore size distribution within the interfacial transition zone of SCC [5].

The time development of tensile strength of SCC and normal vibrated concrete are subjected to a similar dependence. Only few publications about SCC refer to a more rapidly increase of the tensile strength opposite to the compressive strength [5].

It has been noted that while SCC almost always develops its full design strength, it may not develop more of that strength as early as conventional concrete, which means that SCC rate of strength development may be slower than conventional concrete [4]. Klaus Holschemacher and Yvette Klug [5] also indicated clarification is still needed to determine whether the hardening process and the ultimate strengths of SCC and conventional concrete differ.

SCC mixtures with fly ash and viscosity modifying admixtures have a lower heat of hydration; thereby meaning the amount of heat buildup in a placement will be lower and hence extending the curing time [4].

2.9.2 Shrinkage and Creep

Regarding shrinkage and creep, Bonen and Shah [13] suggest that the shrinkage of SCC is higher than the conventional concrete, since the paste volume of SCC is greater than that of ordinary concrete. Similar conclusions can be made related to creep since SCC contains less aggregate; however to date, research concerning creep of SCC is limited [13]. Similar statements were indicated by Holschemacher and Klung [5], but it is possible to modify the SCC composition in such way that smaller shrinking deformation can be achieved, similar to those from normal vibrated concrete, and then shrinkage can be reduced by a higher content of coarse aggregate. However, a minimum paste volume must be present, in order to ensure optimal self-compaction without segregation.

2.10 MODULUS OF ELASTICITY

As it was mentioned before, the main topic for this research is to study the factors that affect the modulus of elasticity in SCC. In this chapter, only the definition, determination and code expressions to determine modulus of elasticity will be discussed. Further information regarding factors that have influence in modulus of elasticity in concrete will be discussed in chapter 3.

2.10.1 Definition and determination of modulus of elasticity

The modulus of elasticity is defined as the slope of the stress-strain curve within the proportional limit of the material.

Three ways of defining the modulus of elasticity are illustrated in Figure 2-2. The slope of a line that is tangent to a point on the stress-strain curve, such as A, is called the tangent modulus of elasticity, E_t, at the stress corresponding to point A. The slope of the stress-strain curve at the origin is the initial tangent modulus of elasticity. The secant modulus of elasticity at a given stress is the slope of a line through the origin and through the point on the curve representing that stress. Frequently the secant modulus is defined by using the point corresponding to 0.4 $f_c^{'}$. According to ASTM 469, concrete modulus of elasticity can be computed using the secant method as it will be explained in section 4.5.5.

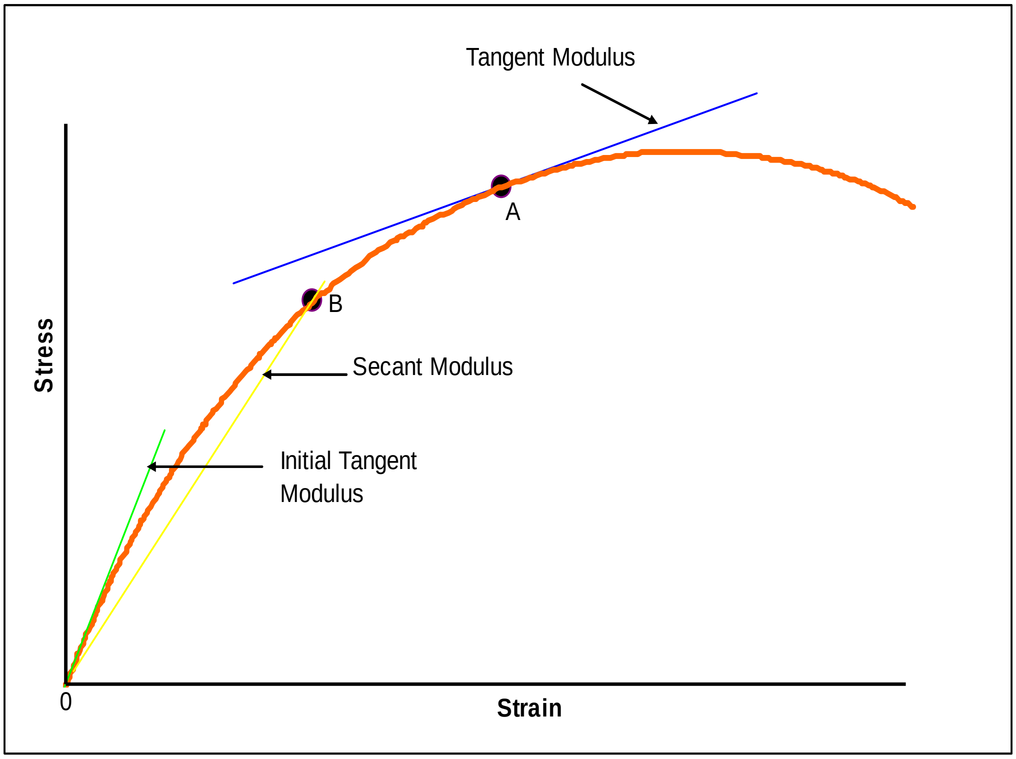

Figure 2-2 Tangent and secant modulus of elasticity (adapted from MacGregor [11])

2.10.2 Calculation of modulus of elasticity according to ACI

Design codes contain expressions for computing the modulus of elasticity as a function of the concrete compressive strength. ACI 318-05 [1] allows computing the concrete modulus of elasticity as:

$$E = w^{1.5} \times 33\sqrt{f_c^{'}} \ (psi) \tag{2-1}$$

where:

$w =$ Unit weight of concrete in lb/ft^3, and

$f_c^{'} =$ Compressive strength of concrete in psi.

Equation 2-1 is valid for w values between 90 and 155 lb/ft^3, and it can overestimate the modulus of elasticity in regions where low-modulus aggregates are prevalent.

For normal-weight concrete with a density of 145 lb/ft^3, ACI 318-05[1] gives the modulus of elasticity as:

$$E = 57000\sqrt{f_c^{'}}\ (psi) \tag{2-2}$$

A study [14] has found that equation 2-1 tends to overestimate the stiffness of high strength concrete. Concretes with 28-day strengths in excess of 6000 psi are referred to as high strength concrete [11],[15]. Another expression is given by ACI committee 363 [15] to compute high-strength concrete modulus of elasticity:

$$E = 40000\sqrt{f_c^{'}} \times \left(\frac{145}{w}\right)^{1.5} + 1.0 \times 10^6\ (psi) \tag{2-3}$$

The equations given previously were proposed for conventional concrete, and regarding to the fact that the type of aggregate is ignored, the scatter of data is very wide [1]. If deflections or vibration characteristics are critical in the design the modulus should be measured for the concrete to be used.

2.11 EVOLUTION OF SCC IN PUERTO RICO

In Puerto Rico SCC started to be formally used in the late 1990's. Figure 2-3 shows the evolution of the material since 2000 to the expected tendency for the year 2010. As seen in Figure 2-3, the precast industry has received a lot of benefits from SCC [16].

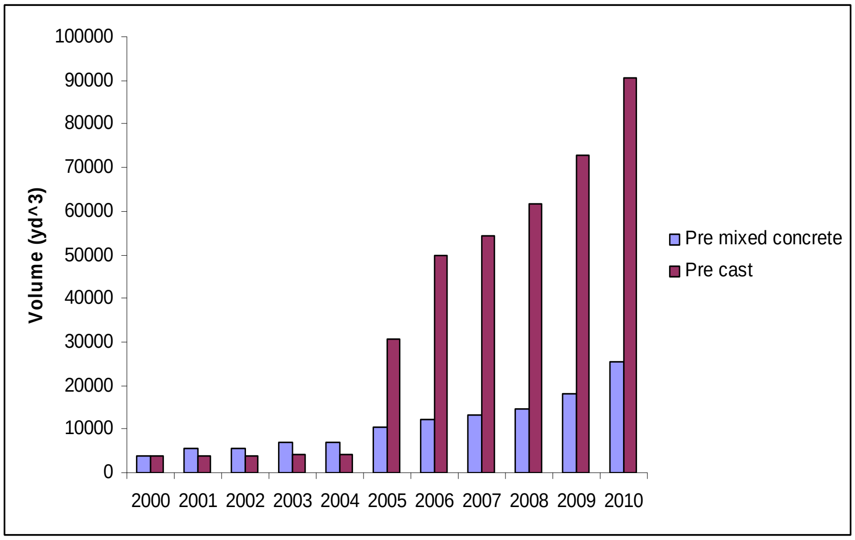

Figure 2-3 Evolution of SCC in Puerto Rico (adapted from Valentín [16])

The interest of the precast industry in SCC may be due to the advantage that SCC offers to precast elements with complicated geometry, and in precast bridge elements where dense prestress and conventional reinforcement is very common.

According to Puerto Rico's Colegio de Ingenieros y Agrimesores [17], approximately four million cubic yards of concrete are annually produced in the island; then SCC covers the 2% of that production for the year 2008 according to Figure 2-3.

CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

This chapter's objective is to provide previous research information regarding modulus of elasticity in self consolidating concrete which is the main topic for this thesis. The chapter also gives information regarding factors affecting modulus of elasticity in conventional concrete.

3.2 FACTORS AFFECTING MODULUS OF ELASTICITY

According to Pauw [18], the modulus of elasticity is mainly affected by concrete strength, age of concrete, properties of aggregates and cement, rate of loading, and type and size of specimen.

Myers [19] indicated that the elastic modulus of concrete is closely related to properties of the cement paste, the stiffness of the selected aggregates, and also the method of determining the modulus.

MacGregor [11], also indicated that the modulus of elasticity of concrete is affected by the modulus of elasticity of the cement paste and by that of the aggregate. Normal weight aggregates have modulus of elasticity ranging from 1.5 to 5 times that of the cement paste. Because of this, the fraction of the total mix that is aggregate also affects the modulus of elasticity. Lightweight aggregates have modulus of elasticity values comparable to that of the paste. Hence, the aggregate fraction has little effect on the modulus for lightweight concrete.

Neville [20] pointed out that for a concrete of a given strength, because normal weight aggregate has a higher elastic modulus of elasticity than hydrated cement paste, a higher aggregate content results in a higher modulus of elasticity of concrete. Figure 3-1 shows the stress-strain relation of aggregate, cement paste and concrete.

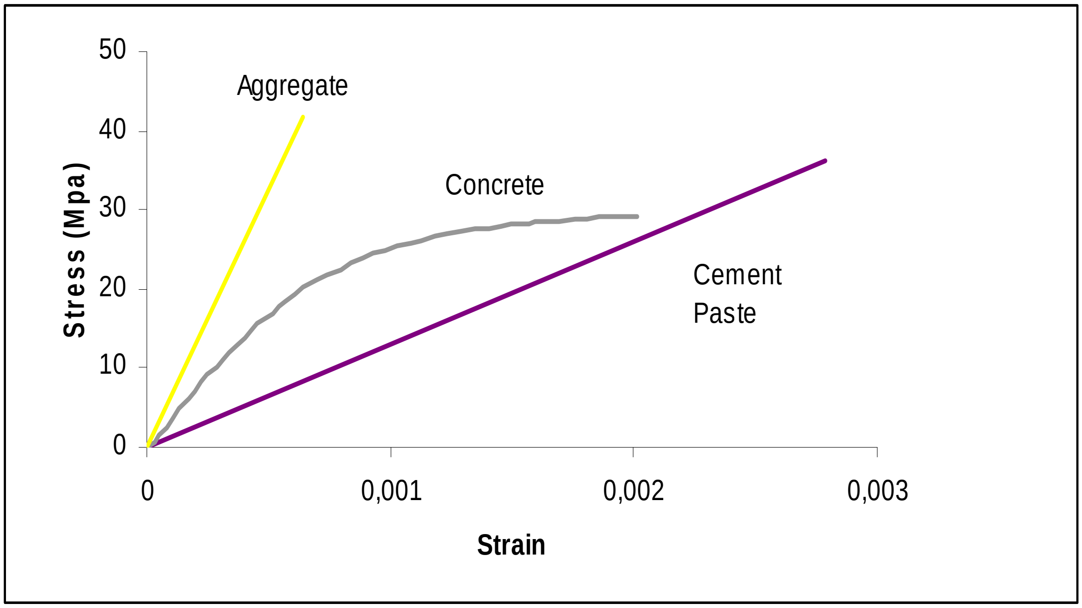

Figure 3-1 Stress-strain relations for aggregate, cement and concrete (adapted from Neville [20])

It has been observed by many investigators that the modulus of elasticity of lightweight aggregate concrete is considerable lower than the values of normal weight concrete of comparable compressive strength, and that the modulus appears to be a function of the concrete weight [18]. In the case of lightweight aggregate, its modulus of elasticity differs little from the modulus of elasticity of hardened cement paste, so that the volumetric content of aggregate in the concrete does not affect significantly the modulus of elasticity of lightweight aggregate concrete [21].

Coarse aggregate type is another important factor affecting concrete modulus of elasticity. Even of the same type of aggregate but from different location has a considerable influence in modulus of elasticity [22]. The effects of expanded clay, sintered fly ash, limestone gravel, glass and steel aggregate was investigated by Zhou [23]. Shideler (1957) made the same conclusion on concrete mixtures using gravel and expanded clay. Figure 3-2 shows the plot of elastic modulus versus compressive strength made with different aggregate types.

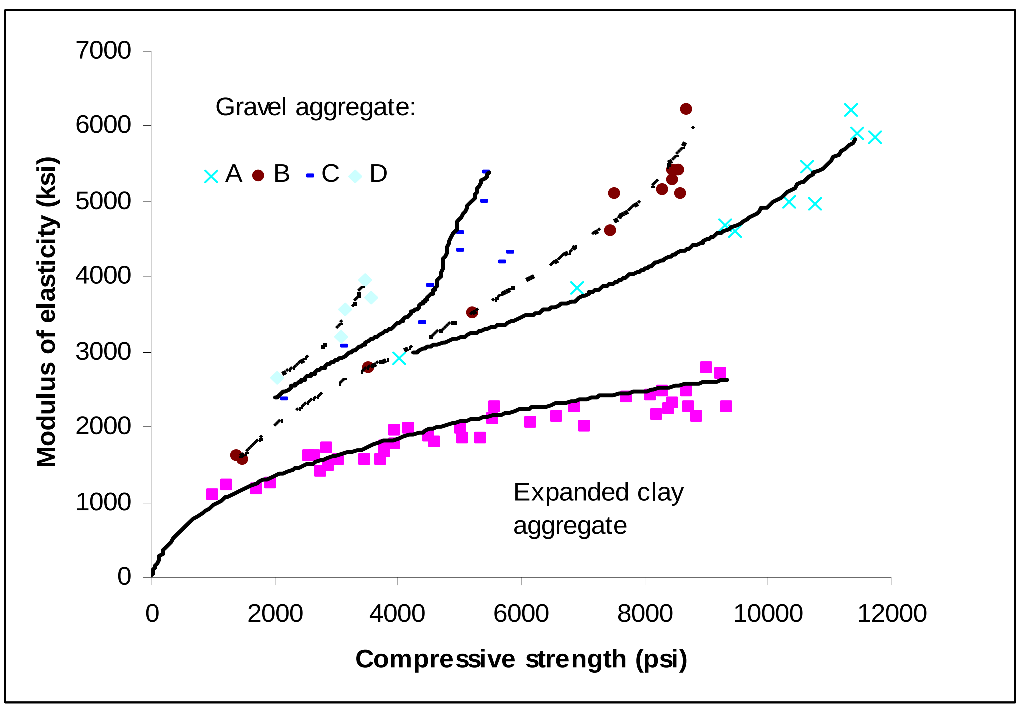

Figure 3-2 Static Modulus of Elasticity of Concrete made with gravel and expanded clay (Shideler, adapted from Mang Tia, et al [22])

3.3 RELATIONSHIP BETWEEN MODULUS OF ELASTICITY, COMPRESSIVE STRENGTH AND CONCRETE WEIGHT

The broad relation between the modulus of elasticity and its compressive strength is well known but there is no agreement on the precise form of the relation. According to Neville [21] there can be no unique relation because the modulus of elasticity of concrete is affected by the modulus of elasticity of aggregate and by the volumetric content of aggregate in the concrete.

While the volumetric content of aggregate is easily calculated, the modulus of elasticity of aggregate is rarely known. This is probably the reason why some expressions for concrete modulus of elasticity indicated in codes allow for the modulus of elasticity of aggregate by a coefficient that is a function of density of concrete, usually unit mass raised to power 1.5 [21]. Whatever the value of the power index, at a constant aggregate content by volume, the density of concrete increases with an increase in the density of aggregate. The consideration of density is equally applicable in the case of normal-weight and lightweight aggregates, so that the ACI equation 2-1 can be used for concrete made with either type of aggregate.

Pauw [18] proposed an empirical formula, which relates the modulus of elasticity with the concrete unit weight (w) and its compressive strength ($f'c$), studying the static modulus for a large variety of aggregates and concrete strengths, based on other author studies. The formula is applicable to both lightweight and normal weight structural concrete and it is basically the formula used recently by codes.

The proposed formula resulted in the following form, and the constant A, B and C can be obtained using statical methods.

$$E = Aw^{B} \times (f_c^{'})^{C} \; (psi) \tag{3-1}$$

Figure 3-3 shows the data analyzed by Pauw to derive the formula, which is actually used by design codes.

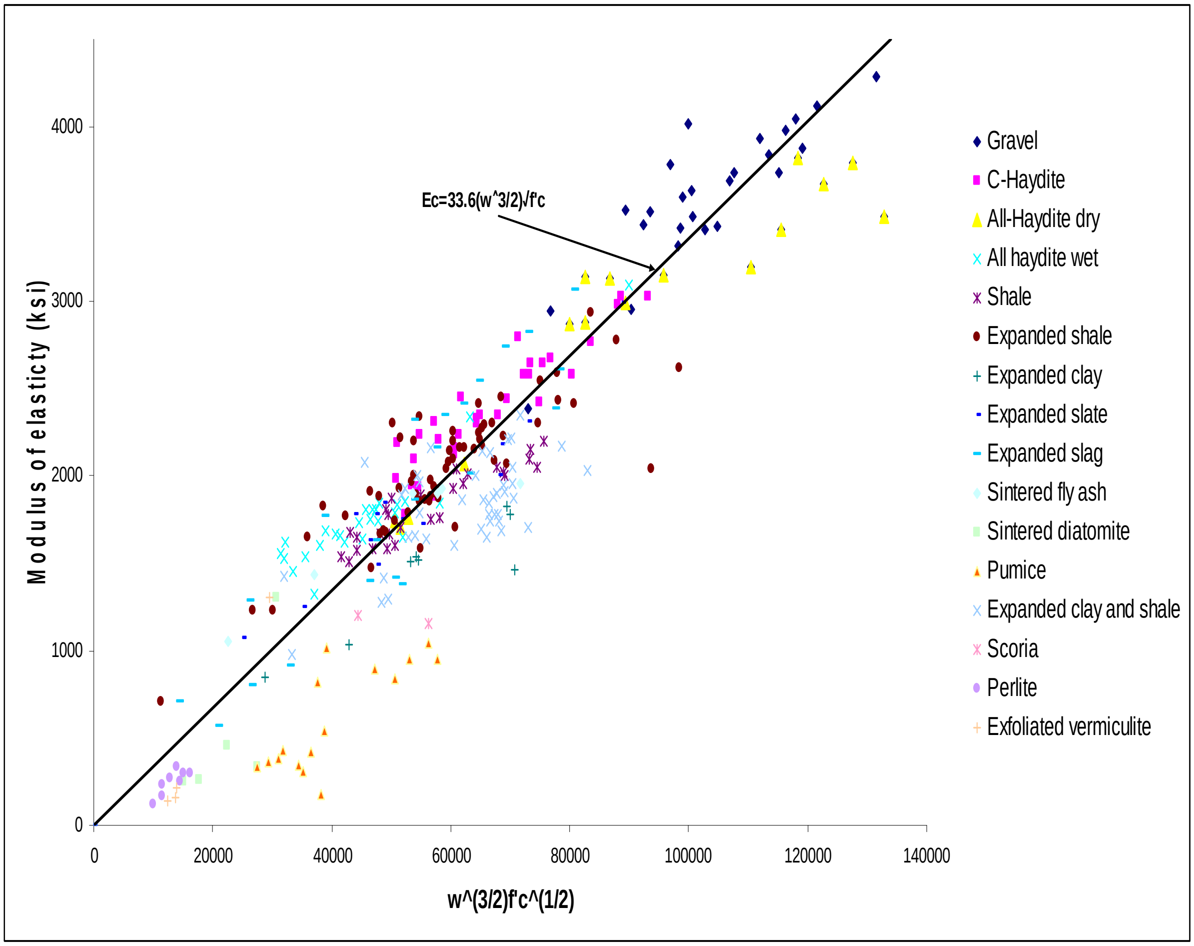

Figure 3-3 Correlation of test data to derive Pauw's formula (adopted from Pauw [18])

3.4 PREVIOUS RESEARCH FOR MODULUS OF ELASTICITY IN SCC

Because the elastic modulus of common aggregate is greater than that of the paste, and because the absolute volume of the paste of SCC is greater than that of ordinary concrete, one might expect that the elastic modulus of SCC would be smaller than that of ordinary concrete with a comparable compressive strength.

However, there is still no consensus in the literature whether SCC modulus of elasticity is lower than that of conventional concrete. ACI committee 237 [3] indicates that some observation have shown that for equal compressive strength the modulus of elasticity can be as much as 10 to 15 % lower than that of conventional concrete of similar compressive strength due to the required adjustment of mixture proportions to make SCC . While, others have shown opposite results. Persson (2001) reported that SCC modulus of elasticity was the same as that of normal concrete as long as their compressive strengths were the same [3].

Holschemacher and Klung [5] reported that the modulus of elasticity of SCC can be up to 20% lower compared with normal vibrated concrete having the same compressive strength and made of the same aggregates.

Schindler [24] evaluating the properties of self consolidating concrete for prestressed members, also found a lower modulus of elasticity for SCC comparing ordinary and SCC concrete mixtures with similar compressive strength. However, Schindler [22] indicated that although modulus of elasticity for SCC was found to be lower than that of conventional concrete, it generally slightly exceeded the modulus calculated using the equation given by

ACI-318 [1]. Bonen and Shah [13] also reported that the equations suggested by ACI Building Code for calculating the modulus of elasticity return reasonable estimates.

In the study carried out by Schindler [24], the total aggregate volume in all SCC mixtures was almost the same, while the sand/total aggregate ratio by volume was varied, and cementitious materials such as silica fume, slag and fly ash were used in all SCC mixtures. As a comparison two conventional concrete mixtures were made with no cementitious material, indicating that the higher modulus of elasticity found in the conventional concrete mixtures may be due to the use of only type III cement.

The mixture proportions made by Schindler [24] were also designed to include a viscosity-modifying admixture (VMA) with a maximum ratio of sand/aggregate by volume of 0.46. This limit was deemed sufficiently high for SCC designed specifically for prestressed concrete applications. The main concern was that a higher ratio of sand/aggregate might lead to decreased modulus of elasticity, as well as increased creep and drying shrinkage, three factors that greatly affect prestress losses as well as member deflections.

Other authors [12],[25], have not found difference between SCC and ordinary concrete modulus of elasticity for comparable compressive strengths. Besides, Sonebi [25] indicated that SCC mixes had the same relationship between modulus of elasticity and compressive strength as the ordinary concrete. The ratio of Modulus of elasticity to square root of compressive strength $(E/f_c'^{0.5})$ was close to 4.73 for both ordinary and SCC concrete.

Mortsell and Rodum [26] carried out a study where all mixture proportions for both SCC and conventional concrete were kept constant, indicating that there is no difference in modulus of elasticity for the two concretes. The basic difference in the preparation of the concrete mixtures was the higher dosages of chemical admixtures used in SCC.

CHAPTER 4

METHODOLOGY

4.1 INTRODUCTION

The objective of this chapter is to discuss the methodology used to carry out this research. It includes a brief description of the materials used in the concrete mixtures, proportions and the parameters that are studied. The procedure used to determine some of the self-consolidating concrete properties such as spread, segregation index, compressive strength and modulus of elasticity which is the main topic of this research, are also described.

Due to concrete industry interest on research regarding SCC, CEMEX Puerto Rico offered its laboratory facilities and materials to carry out this project. All the concrete mixes were made at CEMEX laboratory located in the city of Carolina using materials commercially available and commonly used by this company.

Compressive strength and modulus of elasticity properties were determined in the civil engineering materials laboratory at the University of Puerto Rico, Mayaguez Campus.

4.2 MATERIALS

The experimental program proposed for this research project was carried out using the following materials:

4.2.1 Aggregates

Coarse aggregate commercially available in Puerto Rico with specific gravity of 2.70, nominal maximum size of ½ in (SCC mixtures) and ¾ in (conventional mixtures), and absorption of 1.69%. Coarse aggregate grading curves can be seen in Figure 4-1 and Figure 4-2.

The fine aggregate consisted of manufactured sand commercially available in Puerto Rico with specific gravity of 2.56, absorption of 2.77 %, and fineness modulus of 2.73. Fine aggregate grading curve can be seen in Figure 4-3.

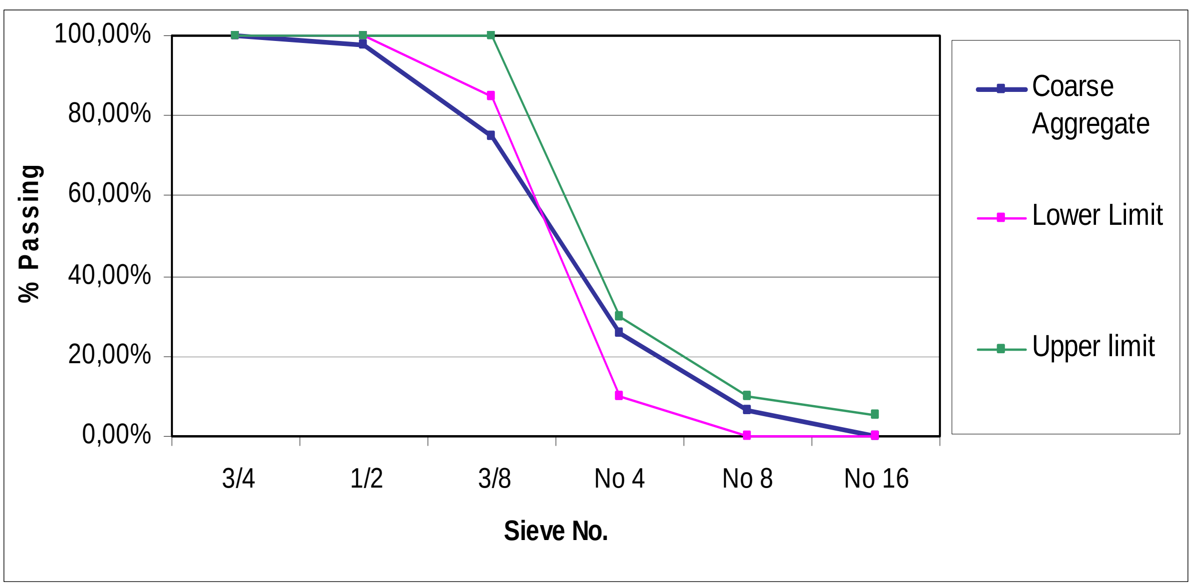

Figure 4-1 Grading Curve for SCC mixture coarse aggregate (Nominal Maximum size ½”)

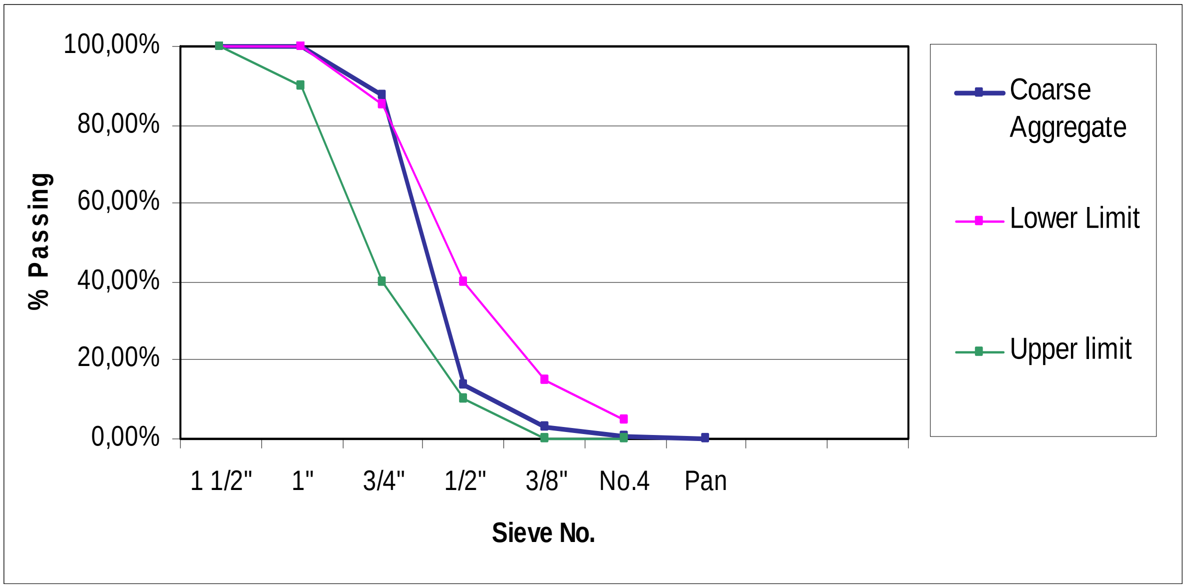

Figure 4-2 Grading Curve for conventional concrete mixture coarse aggregate (Nominal Maximum size 3/4")

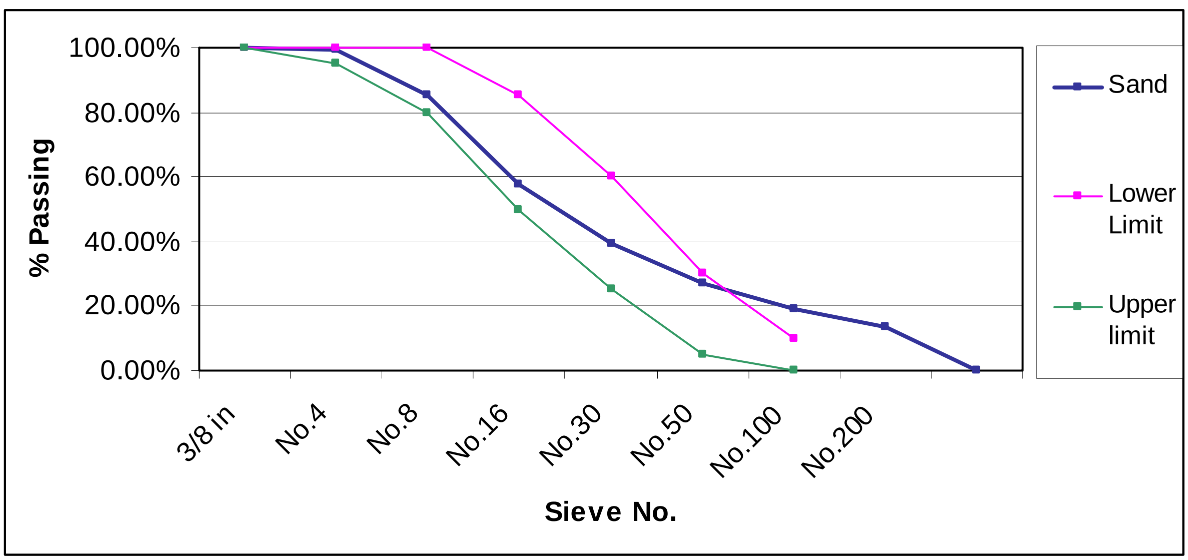

Figure 4-3 Grading Curve for fine aggregate

4.2.2 Cement

ASTM type I Portland cement produced by CEMEX Puerto Rico was used. The physical minimum properties of the cement are indicated by ASTM C150 as shown in Table 4-1. The chemical characteristics are reported in Table 4-2.

Table 4-1 Physical characteristics of Portland cement

CHARACTERISTIC	ASTM C150
Specific Gravity	3.15
Fineness (specific surface) by Blaine air permeability apparatus (m^2/kg)	280 minimum
Compressive strength (psi) At 7 days	2760 minimum
Initial time of setting	Between 45 to 375

Table 4-2 Chemical composition of Portland cement

CHARACTERISTIC	VALUE (% by mass)	ASTM C 150
Silicon dioxide (SiO_2)	20.55	
Aluminum oxide (Al_2O_3)	5.35	
Ferric oxide (Fe_2O_3)	2.60	
Calcium oxide (CaO)	65.50	
Magnesium (MgO)	1.45	6.0 maximum
Sulfur Trioxide ($S0_3$)	2.42	3.0 maximum
Sodium monoxide (Na_2O)	0.40	
Potassium oxide (K_2O)	0.20	
Loss on ignition	1.28	3.0 maximum
Insoluble residue	0.15	0.75 maximum

4.2.3 Admixtures

Three admixtures were used as they were available at Cemex facility. Figure 4-4 shows the three chemical admixtures in this research to make SCC mixtures, and a description of them is also explained.

Figure 4-4 Chemical admixtures

- High water reducing admixture (Glenium 3000 NS): Glenium 3000 is a very effective water-reducing admixture in producing concretes with different levels of workability. The recommended dosage range varies from 260 to 780 ml per 100 kg of cementitious material.
- Viscosity modifying admixture (RHEOMAC VMA 358): Viscosity modifying admixtures are developed for producing concrete with enhanced viscosity and controlled rheological properties, increasing resistance to segregation. The recommended dosage range for Rheomac VMA 358 is 130 to 390 ml per 100 kg of cementitious material.
- Water-Reducing and Retarding Admixture (POLYHEED 722): Polyheed 722 is an admixture to make more uniform and predictable quality concrete. It meets ASTM C 494

for type D, water reducer and retarder admixtures. It improves workability, reduces segregation, superior finishing characteristics for flat work and cast surfaces. This type of admixture was not needed to make SCC mixtures; however, CEMEX Puerto Rico suggested its inclusion since they use it in common practice to make concrete.

4.3 EXPERIMENTAL PROGRAM

An experimental program was held to measure concrete modulus of elasticity and compressive strength. The effect of the following variables was studied:

- Water/Cement ratios (*w/c*) of 0.40, 0.45, 0.50, 0.55 and 0.60.
- Ratios Coarse Aggregate/Total aggregate (*ca/ta*) by volume of 0.30, 0.35, 0.40, and 0.45.
- The amount of total aggregate volume content in the mixture. Aggregates volume of 61%, 69% and 74% of the total volume will be analyzed. An aggregate volume content of 69% is a typical value in the common practice of CEMEX Puerto Rico, which was established studying their data base of mixtures. One aggregate content bellow that typical value and another above was chosen for this study. Forty SCC mixtures were made varying the parameters mentioned above.

Four additional conventional concrete mixtures were made for comparison purposes. The conventional mixtures were defined with similar water/cement ratio as those in SCC mixtures and with proportions used in the common practice by CEMEX Puerto Rico. Their total volume aggregate content is approximately 70% of the total concrete volume and a ca/ta ratio of 0.5 for the four mixtures (Higher than the values studied for SCC mixtures).

Each SCC mixture was given an identification number, and the conventional concrete mixtures were identified with the word "CONV" and a number. Table 4-4 shows the experimental plan carried out and the parameters studied. Table 4-4 displays all the material proportions used for each mixture.

Table 4-3 Experimental Program

Aggregate Volume (%)	**Coarse/Aggregate by Volume**	**Water to Cement Ratio (w/c)**				
		0.40	0.45	0.50	0.55	0.60
61	0.30	SCC 1	SCC 4	SCC 7		
	0.35	SCC2		SCC 8	SCC 10	
	0.40	SCC 3	SCC 5		SCC 11	SCC 13
	0.45		SCC 6	SCC 9	SCC 12	
69	0.30	SCC 14	SCC 17	SCC 20		SCC 26
	0.35	SCC 15		SCC 21	SCC 23	
	0.40	SCC 16	SCC 18		SCC 24	SCC 27
	0.45		SCC 19	SCC 22	SCC 25	SCC 28
74	0.30	SCC 29	SCC 32	SCC 35		SCC 39
	0.35	SCC 30		SCC 36	SCC 37	
	0.40	SCC 31	SCC 33		SCC 38	SCC 40
	0.45		SCC 34			

Table 4-4 Mixture Proportions

Mixture	Aggregate Volume (%)	w/c	ca/ta	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Cement (lb/yd^3)	Water (lb/yd^3)
SCC1	61	0.40	0.30	832	1842	916	366
SCC2	61	0.40	0.35	971	1710	916	366
SCC3	61	0.40	0.40	1110	1579	916	366
SCC4	61	0.45	0.30	832	1842	856	385
SCC5	61	0,45	0.40	1110	1579	856	385
SCC6	61	0.45	0.45	1249	1447	856	385
SCC7	61	0.50	0.30	832	1842	804	402
SCC8	61	0.50	0.35	971	1710	804	402
SCC9	61	0.50	0.45	1249	1447	804	402
SCC10	61	0.55	0.35	971	1710	757	417
SCC11	61	0.55	0.40	1110	1579	757	417
SCC12	61	0.55	0.45	1249	1447	757	417
SCC13	61	0.60	0.40	1110	1579	716	430
SCC14	69	0.40	0.30	942	2083	728	291
SCC15	69	0.40	0.35	1099	1934	728	291
SCC16	69	0.40	0.40	1256	1786	728	291
SCC17	69	0.45	0.30	942	2083	681	306
SCC18	69	0.45	0.40	1256	1786	681	306
SCC19	69	0.45	0.45	1412	1637	681	306
SCC20	69	0.50	0.30	942	2083	639	319
SCC21	69	0.50	0.35	1099	1934	639	319
SCC22	69	0.50	0.45	1412	1637	639	319
SCC23	69	0.55	0.35	1099	1934	602	331
SCC24	69	0.55	0.40	1256	1786	602	331
SCC25	69	0.55	0.45	1412	1637	602	331
SCC26	69	0.60	0.30	942	2083	569	342
SCC27	69	0.60	0.40	1256	1786	569	342
SCC28	69	0.60	0.45	1412	1637	569	342
SCC29	74	0.40	0.30	1010	2234	611	244
SCC30	74	0.40	0.35	1178	2075	611	244
SCC31	74	0.40	0.40	1346	1915	611	244
SCC32	74	0.45	0.30	1010	2234	571	257
SCC33	74	0.45	0.40	1346	1915	571	257
SCC34	74	0.45	0.45	1515	1755	571	257
SCC35	74	0.50	0.30	1010	2234	536	268
SCC36	74	0.50	0.35	1178	2075	536	268
SCC37	74	0.55	0.35	1178	2075	505	278
SCC38	74	0.55	0.40	1346	1915	505	278
SCC39	74	0.60	0.30	1010	2234	477	286
SCC40	74	0.60	0.40	1346	1915	477	286
CONV 1	70	0.40	0.50	1592	1510	704	282
CONV 2	70	0.50	0.50	1592	1510	618	309
CONV 3	70	0.55	0.50	1592	1510	583	320
CONV 4	70	0.60	0.50	1592	1510	551	331

The admixtures dosages can be seen in Table 4-5. The dosage is given in ml per 100 kg of cement.

Table 4-5 Admixture dosage

ADMIXTURE	SCC	CONVENTIONAL CONCRETE
Glenium 3000	260	26
Rheomac VMA 358	30	
Polyheed 722	170	100

4.4 MIXING AND CURING PROCEDURE

Concrete mixtures were prepared in accordance to ASTM C 192 **"**Standard Practice for making and curing concrete test specimen in the laboratory", using an open mixer as seen in Figure 4-5.

Before starting the mixing procedure the aggregates moisture contents were measured in order to correct the aggregate weights and the amount of water due the aggregates humidity and absorption. This was done using moisture equipment as seen in Figure 4-6 .

Figure 4-5 Open pan mixer

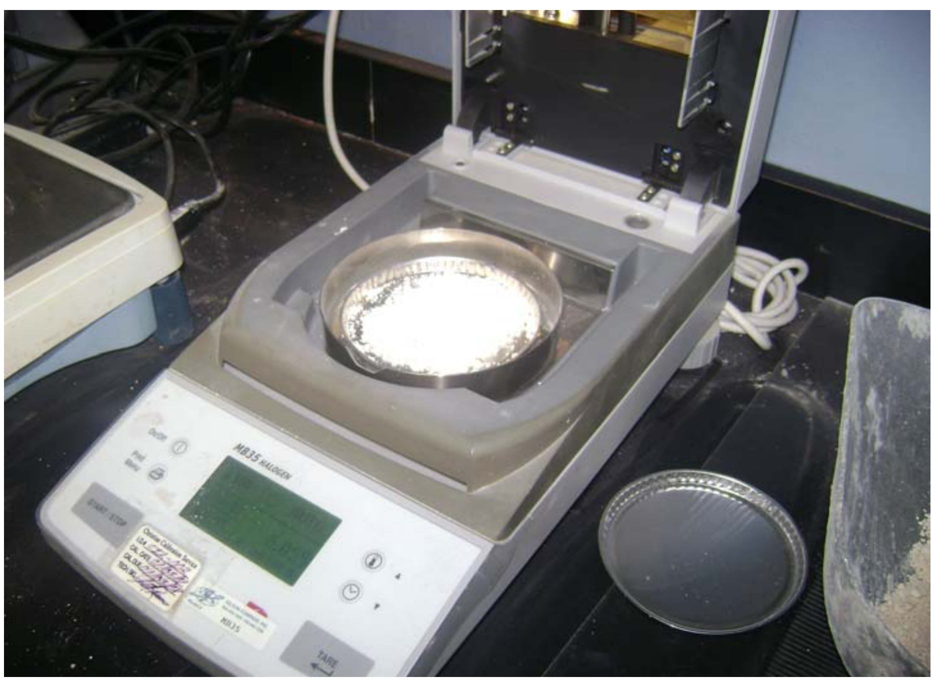

Figure 4-6 Moisture determination

The mixing sequence consisted of mixing coarse and fine aggregates together. Then cement was added and mixed with the aggregates. The chemical admixtures were diluted with the mixing water which was finally added to the mixture. All the concrete constituents were mixed for about 10 minutes.

The concrete specimen for compressive strength and modulus of elasticity were cured in a standard moist room until the age to be tested (28 days) at 71 $\pm$ 3 Fahrenheit degrees.

4.5 LABORATORY TESTS

After finishing the mixing process fresh, SCC properties such as slump flow, visual stability index and unit weight were measured. Three 4” x 8” cylinders (as seen in Figure 4-7) were taken from each mixture.

Figure 4-7 SCC 4”x 8” cylinders

In addition to measuring fresh SCC properties, compressive strength and modulus of elasticity at the age of 28 day were also determined. A brief description of the each testing is presented.

4.5.1 Slump flow

The slump flow is a measurement of the filling ability or how far the concrete will flow into the formwork. A common range of slump flow for SCC is 18 to 30 in [3].The equipment required to perform this test consist of a standard Abraham cone and a slump flow board. The procedure is based on ASTM C143 [27] with a modification for determining the slump of conventional concrete [3].

The Abraham cone is placed in the center of the board but in an inverted position (small opening down). The cone is filled with SCC and then raised allowing the concrete to flow over the board. The diameter of the resulting concrete patty is measured twice (one measurement perpendicular to the other), and finally the slump flow will be the average of the two measurements. Figure 4-8 and Figure 4-9 show the procedure followed to determine slump flow in all mixtures.

Figure 4-8 Slump Flow determination.

Figure 4-9 Measurement of the resulting concrete patty.

4.5.2 Visual Stability Index

The visual stability index (VSI) test involves the visual examination of the SCC slump flow spread resulting from performing the slump flow test explained before.

The visual Stability Test is a subjective visual assessment of the dynamic stability of the slump flow. There is not an ASTM specification for this test yet. There are certain guidelines in the literature that can be used to examine this parameter [28].

The test ranks the stability of SCC on a scale of 0 to 3. A VSI rating of 0 or 1 is an indication that the SCC mixture is stable and should be suitable for the intended use. A VSI rating of 2 or 3 indicates possible segregation potential and that the producer should take action by modifying or adjusting the mixture to ensure stability [3].

The rate is based on the visual inspection in the slump flow test immediately after SCC stops flowing. The appearance of SCC is then compared to pictures and descriptions of the surface bleed and aggregate distribution.

4.5.3 Unit weight

Concrete unit weight was determined according to ASTM C138 [29]. The values were determined at the laboratory after each concrete mixture was made. The test consists of filling a cylinder, whose volume is known, with SCC. The weight of SCC divided by the volume of the cylinder will be the unit weight of the SCC sample. Concrete unit weight test can be seen in Figure 4-10.

Figure 4-10 Concrete unit weight test.

4.5.4 Compressive Strength

Concrete compressive strength was determined according to ASTM C39 [30]. This property will be determined for concrete cylinder cured for 28 days.

The compressive strength of the concrete specimen is determined by dividing the maximum load obtained from the test by the cross sectional area of the specimen as follows:

$$f_c^{'} = \frac{P}{\pi \times r^2} \ (psi) \tag{4-1}$$

where:

$f_c^{'}$ = Specimen compressive strength (psi),

$P =$ Ultimate compressive axial load applied to the specimen (lb), and

$r =$ Radio of cylinder specimen (in).

The testing machine used to determine the specimen compressive strength has a capacity of 600000 lb (see Figure 4-11). The rate of loading ranged from 251 to 629 lb/seg. Figure 4-12 shows the setup for the compressive strength test.

Figure 4-11 Universal Testing Machine

Figure 4-12 Compressive strength setup

4.5.5 Modulus of Elasticity

The modulus of Elasticity was determined according to ASTM C 469 [31]. Modulus of elasticity was computed for cylinders cured for 28 days. Figure 4-13 and Figure 4-14 show the set up for the modulus of elasticity test. A compressometer equipped with a linear variable differential transformer (LVDT) was needed in order to measure the deformation of the concrete specimen during the test. The setup also consisted of a compression testing machine and a computer to download the data from the test.

Figure 4-13 Modulus of elasticity test setup

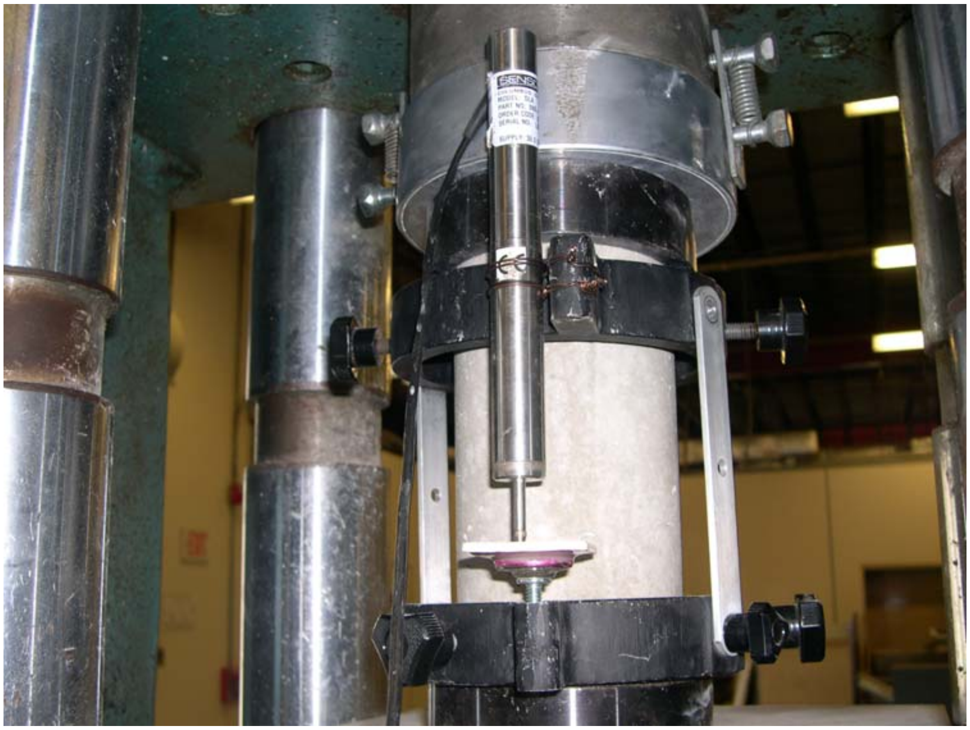

Figure 4-14 Close up of modulus of elasticity test setup.

The loading rate used was the same as that for the compressive strength test. The data from the load cell (in the compression testing machine) and the LVDT were recorded by a computer data acquisition system.

Before modulus of elasticity test was performed, one of the three cylinders for each mixture was tested for compressive strength, in order to calculate the 40% of the ultimate compressive strength, as this property is used in the determination of the concrete modulus of elasticity. On the remaining two cylinders, the modulus of elasticity was run. After that the two cylinders were tested to determine their ultimate compressive strength.

The compressometer used to perform the modulus of elasticity test (see Figure 4-15) consist of two yokes, one of which is rigidly attached to the specimen and the other attached at two diametrically opposite points so that it is free to rotate.

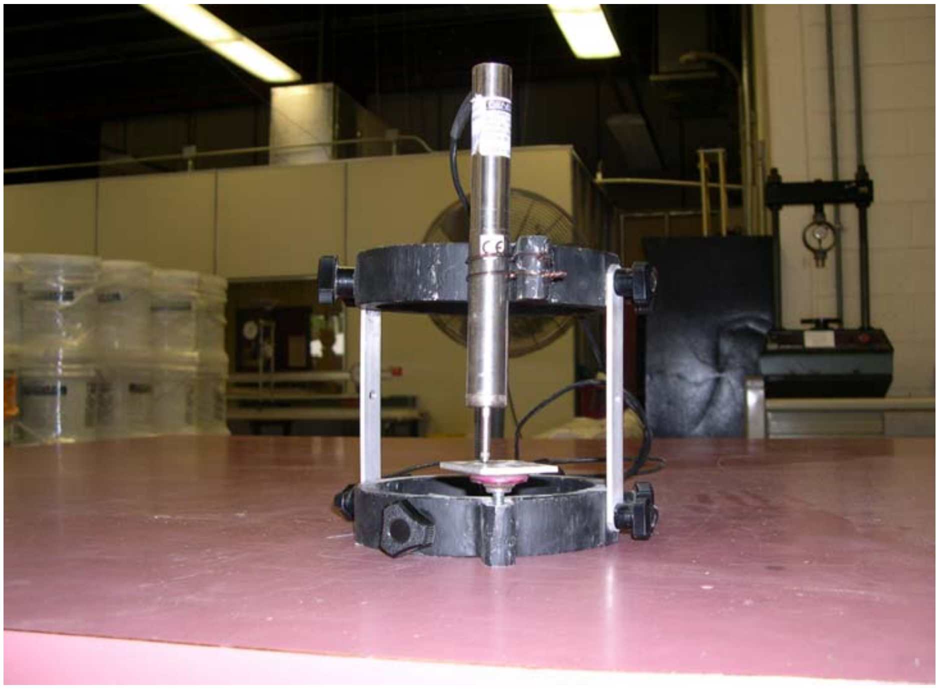

Figure 4-15 Compressometer with an adapted LVDT

At one point on the circumference of the rotating yoke, there is a pivot rod to maintain a constant distance between the two yokes. At the opposite point on the circumference of the rotating yoke, the change in distance between the yokes (that is, the LVDT reading) is equal to the sum of the displacement due to specimen deformation and the displacement due to rotation of the yoke about the pivot rod as seen in Figure 4-16.

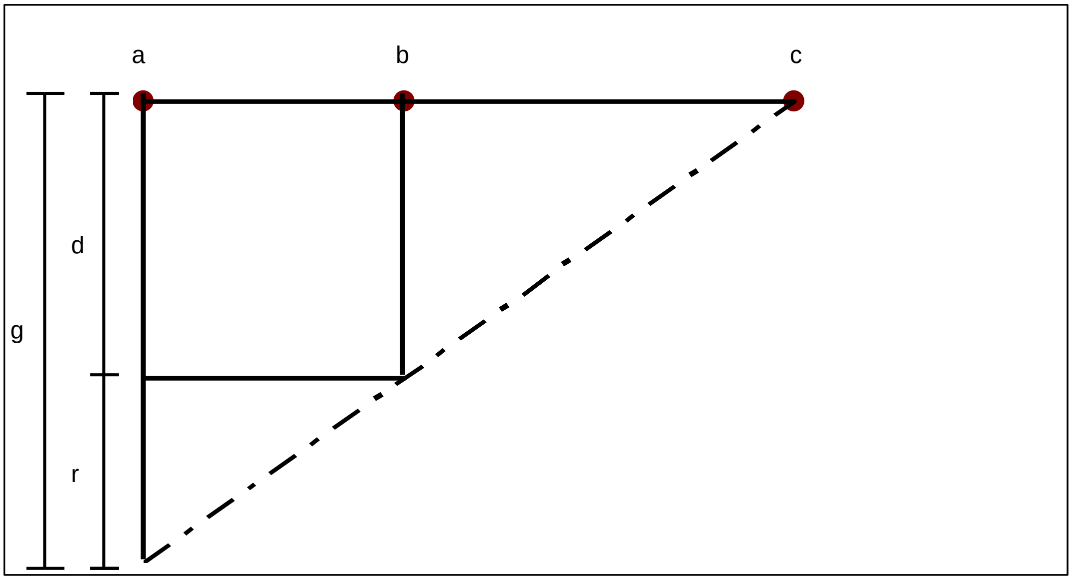

Figure 4-16 Determination of concrete sample displacement during modulus of elasticity test (adapted from ASTM C 469)

In Figure 4-16 :

d = Displacement due to specimen deformation,

r = Displacement due to rotation of the yoke about the pivot rod,

a = Location of the LVDT,

b = Support point of the rotating yoke,

c = Location of pivot rod, and

g = LVDT reading.

If the distances of the pivot rod and the LVDT position from the vertical plane passing through the supports points of the rotating yoke are equal, the deformation of the specimen is equal to one-half the LVDT reading. Those distances were measured carefully prior to the modulus of elasticity test in order to make them equal. The unit strains required to calculate the modulus of elasticity will be the deformation read, divided by the compressometer length (6 inches).

With all the data recorded, the secant modulus of elasticity was determined according to ASTM C469 using the following expression:

$$E = \frac{(S_2 - S_1)}{(\in_2 - 0.000050)}\ (psi) \tag{4-2}$$

where:

E = Chord modulus of elasticity (psi),

S_2 = Stress corresponding to 40% of ultimate load,

S_1 = Stress corresponding to a longitudinal strain $\in_1$ of 50 millionths (psi), and

$\in_2$ = Longitudinal strain produced by stress S_2.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 INTRODUCTION

This chapter presents in detail all the results and their corresponding analysis obtained in the experimental program. The chapter begins with a description of the fresh concrete properties such as slump flow, visual stability index (VSI) and unit weight (w). Modulus of elasticity, which is the main purpose for this research, and compressive strength results are also shown later in this chapter.

5.2 FRESH CONCRETE PROPERTIES

Slump flow, visual stability index (VSI) and unit weight (w) test were performed after mixing the concrete to characterize the fresh properties of the SCC mixtures. These properties are summarized in Table 5-1, where:

ca/ta = coarse aggregate/ total aggregate ratio by volume,

w/c = water to cement ratio,

VSI = Visual Stability Index, and

* = Conventional slump test for conventional concrete.

Table 5-1 Properties of freshly mixed concrete

Mixture ID	Total Aggregate Volume (%)	ca/ta	w/c	Slump flow (in)	VSI	w(lb/ft^3)
SCC1	61	0.30	0.40	30.0	0	144.2
SCC2	61	0.35	0.40	27.0	0	146.0
SCC3	61	0.40	0.40	24.5	1	147.0
SCC4	61	0.30	0.45	28.0	0	145.6
SCC5	61	0.40	0.45	28.5	1	146.4
SCC6	61	0.45	0.45	27.5	0	148.2
SCC7	61	0.30	0.50	29.5	0	146.6
SCC8	61	0.35	0.50	27.5	1	145.8
SCC9	61	0.45	0.50	25.0	1	148.8
SCC10	61	0.35	0.55	30.0	1	145.2
SCC11	61	0.40	0.55	28.0	2	145.8
SCC12	61	0.45	0.55	24.0	3	145.6
SCC13	61	0.40	0.60	26.0	3	146.0
SCC14	69	0.30	0.40	26.0	0	146.4
SCC15	69	0.35	0.40	25.0	0	147.4
SCC16	69	0.40	0.40	24.5	1	149.0
SCC17	69	0.30	0.45	25.0	0	146.8
SCC18	69	0.40	0.45	24.0	0	148.6
SCC19	69	0.45	0.45	22.5	1	147.8
SCC20	69	0.30	0.50	24.0	0	148.4
SCC21	69	0.35	0.50	24.0	0	148.2
SCC22	69	0.45	0.50	22.5	1	148.4
SCC23	69	0.35	0.55	25.5	0	147.6
SCC24	69	0.40	0.55	25.0	1	147.0
SCC25	69	0.45	0.55	22.0	2	148.0
SCC26	69	0.30	0.60	24.0	1	148.2
SCC27	69	0.40	0.60	23.5	2	149.8
SCC28	69	0.45	0.60	22.0	2	148.8
SCC29	74	0.30	0.40	20.0	0	146.0
SCC30	74	0.35	0.40	21.0	0	150.0
SCC31	74	0.40	0.40	19.5	1	149.2
SCC32	74	0.30	0.45	23,5	0	147.0
SCC33	74	0.40	0.45	21.0	1	148.0
SCC34	74	0.45	0.45	18.5	2	148.2
SCC35	74	0.30	0.50	22.5	1	146.6
SCC36	74	0.35	0.50	20.0	3	147.8
SCC37	74	0.35	0.55	20.0	1	148.4
SCC38	74	0.40	0.55	18.0	2	148.0
SCC39	74	0.30	0.60	25.0	2	146.6
SCC40	74	0.40	0.60	16.0	3	147.6
CONV 1	70	0.50	0.40	3*	N/A	152.4
CONV 2	70	0,50	0.50	3*	N/A	151.4
CONV 3	70	0.50	0.55	4*	N/A	151.8
CONV 4	70	0.50	0.60	4*	N/A	150.4

5.2.1 Slump Flow

The results obtained in the slump flow test (Table 5-1) varied from 18 to 30 inches; except from mixture SCC 40 which presented a slump flow of 16 inches .The value was not reported it is not acceptable for SCC. Higher slump flow values were found for mixtures containing lower aggregate volume. The results confirm that increasing the cementitious material content increases the flowability of SCC mixtures [10].

An increase in flowability can be also seen in most of the mixtures for low *ca/ta* relationships, which means that increasing the fine aggregate content and decreasing the coarse aggregate content, reduces the risk of blockage, thus increasing flowability.

Table 5-2 shows the slump flow range values obtained in all SCC mixtures for different aggregate volume and amount of cement. ACI committee 237 [3] indicates that a common range of slump flow for SCC is 18 to 30. The required slump flow value will vary depending on the workability needed for a certain application or project.

Table 5-2 Slump flow ranges for different aggregate volume and amount of cement

Aggregate Volume(%)	Cement (lb/yd^3)	Slump Flow (in)
61	716-916	24-30
69	569-728	22-26
74	477-611	18-23

5.2.2 Visual Stability Index (VSI)

A visual stability index was applied to every mixture in order to examine the segregation resistance of SCC. Table 5-1 shows that VSI varies between 0 and 3. A VSI rating of 0 or 1 was given to a stable SCC mixture with no evidence of segregation in slump flow spread which will be suitable for the intended use. Figure 5-1 shows one of the SCC mixtures with a given VSI of 0.

Figure 5-1 Stable SCC mixture with VSI of 0

Values with VSI of 2 or 3 were given to unstable mixtures. According to ACI 318 committee 237 a VSI rating of 2 or 3 indicates possible segregation potential and the producer should take action by modifying or adjusting the mixture to ensure stability. In this case mixtures with a VSI of 3 were highly unstable and not recommended for self-consolidating concrete applications. Figure 5-2 shows one of the SCC mixtures with a VSI rating of 3.

Figure 5-2 Unstable SCC mixture with a VSI rating of 3

For the three aggregate volumes considered (61%, 69% and 74%), an increase in the *w/c* ratio keeping the amount of cement constant, increased the tendency to segregation. This fact can be explained considering that an increase in the amount of water reduces the ability to maintain a uniform distribution of large coarse aggregate particles [10]. Mixtures with the lowest aggregate content (61%) present segregation problems for *w/c* ratios of 0.55 and 0.60, due to the high amount of water required to maintain the proportion of aggregate volume.

The tendency of segregation for mixtures containing 69% of aggregate volume is lower at high *w/c* ratios, and those containing the highest aggregate volume (74%) the segregation tendency increases at high *w/c* ratio because of the large amount of coarse aggregate content presented in these mixtures, which increases the blockage between particles.

An increase in the coarse aggregate/total aggregate (*ca/ta*) ratio also produces an increase in the segregation tendency for the SCC mixtures. General practice of SCC mixture design recommends that the *ca/ta* ratio should be limited to 0.5. Such a limit is imposed to reduce the interparticle friction between coarse aggregate particles, thus enhancing the ability of SCC to flow [10]. The tendency for segregation in the SCC mixtures was quite visible for ca/ta ratio of 0.45, which is reasonable with the results found in the literature by Hassan El-Chabib and Moncef Nehdi [10].

5.2.3 Unit weight

The unit weights of SCC mixtures vary from 144.2 to 150 lb/ft^3 as it is reported in Table 5-1. It is known that all mineral aggregates have about the same absolute specific gravity. The difference in weight in the mixtures might be the result of voids in the concrete.

5.3 COMPRESSIVE STRENGTH RESULTS

The average compressive strength ($f'c$) and modulus of elasticity (E) for all the mixtures are reported in Table 5-3. The individual sample compressive strength and modulus of elasticity results are shown in Appendix A.

Table 5-3 Compressive strength and modulus of elasticity results

Mixture	Total Volume Agrégate (%)	w/c	ca/ta	f'c(psi)	E (ksi)
SCC1	61	0.40	0.30	10830	6144
SCC2	61	0.40	0.35	10264	5807
SCC3	61	0.40	0.40	9550	5924
SCC4	61	0.45	0.30	8570	5454
SCC5	61	0.45	0.40	8322	5528
SCC6	61	0.45	0.45	7840	5409
SCC7	61	0.50	0.30	7824	5114
SCC8	61	0.50	0.35	7675	5155
SCC9	61	0.50	0.45	7185	5148
SCC10	61	0.55	0.35	6033	4648
SCC11	61	0.55	0.40	5479	4620
SCC12	61	0.55	0.45	5302	4822
SCC13	61	0.60	0.40	5109	4439
SCC14	69	0.40	0.30	9509	6159
SCC15	69	0.40	0.35	9425	6166
SCC16	69	0.40	0.40	9273	6264
SCC17	69	0.45	0.30	7447	5609
SCC18	69	0.45	0.40	7236	5456
SCC19	69	0.45	0.45	6957	5594
SCC20	69	0.50	0.30	6434	5314
SCC21	69	0.50	0.35	6272	5463
SCC22	69	0.50	0.45	6056	5455
SCC23	69	0.55	0.35	5653	4692
SCC24	69	0.55	0.40	5561	4853
SCC25	69	0.55	0.45	5303	5051
SCC26	69	0.60	0.30	5287	4947
SCC27	69	0.60	0.40	5015	5173
SCC28	69	0.60	0.45	4650	4868
SCC29	74	0.40	0.30	8659	5978
SCC30	74	0.40	0.35	8500	6045
SCC31	74	0.40	0.40	8312	6233
SCC32	74	0.45	0.30	7442	5678
SCC33	74	0.45	0.40	7208	5818
SCC34	74	0.45	0.45	6847	5615
SCC35	74	0.50	0.30	6384	5451
SCC36	74	0.50	0.35	5628	5303
SCC37	74	0.55	0.35	5371	5114
SCC38	74	0.55	0.40	5041	5026
SCC39	74	0.60	0.30	4184	4645
SCC40	74	0.60	0.40	4012	4597
CONV 1	70	0.40	0.50	8762	5943
CONV 2	70	0.50	0,50	5809	5209
CONV 3	70	0.55	0.50	5122	5005
CONV 4	70	0.60	0.50	4634	4807

5.3.1 Variation of Compressive strength for different volume aggregate content

Figure 5-3 shows the variation in compressive strength with the *w/c* ratio for different aggregate volumes. An increase in compressive strength can be seen when the total aggregate volume is lower for the same water/cement ratio. The curves shown in Figure 5-3 for each aggregate volume content were adjusted by a power fitting, which was the best fit tendency found for the data. Table 5-4 reports the equations obtained in the power tendency and the corresponding R^2 value.

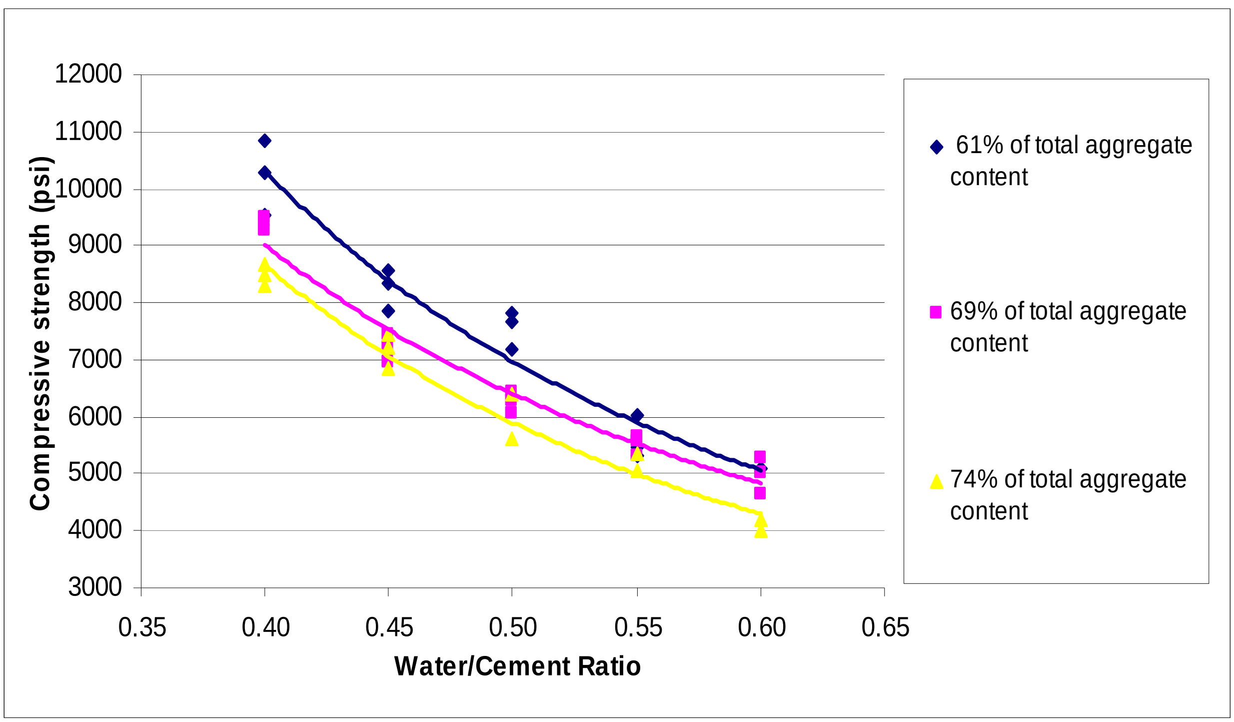

Figure 5-3 Effect of Water/Cement Ratio in compressive strength for different aggregate volume content

Table 5-4 Power fitting to relate water/cement ratio and compressive strength

Aggregate Volume Content (%)	**Equation**	**R^2**
61	$y = 2065.8\ x^{-1.7555}$	0.93
69	$y = 2206.0\ x^{-1.5366}$	0.96
74	$y = 1775.6\ x^{-1.7299}$	0.97

Although in common practice it is expected that the compressive strength will depend basically on the water/cement ratio; higher compressive strength for lower volume aggregate content should also be expected since the amount of cement paste required in this case is higher , thus producing a decrease in the interfacial transition zone between the cement paste and the aggregate.

The hardened cement paste in the interface zone have a much higher porosity than the hardened cement paste farther away from the particles of aggregate. It is known that the higher the porosity the lower the strength. Then a lower volume aggregate content would lead to a lower level of porosity since there would be less interfacial transition zone between cement paste and aggregates.

The same tendency observed in Figure 5-3 can be seen when *ca/ta* ratio is kept constant (see Figure 5-4 through Figure 5-6)

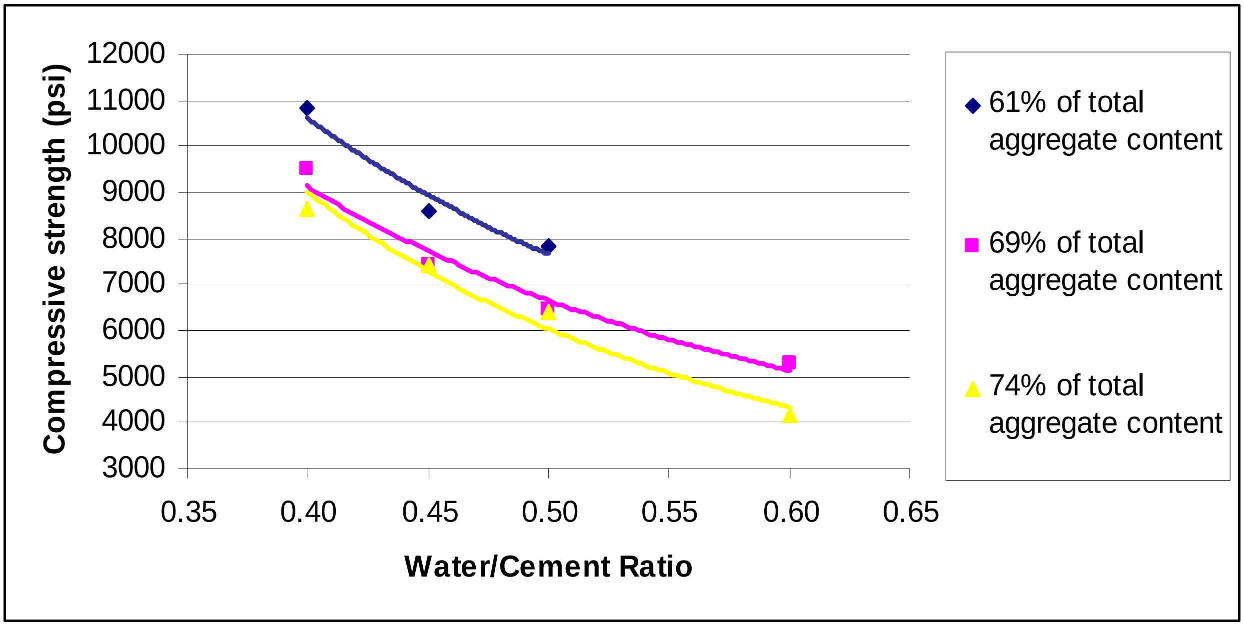

Figure 5-4 Effect of Water/Cement Ratio in compressive strength for different aggregate volume content (*ca/ta* =0.30)

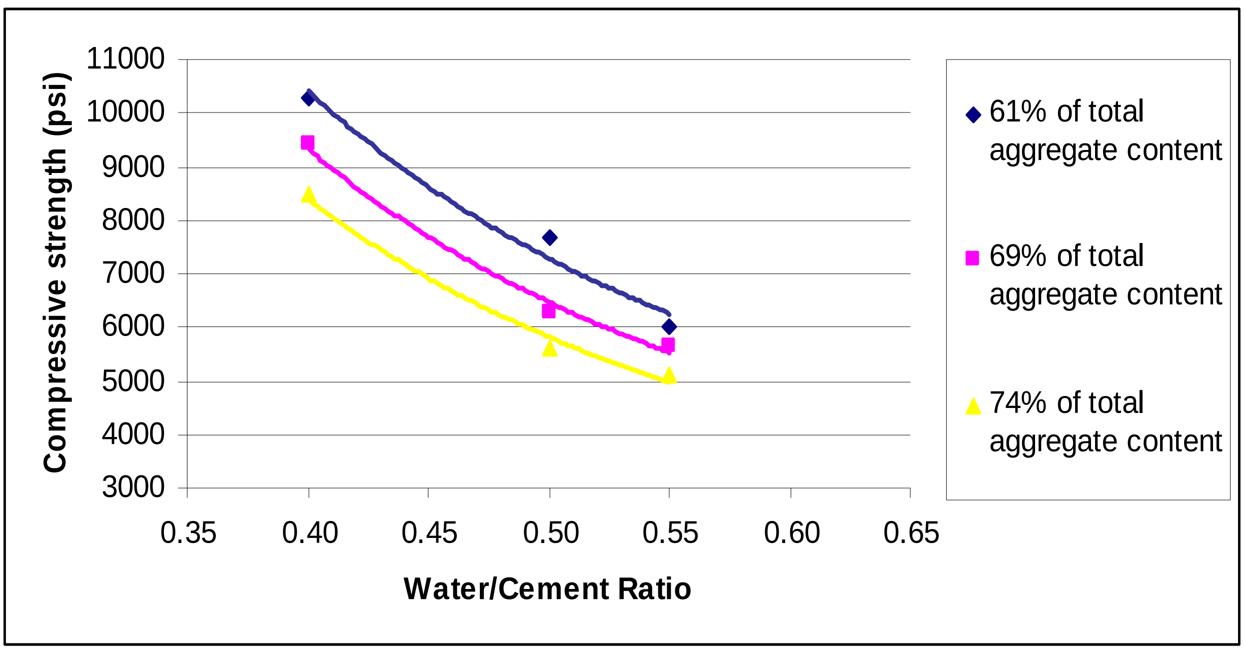

Figure 5-5 Effect of Water/Cement Ratio in compressive strength for different aggregate volume content (*ca/ta* =0.35)

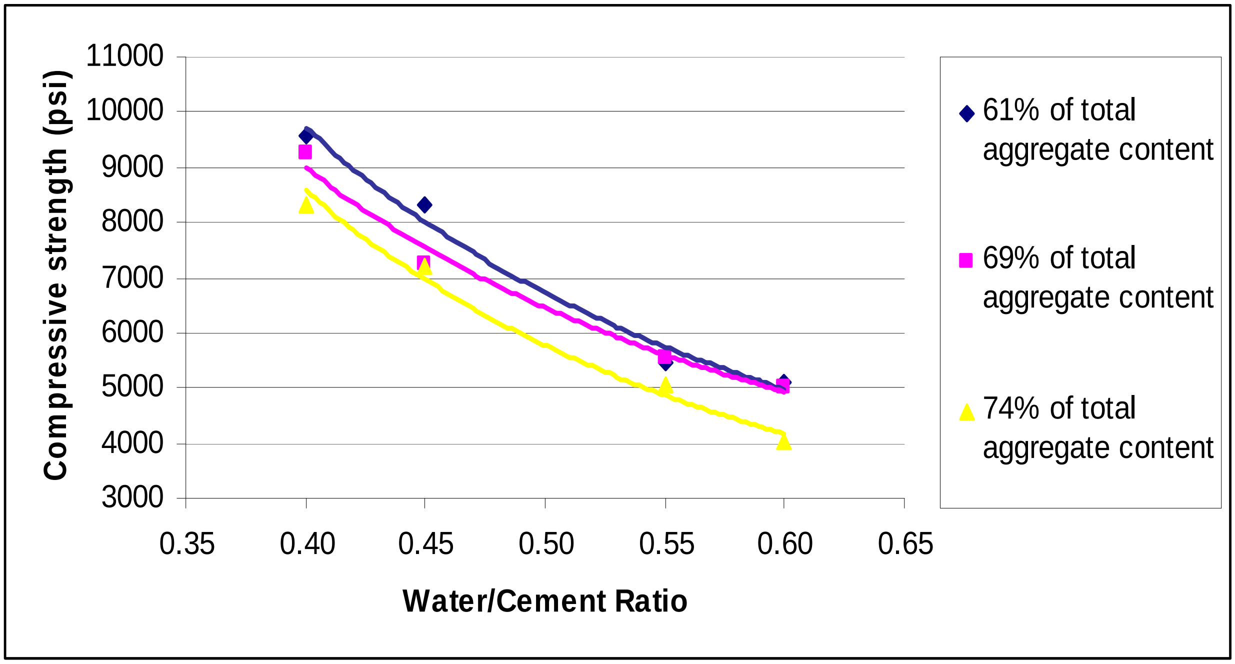

Figure 5-6 Effect of Water/Cement Ratio in compressive strength for different aggregate volume content (*ca/ta* =0.40)

Table 5-5 shows the compressive strength for each aggregate volume for a given *w/c* ratio (the compressive strength was taken as the average for the different *ca/ta* ratios at the same *w/c* ratio for comparison purposes). An increase in compressive strength between 15% and 25% can be obtained when the lowest aggregate volume content (61%) is compared with the highest (74%). The same observations mentioned above can also be seen in Figure 5-7. Mixtures with lower volume aggregate content present the higher compressive strength for a given *w/c* ratio. As expected, higher compressive strengths when *w/c* ratio decreases is also observed.

Table 5-5 Compressive strength values for each aggregate volume content

Water/ Cement Ratio	Compressive strength for different aggregate volume content (psi)		
	61%	**69%**	**74%**
0.40	10215	9402	8490
0.45	8244	7213	7166
0.50	7561	6254	6006
0.55	5605	5506	5206
0.60	5109	4984	4097

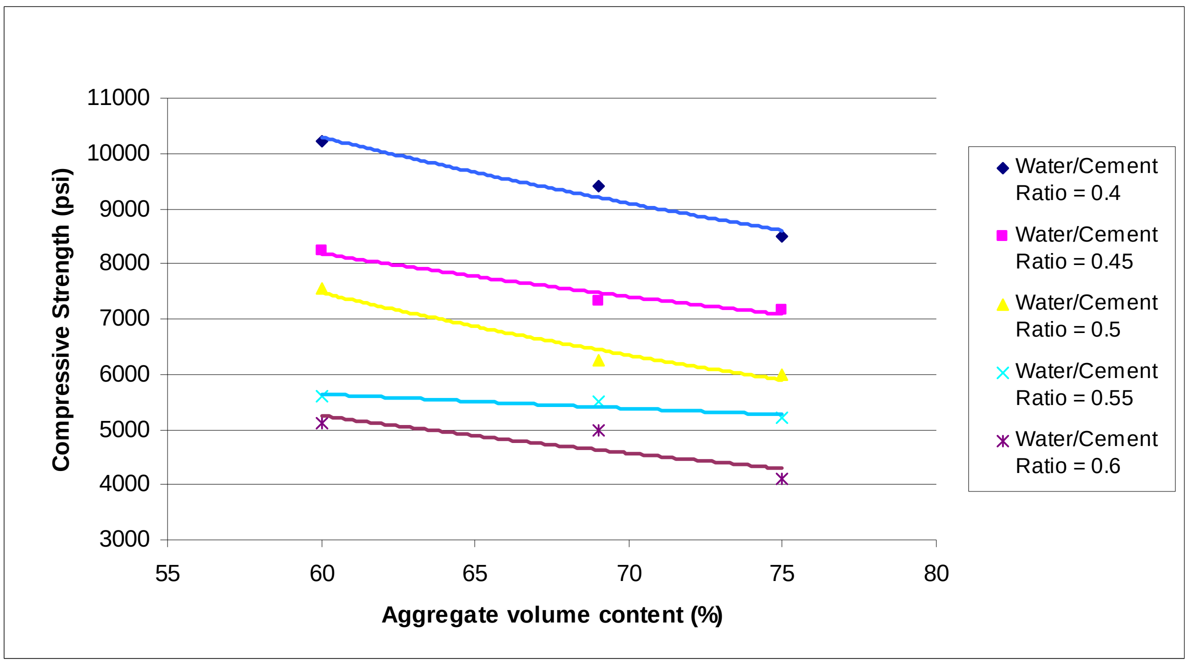

Figure 5-7 Effect of aggregate volume content in compressive strength

5.3.2 Variation of compressive strength for different coarse aggregate/total aggregate ratio (*ca/ta*)

To explain the effect of *ca/ta* in the compressive strength, the obtained data was analyzed plotting the compressive strength values and water/cement ratio for each of the *ca/ta* ratio studied (0.30 to 0.45), keeping the total volume aggregate content constant. Figure 5-8 shows that there is no a significant effect in compressive strength for a given *w/c* when *ca/ta* is varied except from those mixtures containing *ca/ta* = 0.45 where some slight decrease in compressive strength can be appreciated.

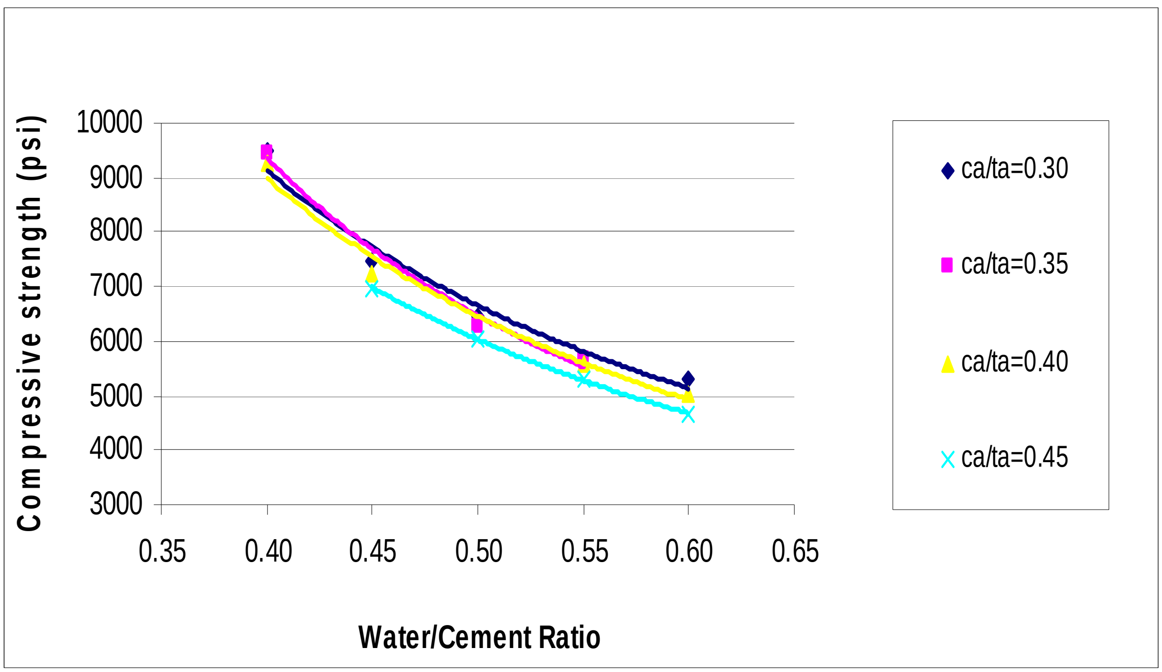

Figure 5-8 Effect of *ca/ta* in compressive strength for a total volume content of 69%

As it was mentioned before, mixtures with *ca/ta* = 0.45 present a high tendency for segregation. Concrete that segregates will not have uniform mechanical properties, including strength [4]. Then, the slight decrease in compressive strength presented in mixtures with ca/ta = 0.45 might be due to the segregation tendency of those mixtures.

The same tendency can be observed for aggregate volume content of 61% and 74%, as seen in Figure 5-9 and Figure 5-10 respectively.

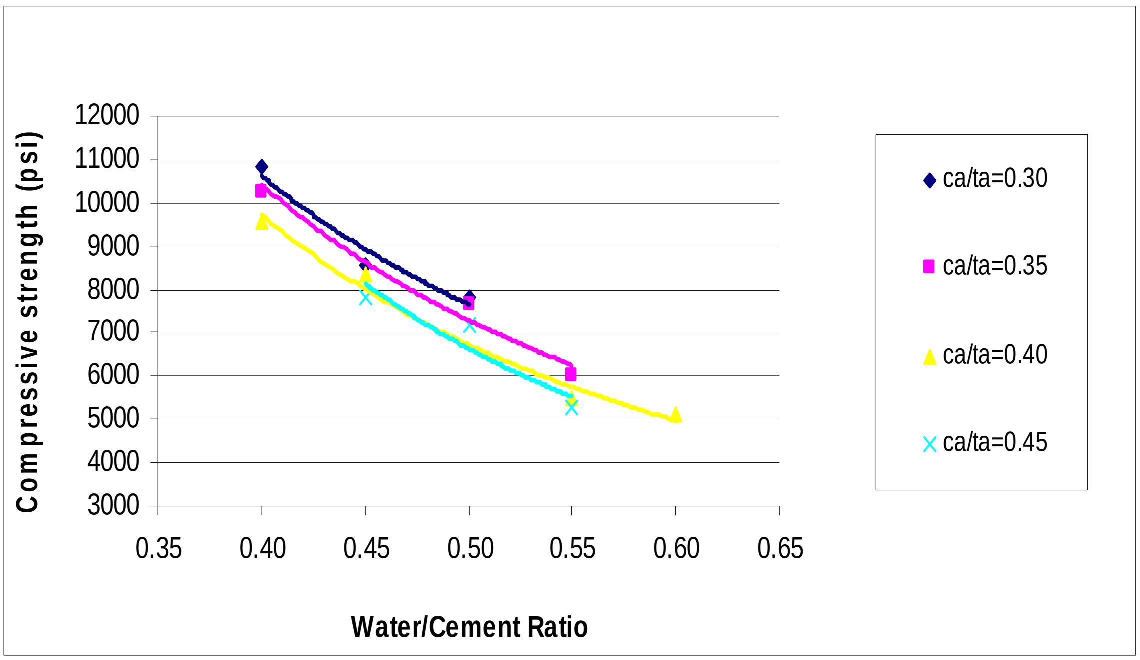

Figure 5-9 Effect of *ca/ta* in compressive strength for a total volume content of 61%

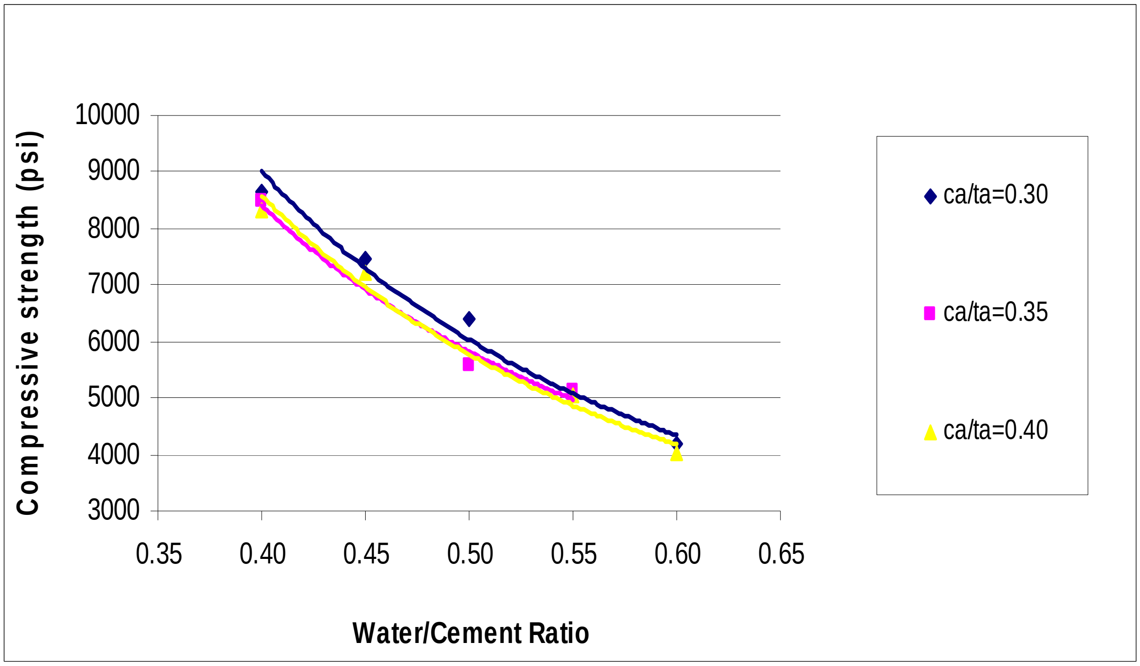

Figure 5-10 Effect of *ca/ta* in compressive strength for a total volume content of 74%

The little effect of *ca/ta* in compressive strength can be also seen in Figure 5-11. The small decrease in compressive strength when the *ca/ta* is increased might be due to the corresponding increase in coarse aggregate which tends to weaken the interfacial transition zone between cement paste and aggregate. However, the transition zone between fine aggregate and cement paste can also produce a decrease in compressive strength. Then, variations in compressive strength may be also due to the natural variation of concrete. As expected the compressive strength increases with a decrease in *w/c* ratio. The same tendency was seen for the other aggregate volume contents (61% and 74%).

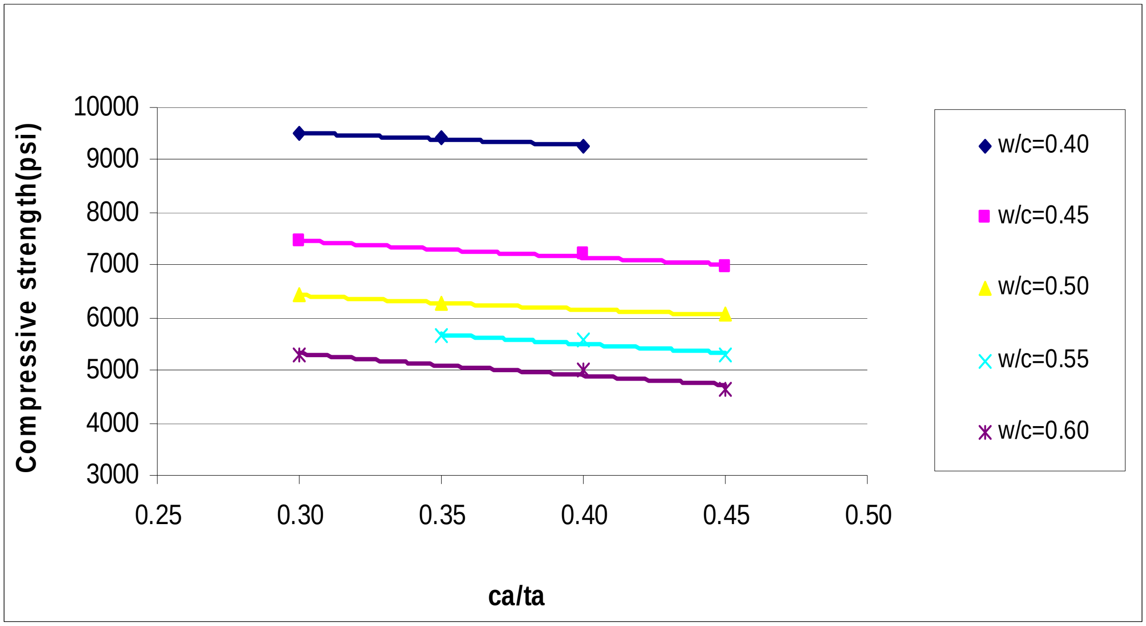

Figure 5-11 Effect of the *ca/ta* in compressive strength for different Water/Cement Ratios (volume aggregate content = 69%)

5.3.3 Comparison between compressive strength in self-consolidating concrete and conventional concrete samples

Four conventional concrete mixtures with *w/c* ratio of 0.40, 0.50, 0.55 and 0.60, were made in order to compare compressive strength and modulus elasticity values between the two types of concrete. The basis to compare both types of concrete will be their *w/c* ratio.

The material proportions and the dosage of the admixtures used for conventional concrete are indicated in section 4.3. Conventional concrete mixtures were defined according to the common practice used in CEMEX Puerto Rico. The total aggregate volume content of the 4 mixtures is approximately 70% with a coarse aggregate/total aggregate ratio (*ca/ta*) of 0.50, which is higher than those of SCC mixtures.

Figure 5-12, which uses the same data as Figure 5-3, shows the differences in compressive strength for the two types of concrete for different aggregate volume contents in the SCC mixtures. Conventional concrete mixtures present similar compressive strength as those for SCC containing total volume aggregate of 74% with the same *w/c* ratio. However, when conventional concrete strength are compared with those of similar aggregate volume content in SCC mixtures (69%) for the same *w/c* ratio, an increase in compressive strength can be observed in SCC mixtures.

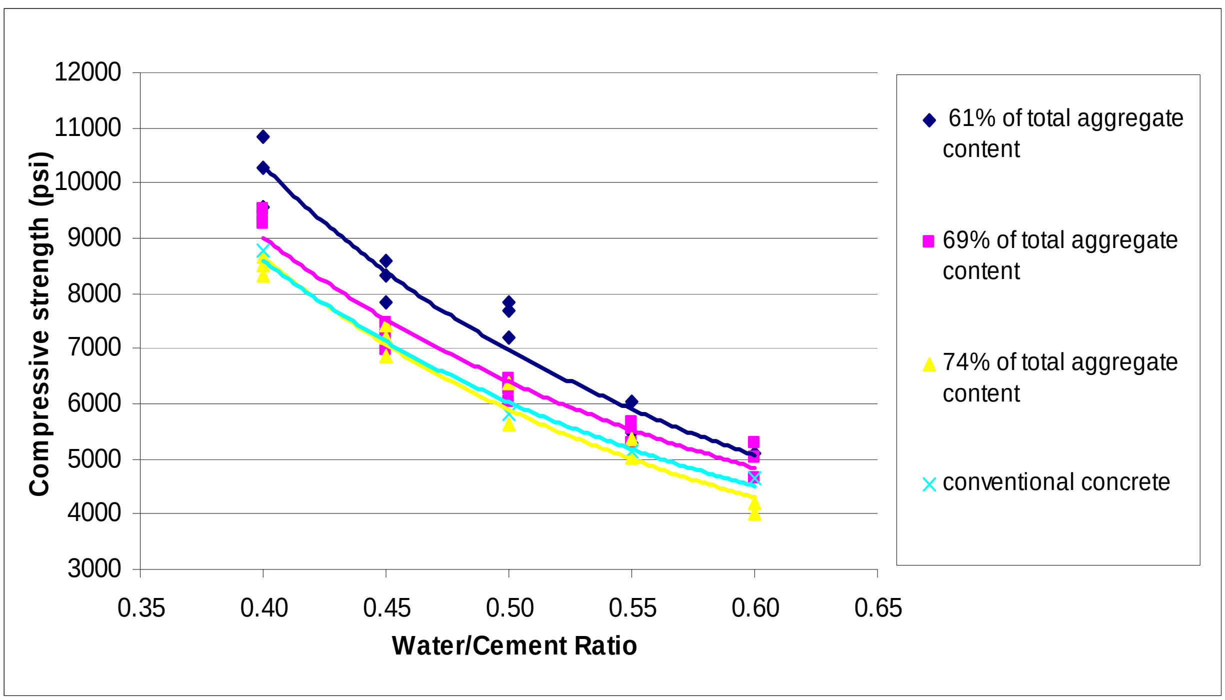

Figure 5-12 Comparison between compressive strength for SCC and conventional mixtures

The increase in compressive strength might be due to the considerable higher dosage of full range water reducing admixture (Glenium 3030) needed in the SCC mixtures compared with the dosage used in the conventional mixtures. Data obtained from the chemical company BASF (manufacturer of Glenium 3030) indicates that one of the main features of this admixture is the increase of the compressive strength and flexural strength performance at all ages.

Another study [5] indicated that after 28 days the reached compressive strength of SCC and normal vibrated concrete of similar composition does not differ significantly in published test results. Isolated cases, however, showed that at the same water/cement ratio slightly compressive strength were reached for SCC. They also indicated that there is insufficient research to result in generalized conclusions with this fact.

The higher *ca/ta* ratio used in conventional concrete mixture might slightly affect the compressive strength, since an increase in volume of coarse aggregate increases the interfacial transition zone; however, as mentioned before the effect of *ca/ta* in compressive strength is very small.

Table 5-6 displays the difference in compressive strength for the two types of concretes. As it was mentioned before conventional concrete mixtures have approximately the same compressive strength as those SCC mixtures containing 74% of aggregate volume for the same *w/c* ratio; except at a *w/c* ratio of 0.60 where an increase in compressive strength in the conventional mixture is observed.

An increase in SCC compressive strength between 7 and 12% is achieved in those mixtures containing 69% of aggregate volume when they are compared with those of conventional concrete with the same *w/c* ratio.

Table 5-6 Comparison between SCC and Conventional concrete compressive strength

Water/ cement ratio	Compressive strength for different aggregate volume content (psi)			
	61%	69%	74%	Conventional concrete
0.40	10215	9402	8490	8762
0.50	7561	6254	6006	5809
0.55	5605	5506	5206	5122
0.60	5109	4984	4097	4634

The increase in compressive strength in SCC mixtures containing 61 % is between 16 and 30% when they are compared with those of conventional concrete with *w/c* ratio of 0.40 and 0.50. For *w/c* ratios of 0.55 and 0.60 the increase in compressive strength is just 10%, which may be due to the decrease in the interfacial transition area between cement paste and aggregate, and the decrease in the amount of cement.

5.4 MODULUS OF ELASTICITY RESULTS

Table 5-3 shows the average values of the modulus elasticity obtained for each SCC and conventional mixtures. The individual results of the two concrete cylinders tested for modulus of elasticity can be seen in Appendix A.

5.4.1 Variation of modulus of elasticity for different volume aggregate contents

Figure 5-13 shows the relationship between compressive strength and modulus of elasticity for different aggregate contents. As it is expected there is an increase in modulus of elasticity with a corresponding increase in the volume aggregate content for a given compressive strength. The influence of the aggregate content is expected; knowing that coarse aggregate modulus of elasticity is higher than that of the cement paste in concrete, giving more stiffness to the material.

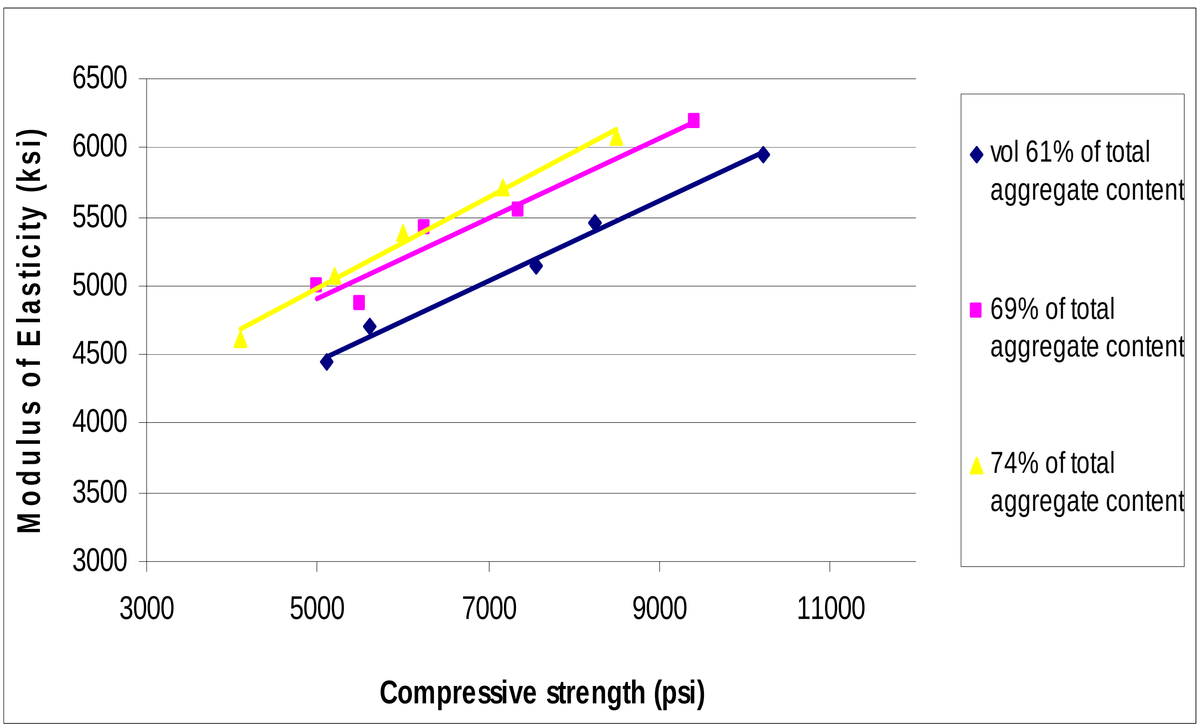

Figure 5-13 Relationship between compressive strength and modulus of elasticity for different aggregate content

The differences in modulus of elasticity between mixtures with aggregate volume content of 74% and 69% is not as wide as those mixtures containing a volume of 61%, which obviously presented the lowest modulus of elasticity for a given compressive strength. Similar conclusion has been made by Neville [20], who indicated that the volumetric proportions of aggregate and hydrated cement paste affect the value of the modulus of elasticity at a given strength of concrete.

In Figure 5-13, the modulus of elasticity values were plotted taking an average for the different *ca/ta* ratios at a given *w/c* ratio; since the influence of *ca/ta* in modulus of elasticity in negligible as it will be discussed later in this chapter.

The influence of the volume aggregate content for a given *w/c* ratio is shown in Figure 5-14,. It can be seen in this figure that *w/c* ratio has practically no effect on the modulus of elasticity in mixtures containing 69% and 74% of aggregate content. Comparing Figure 5-13 and Figure 5-14, it can be observed that the differences in modulus of elasticity when the total aggregate content is varied, are more appreciable when the modulus are compared for a given compressive strength and not for *w/c*. This fact can be explained by considering that for a given *w/c* ratio, compressive strengths vary depending on the aggregate volume content as can be seen in Figure 5-3. Then, in this case the modulus of elasticity is being affected more by the compressive strength as can be seen in Figure 5-13 than by for the *w/c* ratio.

ACI committee 237 [3] indicates that modulus of elasticity is related to compressive strength, aggregate type and content, and unit weight; therefore it would be more logical not to include *w/c* ratio as a factor that affects directly the modulus of elasticity, since compressive strength might vary depending on the volume aggregate content for a constant *W/C* ratio as it was already illustrated in Figure 5-3.

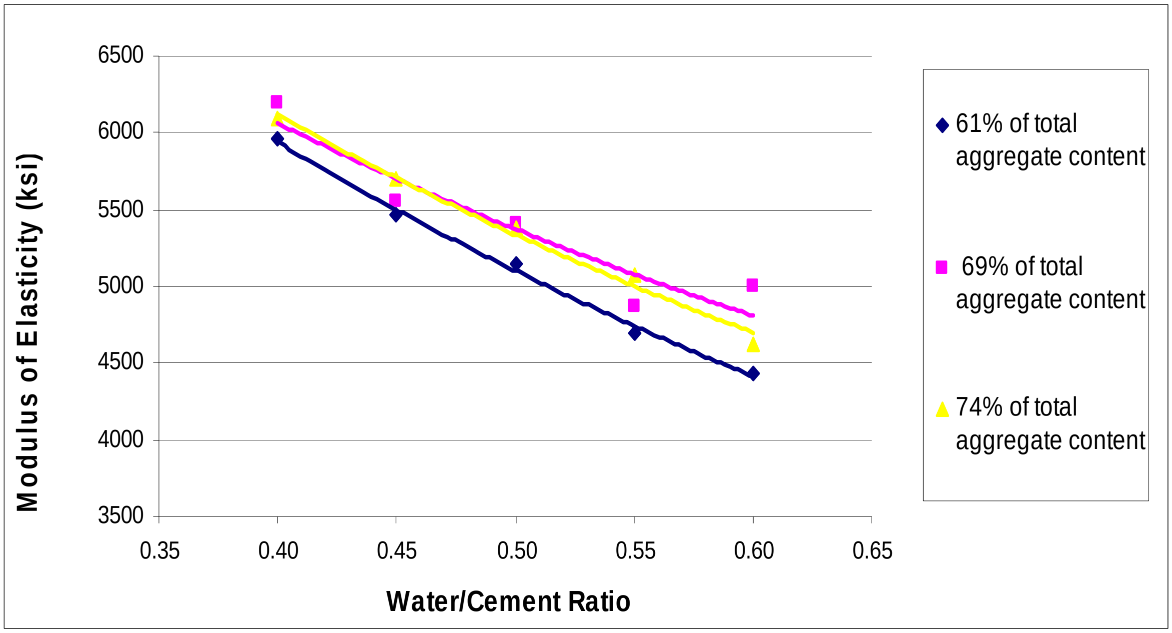

Figure 5-14 Relationship between Water/Cement Ratio and modulus of elasticity for different aggregate content

5.4.2 Variation of modulus of elasticity for different coarse aggregate/total aggregate ratio (*ca/ta*)

To explain the effect of *ca/ta* ratio in the modulus of elasticity the obtained data was analyzed plotting the modulus of elasticity values and water/cement ratio for each of the *ca/ta* ratio studied (0.30 to 0.45), keeping the total volume aggregate content constant.

As it can be seen in Figure 5-15 the *ca/ta* ratio have little effect on the modulus of elasticity. Similar finding were reported by Anton K. Schindler, and sue et al. [24], who concluded that when the volume of aggregate is held constant, the ratio sand / total aggregate does not affect significantly the modulus of elasticity of concrete [24]. A slightly higher modulus of elasticity might be expected for higher ca/ta ratios; since coarse aggregates tend to have higher modulus of elasticity than sand, giving more stiffness to concrete. The same tendency is seen in Figure 5-16 and Figure 5-17 for aggregate volume content of 61 and 74%.

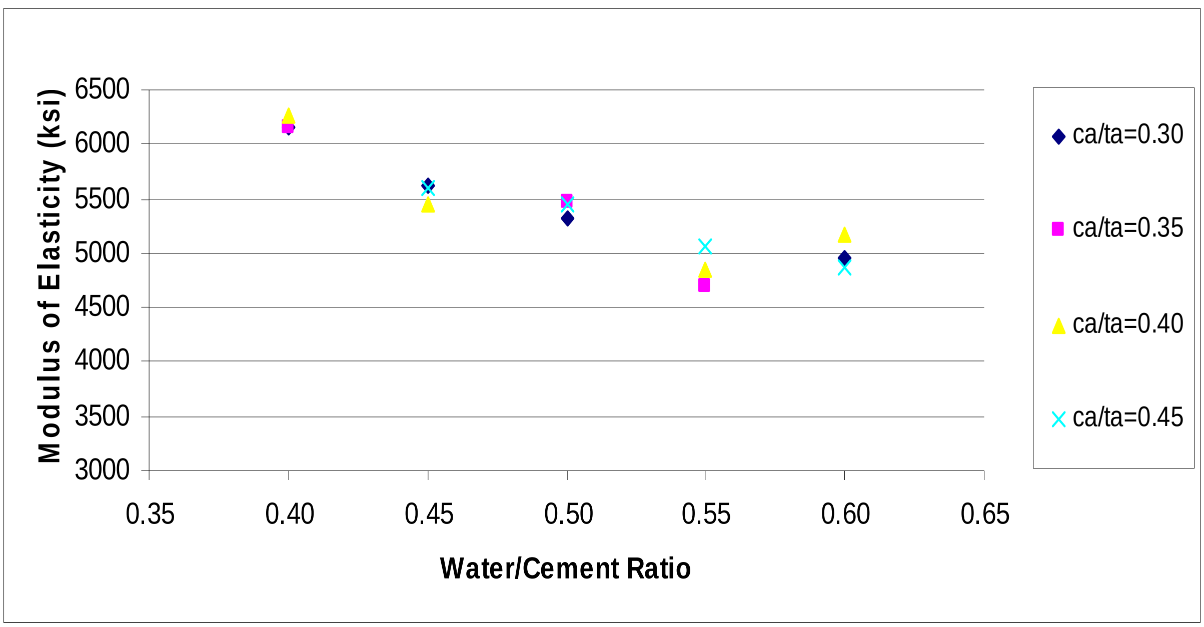

Figure 5-15 Effect of Water/Cement Ratio in modulus of elasticity for different *ca/ta* ratios (volume aggregate content = 69%)

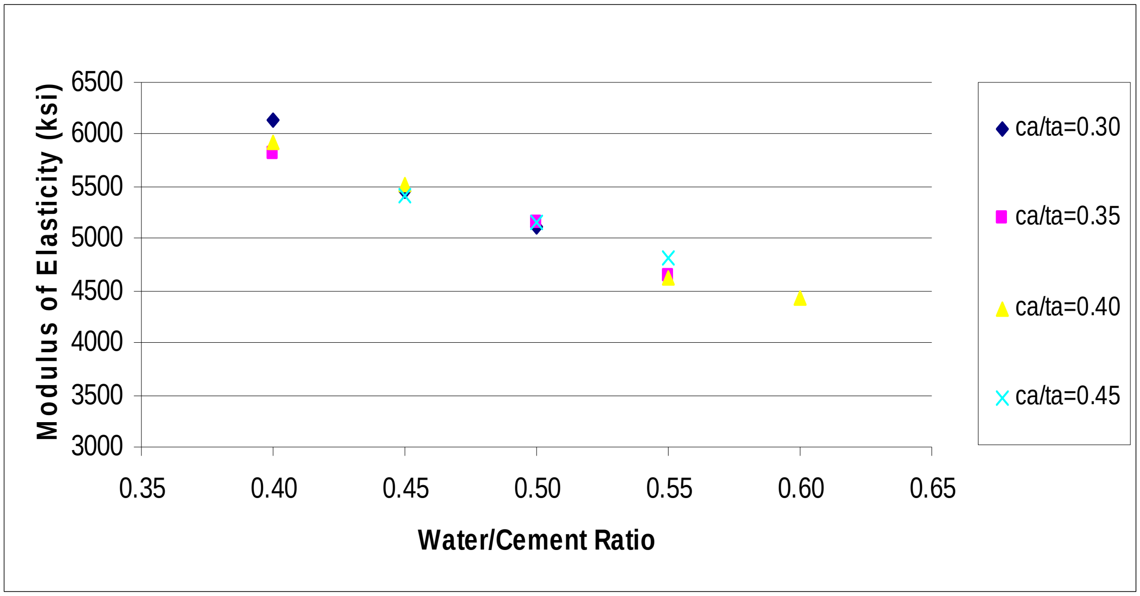

Figure 5-16 Effect of Water/Cement Ratio in modulus of elasticity for different *ca/ta* ratios (volume aggregate content = 61%)

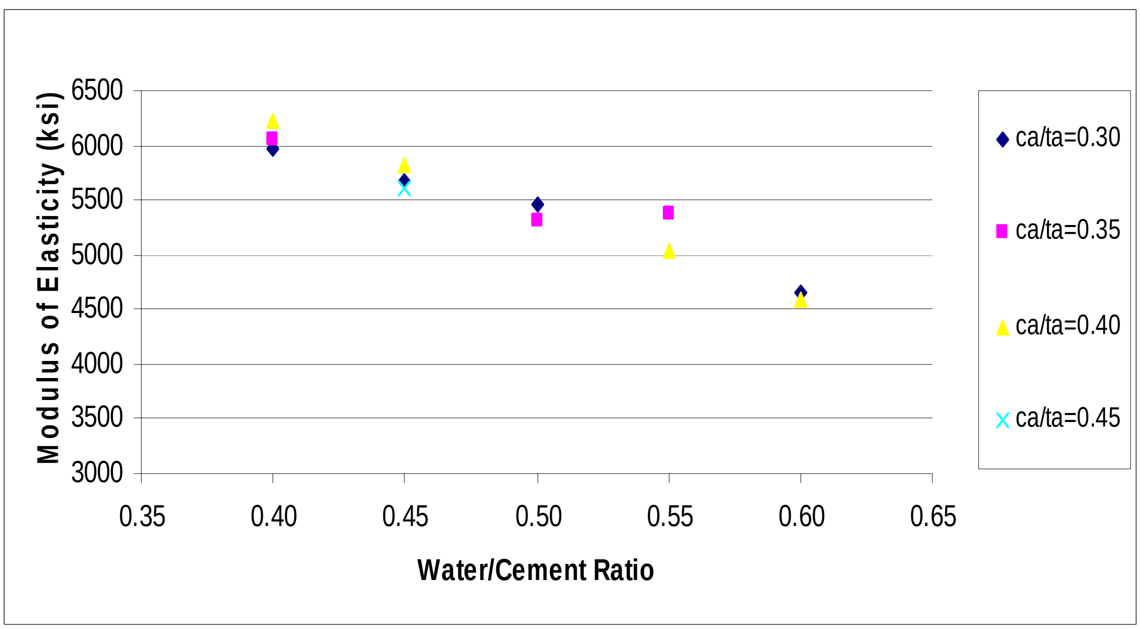

Figure 5-17 Effect of Water/Cement Ratio in modulus of elasticity for different *ca/ta* ratios (volume aggregate content = 74%)

Little variation in modulus of elasticity can be also observed for different *ca/ta* ratios in mixtures having approximately the same compressive strength (See Figure 5-18 through Figure 5-20).

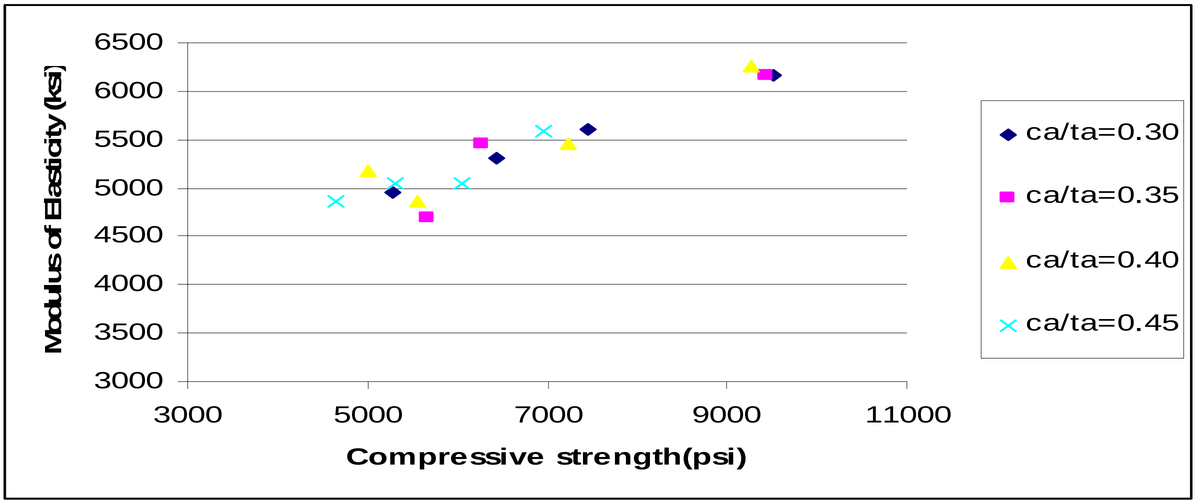

Figure 5-18 Relationship between compressive strength and modulus of elasticity for different *ca/ta* ratios (volume aggregate content = 69%)

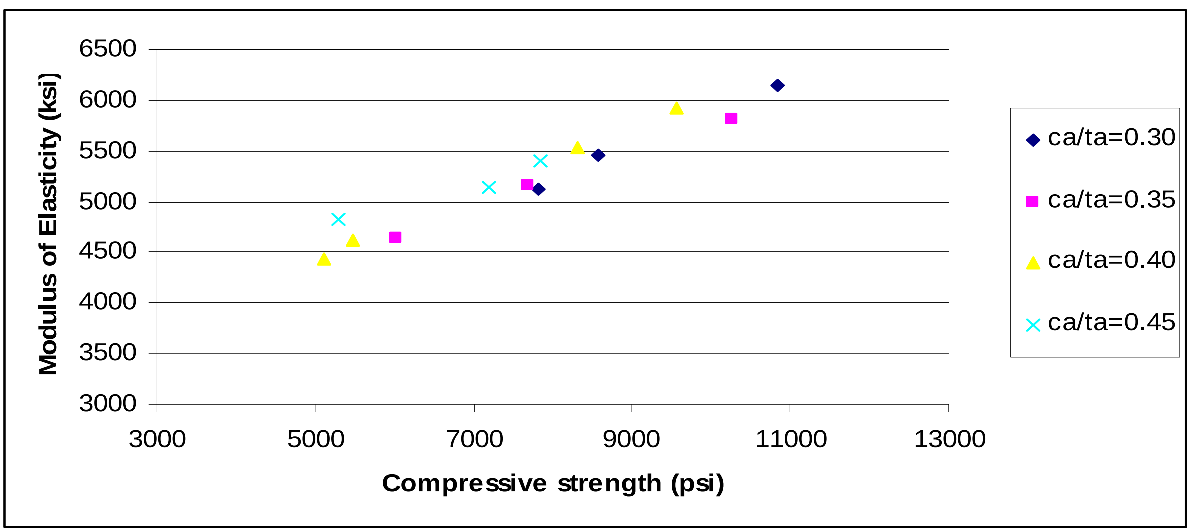

Figure 5-19 Relationship between compressive strength and modulus of elasticity for different ca/ta ratios (volume aggregate content = 61%)

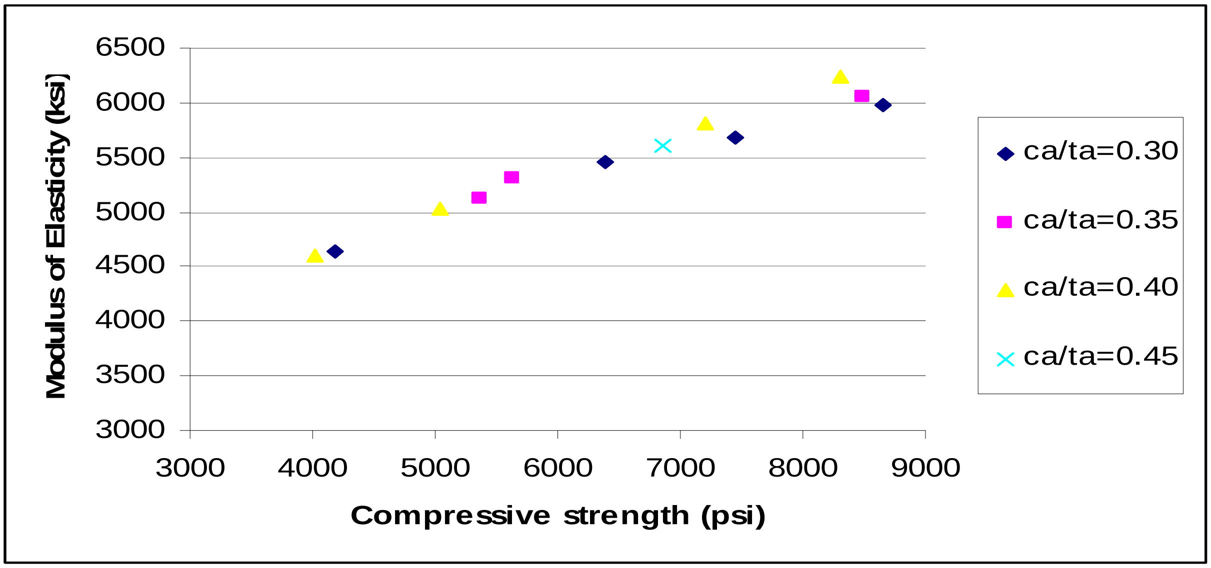

Figure 5-20 Relationship between compressive strength and modulus of elasticity for different ca/ta ratios (volume aggregate content = 74%)

5.4.3 Comparison between compressive strength in self-consolidating concrete and conventional concrete samples

Figure 5-21 shows the modulus of elasticity of all SCC and conventional concrete mixtures. As it is expected, SCC mixtures with a volume aggregate content of 61% present the lowest modulus of elasticity, and in fact there is a visible difference in modulus between these mixtures and the modulus obtained for conventional concrete mixtures at a given compressive strength. The higher modulus of elasticity in conventional concrete mixtures in this case, is due to the higher aggregate volume content, which was previously explained, for the same compressive strength.

However, a lower modulus of elasticity for SCC cannot be generalized for all cases. It will depend basically on the proportions of aggregate used. As seen in Figure 5-21, conventional concrete, and SCC mixtures with volume aggregate content of 69 and 74% of aggregate volume content, present similar modulus of elasticity at a given compressive strength.

For an easier comparison, the ratio of modulus of elasticity to square root of compressive strength for all mixtures is reported in Table 5-7 . A relationship of this form has been widely reported and it is permitted by design codes for the computation of modulus of elasticity [1].

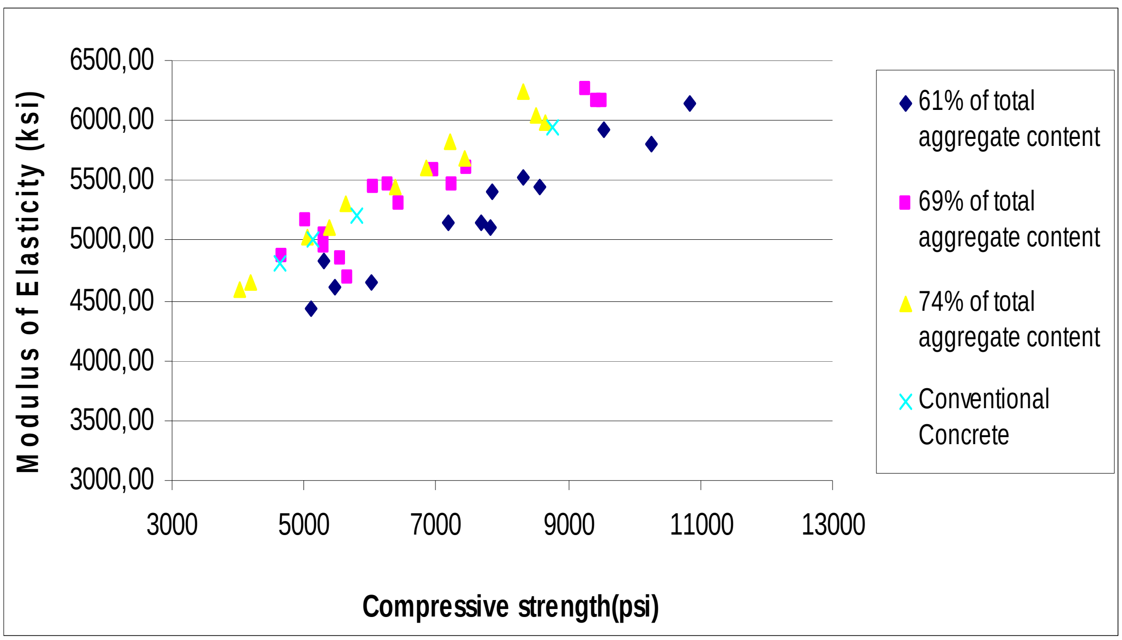

Figure 5-21 Comparison between SCC and conventional concrete modulus of elasticity

The ratio modulus of elasticity to square root of compressive strength for each aggregate volume content was taken as an average of all the mixtures with that aggregate volume. Appendix A shows all the relationship values for each mixture.

Table 5-7 Ratio $E/(f'c)^{0.5}$ for all mixtures

CONCRETE TYPE (Aggregate volume)	**$E/(f'c)^{0.5}$**
SCC (61%)	60427
SCC (69%)	66837
SCC (74%)	68687
Conventional	68094

SCC mixtures with 69% and 74% of aggregate volume content, and the conventional concrete mixtures have similar $E/(f'c)^{0.5}$ ratios. However, a difference can be noted with the SCC mixtures with 61% of total aggregate volume. The difference between modulus of elasticity for SCC mixtures with 61% of total volume aggregate and the other mixtures, including conventional concrete, are around 13% for a given compressive strength.

5.5 MODULUS OF ELASTICITY RESULTS AND ACI 318 EQUATIONS

Design codes provide certain expressions that allow engineers to compute approximately modulus of elasticity. Those expressions were already discussed in section 2.10. However, for the reader's convenience, they will be described again as follows:

$$E = w^{1.5} \times 33\sqrt{f_c^{'}}\ (psi) \qquad (2\text{-}1)$$

$$E = 57000\sqrt{f_c^{'}} \ (psi) \qquad (2\text{-}2)$$

$$E = 40000\sqrt{f_c^{'}} \times \left(\frac{145}{w}\right)^{1.5} + 1.0 \times 10^6 \ (psi) \qquad (2\text{-}3)$$

where:

$w =$ Unit weight of concrete in lb/ft^3, and

$f_c^{'} =$ Compressive strength of concrete in psi.

According to ACI 318 [1], equation 2-1 is valid for w values between 90 and 155 lb/ft^3, while is permitted to use equation 2-2 for $w = 145$ lb/ft^3.Equation 2-3 is recommended by ACI 363 committee 363 for high-strength concrete (concretes with a compressive strength higher than 6000).

The unit weight (w) indicated in equations 2-1 and 2-3 corresponds to dry concrete unit weight [1]. Pauw [18], who derived equation 2-1, indicated that in most of the analyzed data to derive this equation, dry concrete unit weight was not reported, being necessary to estimate it making practical assumptions. In fact, in common practice this value is not usually reported. Then, equation 2-2 is constantly used by engineers to compute modulus of elasticity.

In order to estimate dry concrete unit weight to analyze the data for this thesis, it is necessary to explain that in concrete, two types of water can be distinguished: evaporable and non-evaporable water. Non-evaporable water (w_n) approximately measures the amount of water combined structurally in the hydration products, and it is proportional to the amount of hydration that has occurred. Midness [32] indicates that w_n can be computed using the following equation:

$$w_n = 0.24\alpha \text{ gr/gr of original cement} \tag{5-1}$$

where:

w_n = Non-evaporable water, and

α = Degree of hydration.

When $\alpha = 1.0$ all cement is hydrated, and 0.24 grams of non-evaporable water is combined with each gram of cement [32]. Then, dry concrete unit weight could be estimated by computing non-evaporable water with equations like 5-1, and knowing all the concrete mixture components weights (cement, sand, and coarse aggregate). In this thesis dry concrete unit weights in all SCC mixtures were estimated by assuming that 0.25 grams of non-evaporable water is combined with each gram of cement in order to estimate non-evaporable weight. Cement, sand, and coarse aggregate weights in each SCC mixture were shown in section 4.3.

Table 5-8 displays the experimental SCC modulus of elasticity and its corresponding value calculated with ACI equations 2-1 and 2-3 .The estimated dry concrete for each mixture is also shown, and the variation ranges between the experimental modulus of elasticity and those computed with ACI equations are also indicated.

Table 5-8 Comparison between experimental modulus of elasticity and ACI equations

Mixture	Dry unit weight (lb/ft^3)	Experimental E (ksi)	ACI E (2-1) (ksi)	ACI E (2-3) (ksi)	Variation Range (2-1) (%)	Variation Range (2-3) (%)
SCC1	141.4	6144	5777	5036	6.4	22.0
SCC2	141.7	5807	5640	4938	3.0	17.6
SCC3	142.0	5924	5456	4807	8.6	23.2
SCC4	138.7	5454	4989	4498	9.3	21.3
SCC5	139.2	5528	4945	4463	11.8	23.9
SCC6	139.5	5409	4813	4369	12.4	23.8
SCC7	136.3	5114	4643	4264	10.2	19.9
SCC8	136.5	5155	4612	4241	11.8	21.5
SCC9	137.1	5148	4488	4150	14.7	24.1
SCC10	134.4	4648	3993	3806	16.4	22.1
SCC11	134.6	4620	3816	N/A	21.1	N/A
SCC12	134.9	4822	3765	N/A	28.1	N/A
SCC13	132.7	4439	3607	N/A	23.1	N/A
SCC14	145.7	6159	5661	4925	8.8	25.0
SCC15	146.0	6166	5654	4918	9.1	25.4
SCC16	146.3	6264	5625	4897	11.3	27.9
SCC17	143.5	5609	4897	4407	14.5	27.3
SCC18	144.1	5456	4858	4377	12.3	24.7
SCC19	144.4	5594	4778	4320	17.1	29.5
SCC20	141.6	5314	4461	4110	19.1	29.3
SCC21	141.9	5463	4418	4079	23.6	33.9
SCC22	142.5	5455	4369	4042	24.9	34.9
SCC23	140.2	4692	4119	N/A	13.9	N/A
SCC24	140.5	4853	4099	N/A	18.4	N/A
SCC25	140.8	5051	4015	N/A	25.8	N/A
SCC26	138.4	4947	3906	N/A	26.6	N/A
SCC27	139.0	5173	3829	N/A	35.1	N/A
SCC28	139.3	4868	3699	N/A	31.6	N/A
SCC29	148.4	5978	5552	4833	7.7	23.7
SCC30	148.7	6045	5519	4809	9.5	25.7
SCC31	149.1	6233	5475	4777	13.8	30.5
SCC32	146.6	5678	5052	4499	12.4	26.2
SCC33	147.2	5818	5005	4463	16.2	30.3
SCC34	147.5	5615	4894	4386	14.7	28.0
SCC35	145.0	5451	4602	4195	18.5	29.9
SCC36	145.3	5303	4335	N/A	22.3	N/A
SCC37	143.9	5114	4173	N/A	22.6	N/A
SCC38	144.2	5026	4056	N/A	23.9	N/A
SCC39	142.3	4645	3622	N/A	28.2	N/A
SCC40	142.9	4597	3570	N/A	28.7	N/A
CONV 1	147.5	5943	5533	4826	7.4	23.2
CONV 2	143.5	5209	4324	N/A	20.5	N/A
CONV 3	141.9	5005	3990	N/A	25.4	N/A
CONV 4	140.4	4807	3737	N/A	28.6	N/A

As seen in Table 5-8, all experimental modulus of elasticity data obtained in this thesis exceeded those moduli computed using ACI equations. The variation range between the experimental modulus of elasticity and the values given by equation 2-1 is between 3% and 29%; and between 17% and 35% for values given by equation 2-3. The calculation of modulus of elasticity using equation 2-3 was limited to mixtures with compressive strength above 6000 psi.

The experimental modulus of elasticity values are expected to differ from those computed from ACI equations, since the equations were derived using different kind of aggregates. Then a variation range is expected, knowing that concrete modulus of elasticity is quite sensitive to the modulus of elasticity of the aggregate. Therefore, these variation ranges can be considered reasonable considering the wide variation involved. Figure 5-22 displays the modulus of elasticity computed with equation 2-1; which is the equation indicating in ACI 318, versus the experimental modulus of elasticity.

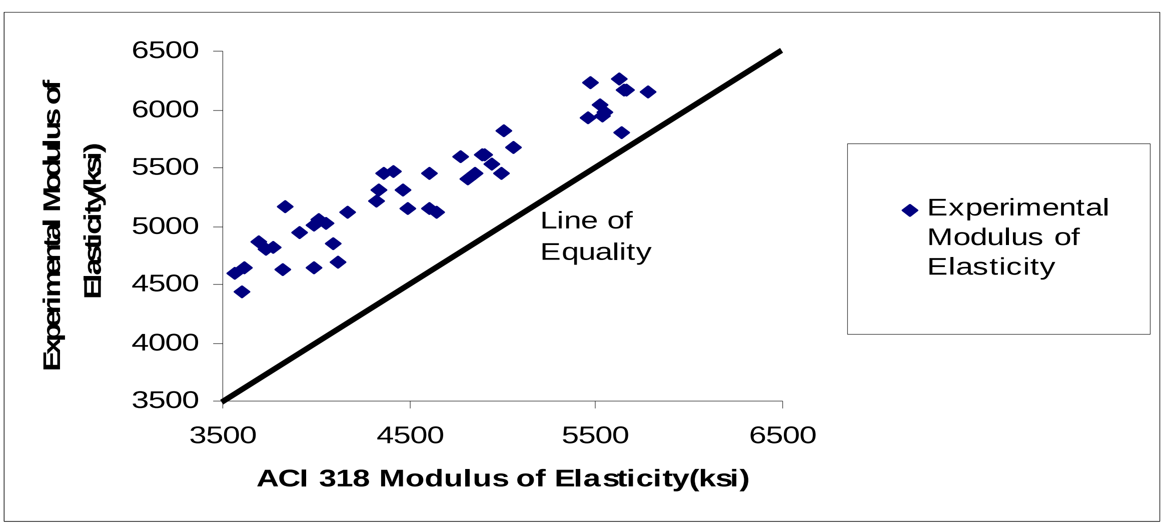

Figure 5-22 Modulus of elasticity computed with ACI 318 equation (2-1) versus experimental modulus of elasticity

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 INTRODUCTION

This objective of this chapter is to describe the work carried out and to summarize the conclusions made from the findings of this thesis. Recommendations for future research work are also indicated.

6.2 SUMMARY AND CONLUSIONS

This thesis presented a parametric study to evaluate the modulus of elasticity of self–consolidating (SCC) concrete. Other properties such as compressive strength, slump flow and segregation tendency were also evaluated.

Forty SCC mixtures were made varying the following parameters: water/cement ratio, total aggregate volume, and coarse aggregate/total aggregate ratios *(ca/ta)***.** Four additional conventional concrete mixtures were made for comparison purposes.

The data obtained in the experimental program was analyzed in the following order:

- Fresh concrete properties: Slump flow, segregation tendency using the visual stability index (VSI), and unit weight results were shown and explained.
- Compressive strength results: The influence of water/cement ratio (*w/c*), total aggregate volume content, and coarse aggregate/total aggregate ratio by volume (*ca/ta*)**,** in SCC

compressive strength was studied. A comparison between SCC and conventional concrete compressive strength was also reported.

- Modulus of elasticity results: The influence of the proposed parameters (*w/c* ratio, total aggregate volume content, and *ca/ta*) and the compressive strength results in the SCC modulus of elasticity was analyzed. A comparison between SCC and conventional concrete modulus of elasticity was also reported.
- SCC modulus of elasticity and ACI equations: The experimental SCC modulus of elasticity was compared to those computed using design codes (ACI 318-05) to know whether those expressions are suitable for SCC or not.

Based on the analysis mentioned above the main conclusions of this work are summarized as follows:

- Higher moduli of elasticity were observed when the total aggregate volume content was increased at a given compressive strength based on the fact that aggregate is stiffer than concrete paste.
- ca/ta have negligible effect on SCC modulus of elasticity when the total aggregate volume is kept constant for the same *w/c* ratio and similar compressive strength.
- SCC and conventional concrete modulus of elasticity have approximately the same values when they have similar proportions and compressive strengths. A lower modulus of elasticity is expected for SCC when the total aggregate volume content is decreased. A decrease in SCC modulus of elasticity (mixtures containing 61% of aggregate volume content) of about 12 % was observed when compared to conventional concrete mixtures modulus of elasticity.

- An improvement in SCC modulus of elasticity can be obtained when the total aggregate volume is increased. However, the mixture proportion should be made carefully to avoid segregation tendency as observed in some of the mixtures containing 74% of total aggregate volume.
- Equations suggested by design codes (ACI 318-05) for calculating concrete modulus of elasticity returned reasonable estimates in computing SCC modulus of elasticity. The equation given for high strength concrete seems to produce more conservative results, especially in those cases with high strength mixtures containing the lowest aggregate volume content (61%).
- In common practice, when it is required to change a building project, which was originally planned to be built using conventional concrete, to be built with SCC, it should be considered that if the total aggregate volume in SCC is lower, a decrease in modulus of elasticity is expected for a given compressive strength. Although, equations given by ACI code returned conservative results for the data analyzed in this thesis, precaution should be taken when different aggregate type are used; specially lightweight aggregate, when the aggregate content is low.
- SCC compressive strength increased with a decrease in *w/c* ratio as expected keeping the total aggregate constant. However, an increase in compressive strength was also observed when the total aggregate volume is decreased for the same *w/c* ratio. This fact can be explained since the interfacial transition zone between aggregate and paste is lower when the aggregate volume is decreased.
- The variation of ca/ta produced negligible effects on compressive strength for a given aggregate volume content and the same w/c ratio.

- Slightly higher compressive strengths were observed in SCC mixtures when compared to those of similar proportions and the same *w/c* ratio. The higher strength observed in SCC mixtures might be due to the higher dosage of water- reducing admixture. The increase in ca/ta (0.5 in conventional concrete) may not have a major influence in compressive strength, since as it was mentioned before ca/ta has little effect on compressive strength at the same aggregate volume content.
- An increase in cement increases the flowability of SCC mixtures. The same tendency was observed when the fine aggregate content was increased (for lower *ca/ta* ratios). Then, an increase in the fine materials (cement and sand) increases the flowability of SCC mixtures by reducing the risk of blockage with the coarse aggregate.
- The segregation tendency was higher with an increase in the amount of water. An increase in the water content reduces the ability to maintain a uniform distribution of large coarse aggregate. For mixtures containing the lowest aggregate volume content (61%) unacceptable segregation behavior were observed for *w/c* ratios of 0.55 and 0.6. For mixtures containing the highest aggregate content (74%) higher segregation tendency were observed for ca/ta ratio of 0.4 and 0.45 due to the high coarse aggregate content required in these mixtures.

6.3 RECOMMENDATIONS FOR FUTURE WORK

The following recommendations for future research work are proposed in order to evaluate the influence of other parameters in modulus of elasticity, which were not studied in this research project:

- A study using different types of aggregate, including lightweight aggregate, should be carried out, since as it is known, modulus of elasticity is greatly affected by the modulus of elasticity of aggregate and besides, the expressions given by codes were derived from a wide variety of aggregates.
- The effect of cementitious materials such as silica fume, fly ash and slag in the modulus of elasticity varying different aggregate volume content should also be studied in order to determine if they have direct influence on SCC modulus of elasticity.

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APPENDIX A

TABULATED DATA

Table A.1 shows the ultimate compressive strength obtained in the first cylinder tested in order to get the 40% of concrete compressive strength required to determine modulus of elasticity.

Table A.2 displays all the compressive strength (f'c) and modulus of elasticity (E) values obtained for each concrete cylinder in all the mixtures. The compressive strength was computed by dividing the compressive load of each sample; as seen in table A.2.2, by the cross sectional area of the specimen (12.566 in^2).

Finally, Table A.3 shows the ratios modulus of elasticity to square root of compressive strength (K) for all mixtures.

Table A-1 40% of Compressive strength to determine modulus of elasticity

Mixture	Ultimate Compressive Load (p)	Ultimate compressive Stress (psi)	40% Ultimate Compressive Strength (psi)
SCC1	139810	11126	4450
SCC2	130710	10402	4161
SCC3	120340	9581	3832
SCC4	105700	8412	3365
SCC5	103820	8262	3305
SCC6	95330	7586	3035
SCC7	97420	7753	3101
SCC8	96540	7683	3073
SCC9	92610	7370	2948
SCC10	76840	6115	2446
SCC11	71210	5667	2267
SCC12	67390	5363	2145
SCC13	65020	5174	2070
SCC14	119020	9472	3789
SCC15	120340	9577	3831
SCC16	116580	9277	3711
SCC17	89720	7140	2856
SCC18	90370	7192	2877
SCC19	89550	7126	2851
SCC20	81330	6472	2589
SCC21	80020	6368	2547
SCC22	77160	6140	2456
SCC23	74640	5940	2376
SCC24	72210	5746	2299
SCC25	70460	5607	2243
SCC26	67830	5398	2159
SCC27	62260	4955	1982
SCC28	59310	4720	1888
SCC29	111180	8848	3539
SCC30	106260	8456	3382
SCC31	105540	8399	3360
SCC32	93920	7474	2990
SCC33	92170	7335	2934
SCC34	87260	6944	2778
SCC35	78650	6259	2504
SCC36	72320	5755	2302
SCC37	69030	5493	2197
SCC38	64370	5123	2049
SCC39	53790	4281	1712
SCC40	52010	4139	1656
CONV 1	110970	8831	3532
CONV 2	73730	5867	2347
CONV 3	64260	5114	2046
CONV 4	58700	4671	1869

Table A-2 Compressive Strength and Modulus of Elasticity Data

Mixture	Compressive Load Sample 1 (p)	Compressive Load Sample 2 (p)	f'c Sample 1 (psi)	f'c Sample 2 (psi)	Average f'c (psi)	E Sample 1 (ksi)	E Sample 2 (ksi)	Average E (ksi)
SCC1	134540	137640	10707	10953	10830	5887	6402	6144
SCC2	129500	128460	10306	10223	10264	5581	6033	5807
SCC3	117770	122250	9372	9729	9550	5744	6103	5924
SCC4	105670	109700	8409	8730	8570	5324	5584	5454
SCC5	104250	104900	8296	8348	8322	5748	5309	5528
SCC6	99840	97190	7945	7734	7840	5243	5574	5409
SCC7	98790	97840	7862	7786	7824	5230	4998	5114
SCC8	94370	98510	7510	7839	7675	5303	5007	5155
SCC9	90630	89940	7212	7157	7185	5288	5008	5148
SCC10	75320	76300	5994	6072	6033	4789	4506	4648
SCC11	69140	68560	5502	5456	5479	4579	4662	4620
SCC12	68570	64670	5457	5146	5302	5045	4599	4822
SCC13	64750	63640	5153	5064	5109	4576	4301	4439
SCC14	117950	121020	9386	9631	9509	5909	6409	6159
SCC15	119230	117640	9488	9362	9425	6010	6321	6166
SCC16	116030	117020	9234	9312	9273	6133	6395	6264
SCC17	91820	95330	7307	7586	7447	5829	5390	5609
SCC18	90400	91460	7194	7278	7236	5304	5609	5456
SCC19	88520	86320	7044	6869	6957	5403	5784	5594
SCC20	80430	81250	6401	6466	6434	5165	5463	5314
SCC21	78490	79140	6246	6298	6272	5576	5349	5463
SCC22	76000	76190	6048	6063	6056	5402	5508	5455
SCC23	72020	70060	5731	5575	5653	4607	4777	4692
SCC24	69240	70510	5510	5611	5561	4712	4995	4853
SCC25	65960	67690	5249	5387	5318	4996	5106	5051
SCC26	67200	65680	5348	5227	5287	5014	4879	4947
SCC27	64040	61990	5096	4933	5015	5258	5088	5173
SCC28	55900	60970	4449	4852	4650	4709	5027	4868

Mixture	Compressive Load Sample 1 (p)	Compressive Load Sample 2 (p)	f'c Sample 1 (psi)	f'c Sample 2 (psi)	Average f'c (psi)	E Sample 1 (ksi)	E Sample 2 (ksi)	Average E (ksi)
SCC29	109050	108570	8678	8640	8659	5908	6049	5978
SCC30	106320	107290	8461	8538	8500	6112	5978	6045
SCC31	104900	104000	8348	8276	8312	6347	6118	6233
SCC32	92860	94170	7390	7494	7442	5773	5583	5678
SCC33	91530	89630	7284	7133	7208	5648	5988	5818
SCC34	87030	85050	6926	6768	6847	5721	5509	5615
SCC35	79480	80960	6325	6443	6384	5578	5323	5451
SCC36	71150	70290	5662	5594	5628	5487	5119	5303
SCC37	67960	67030	5408	5334	5371	5182	5047	5114
SCC38	61490	65200	4893	5189	5041	4838	5213	5026
SCC39	54670	50490	4351	4018	4184	4787	4502	4645
SCC40	49040	51780	3903	4121	4012	4802	4391	4597
CONV 1	109180	111030	8689	8836	8762	5878	6009	5943
CONV 2	73210	72780	5826	5792	5809	5079	5340	5209
CONV 3	64850	63880	5161	5084	5122	4825	5184	5005
CONV 4	57640	58830	4587	4682	4634	4913	4701	4807

Table A-3 Ratios modulus of elasticity to square root of compressive strength (K) for all mixtures

Mixture	w/c	ca/ta	Average f'c (psi)	Average E (ksi)	K
SCC1	0.4	0.3	10830	6144	59042
SCC2	0.4	0.35	10264	5807	57319
SCC3	0.4	0.4	9550	5924	60614
SCC4	0.45	0.3	8570	5454	58916
SCC5	0.45	0.4	8322	5528	60600
SCC6	0.45	0.45	7840	5409	61085
SCC7	0.5	0.3	7824	5114	57818
SCC8	0.5	0.35	7675	5155	58841
SCC9	0.5	0.45	7185	5148	60738
SCC10	0.55	0.35	6033	4648	59836
SCC11	0.55	0.4	5479	4620	62422
SCC12	0.55	0.45	5302	4822	66223
SCC13	0.6	0.4	5109	4439	62102
SCC14	0.4	0.3	9509	6159	63161
SCC15	0.4	0.35	9425	6166	63510
SCC16	0.4	0.4	9273	6264	65048
SCC17	0.45	0.3	7447	5609	65001
SCC18	0.45	0.4	7236	5456	64144
SCC19	0.45	0.45	6957	5594	67062
SCC20	0.5	0.3	6434	5314	66252
SCC21	0.5	0.35	6272	5463	68975
SCC22	0.5	0.45	6056	5455	70099
SCC23	0.55	0.35	5653	4692	62400
SCC24	0.55	0.4	5561	4853	65083
SCC25	0.55	0.45	5303	5051	69362
SCC26	0.6	0.3	5287	4947	68029
SCC27	0.6	0.4	5015	5173	73047
SCC28	0.6	0.45	4650	4868	71383
SCC29	0.4	0.3	8659	5978	64247
SCC30	0.4	0.35	8500	6045	65573
SCC31	0.4	0.4	8312	6233	68362
SCC32	0.45	0.3	7442	5678	65821
SCC33	0.45	0.4	7208	5818	68526
SCC34	0.45	0.45	6847	5615	67857
SCC35	0.5	0.3	6384	5451	68221
SCC36	0.5	0.35	5628	5303	70689
SCC37	0.55	0.35	5371	5114	69785
SCC38	0.55	0.4	5041	5026	70789
SCC39	0.6	0.3	4184	4645	71804
SCC40	0.6	0.4	4012	4597	72577
CONV 1	0.4	0.5	8762	5943	63490
CONV 2	0.5	0.5	5809	5209	68349
CONV 3	0.55	0.5	5122	5005	69926
CONV 4	0.6	0.5	4634	4807	70609

APPENDIX B

EXAMPLE TO DETERMINE MODULUS OF ELASTICITY

Figure B-1 is an example of the way to determine the concrete modulus of elasticity in this thesis according to ASTM C469. Table B.1 shows all the output data obtained the data acquisition program (Lab View) for one of the two cylinders tested for modulus of elasticity in Mixture SCC7, the same procedure was made for the rest of the mixtures. The displacements and strains were determined as it was explained in chapter 4. The 40% percent of the ultimate compressive strength and its corresponding strain were obtained by interpolating in the two values underlined. The same procedure was made to get the stress corresponding to a 0.000050 strain. Two typical stress-strain diagrams are shown in figure B-2 and B-3.

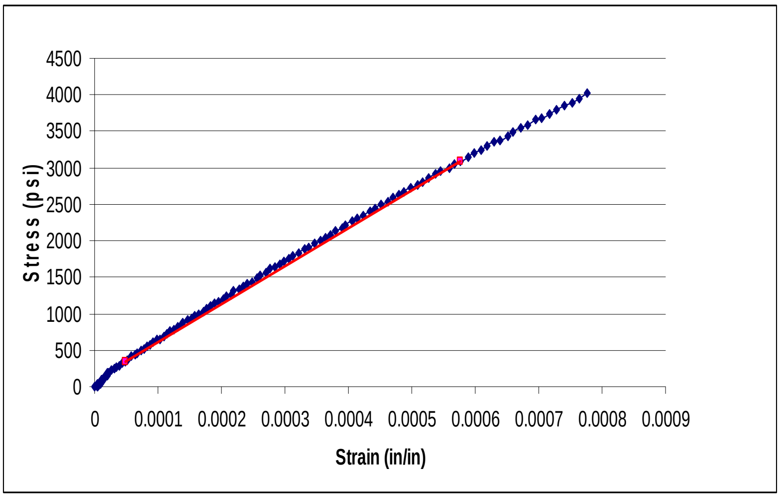

Figure B-1 Stress-Strain diagram example to determine modulus of elasticity

Table B-1 Data obtained from the data acquisition program to compute modulus of elasticity

Mixture SCC 7 (Sample 1)					
Test Starts at a Displacement of:			0.255081765 in		
Read Displacement by LVDT (in)	**Load (Load Cell) (p)**	**Displacement (in)**	**Real DisplacementI(in)**	**Strain (in/in)**	**Stress (psi)**
0.25508176	0	0	0	0	0
0.255026	85.351518	-5.5765E-05	2.7882E-05	4.6471E-06	6.79550303
0.255041	232.142751	-4.0765E-05	2.0382E-05	3.3971E-06	18.4827031
0.255026	53.791403	-5.5765E-05	2.7882E-05	4.6471E-06	4.28275502
0.255026	374.530246	-5.5765E-05	2.7882E-05	4.6471E-06	29.8192871
0.255026	161.682959	-5.5765E-05	2.7882E-05	4.6471E-06	12.8728471
0.255026	202.050548	-5.5765E-05	2.7882E-05	4.6471E-06	16.0868271
0.255026	378.200027	-5.5765E-05	2.7882E-05	4.6471E-06	30.1114671
0.255011	166.086696	-7.0765E-05	3.5382E-05	5.8971E-06	13.2234631
0.255011	380.401896	-7.0765E-05	3.5382E-05	5.8971E-06	30.2867752
0.255011	379.667939	-7.0765E-05	3.5382E-05	5.8971E-06	30.2283391
0.255011	413.429923	-7.0765E-05	3.5382E-05	5.8971E-06	32.9163951
0.255011	237.280444	-7.0765E-05	3.5382E-05	5.8971E-06	18.8917551
0.255011	345.905956	-7.0765E-05	3.5382E-05	5.8971E-06	27.5402831
0.254996	486.091583	-8.5765E-05	4.2882E-05	7.1471E-06	38.7015592
0.254996	527.193128	-8.5765E-05	4.2882E-05	7.1471E-06	41.9739752
0.254995	419.301572	-8.6765E-05	4.3382E-05	7.2304E-06	33.3838831
0.25498	420.035528	-0.00010176	5.0882E-05	8.4804E-06	33.4423191
0.254995	384.071676	-8.6765E-05	4.3382E-05	7.2304E-06	30.5789551
0.254965	494.165101	-0.00011676	5.8382E-05	9.7304E-06	39.3443552
0.254949	745.178108	-0.00013276	6.6382E-05	1.1064E-05	59.3294672
0.254964	747.379977	-0.00011776	5.8882E-05	9.8137E-06	59.5047752
0.25498	824.445374	-0.00010176	5.0882E-05	8.4804E-06	65.6405553
0.254934	1078.39421	-0.00014776	7.3882E-05	1.2314E-05	85.8594113
0.254949	1081.33003	-0.00013276	6.6382E-05	1.1064E-05	86.0931553
0.254933	1225.91939	-0.00014876	7.4382E-05	1.2397E-05	97.6050473
0.254918	1409.40844	-0.00016376	8.1882E-05	1.3647E-05	112.214047
0.254903	1555.46571	-0.00017876	8.9382E-05	1.4897E-05	123.842811
0.254887	1592.16352	-0.00019476	9.7382E-05	1.623E-05	126.764611
0.254841	1922.44379	-0.00024076	0.00012038	2.0064E-05	153.060811
0.254841	2069.96898	-0.00024076	0.00012038	2.0064E-05	164.806448
0.25481	2325.38573	-0.00027176	0.00013588	2.2647E-05	185.142176
0.254841	2474.37883	-0.00024076	0.00012038	2.0064E-05	197.004684
0.254764	2949.24846	-0.00031776	0.00015888	2.648E-05	234.812776
0.254702	3062.27771	-0.00037976	0.00018988	3.1647E-05	243.81192
0.254671	3465.9536	-0.00041076	0.00020538	3.423E-05	275.95172
0.25461	3580.45076	-0.00047176	0.00023588	3.9314E-05	285.067736
0.254563	4091.28425	-0.00051876	0.00025938	4.323E-05	325.739192
0.254501	4236.60757	-0.00058076	0.00029038	4.8397E-05	337.30952
0.254455	4640.28346	-0.00062676	0.00031338	5.223E-05	369.44932
0.254393	5152.58486	-0.00068876	0.00034438	5.7397E-05	410.237648
0.254317	5449.83711	-0.00076476	0.00038238	6.373E-05	433.904228
0.25427	5815.34728	-0.00081176	0.00040588	6.7647E-05	463.005356
0.254208	6216.8213	-0.00087376	0.00043688	7.2814E-05	494.969848
0.254147	6548.56948	-0.00093476	0.00046738	7.7897E-05	521.382921
0.254085	6986.74131	-0.00099676	0.00049838	8.3064E-05	556.269213

0.254039	7209.86399	-0.00104276	0.00052138	8.6897E-05	574.033757
0.253977	7573.90624	-0.00110476	0.00055238	9.2064E-05	603.018013
0.2539	8160.33722	-0.00118176	0.00059088	9.848E-05	649.708377
0.253853	8235.9347	-0.00122876	0.00061438	0.0001024	655.727285
0.253761	8711.53829	-0.00132076	0.00066038	0.00011006	693.593813
0.253715	9044.02043	-0.00136676	0.00068338	0.0001139	720.065321
0.253653	9663.47944	-0.00142876	0.00071438	0.00011906	769.385305
0.253591	9849.9043	-0.00149076	0.00074538	0.00012423	784.228049
0.253514	10218.3503	-0.00156776	0.00078388	0.00013065	813.562921
0.253437	10801.1115	-0.00164476	0.00082238	0.00013706	859.961106
0.253406	11061.6659	-0.00167576	0.00083788	0.00013965	880.705886
0.253313	11463.1399	-0.00176876	0.00088438	0.0001474	912.670378
0.253236	11725.1623	-0.00184576	0.00092288	0.00015381	933.53203
0.25319	12164.802	-0.00189176	0.00094588	0.00015765	968.535194
0.253113	12569.9458	-0.00196876	0.00098438	0.00016406	1000.79187
0.25302	13005.9158	-0.00206176	0.00103088	0.00017181	1035.50285
0.252959	13375.8297	-0.00212276	0.00106138	0.0001769	1064.95459
0.252897	13957.8569	-0.00218476	0.00109238	0.00018206	1111.29434
0.252804	14251.4394	-0.00227776	0.00113888	0.00018981	1134.66874
0.252743	14585.3895	-0.00233876	0.00116938	0.0001949	1161.25712
0.25265	15099.1588	-0.00243176	0.00121588	0.00020265	1202.16232
0.252588	15608.5243	-0.00249376	0.00124688	0.00020781	1242.71691
0.252496	15833.1149	-0.00258576	0.00129288	0.00021548	1260.59832
0.252449	16418.812	-0.00263276	0.00131638	0.0002194	1307.23025
0.252342	16789.4598	-0.00273976	0.00136988	0.00022831	1336.74043
0.252264	17262.8615	-0.00281776	0.00140888	0.00023481	1374.43165
0.252187	17738.4651	-0.00289476	0.00144738	0.00024123	1412.29818
0.252095	18077.5529	-0.00298676	0.00149338	0.0002489	1439.29561
0.252002	18694.0761	-0.00307976	0.00153988	0.00025665	1488.38185
0.251955	19245.2771	-0.00312676	0.00156338	0.00026056	1532.26729
0.251832	19646.7512	-0.00324976	0.00162488	0.00027081	1564.23178
0.251755	20341.8076	-0.00332676	0.00166338	0.00027723	1619.57067
0.251663	20600.8942	-0.00341876	0.00170938	0.0002849	1640.19858
0.25157	21075.7638	-0.00351176	0.00175588	0.00029265	1678.00667
0.251493	21523.4771	-0.00358876	0.00179438	0.00029906	1713.65263
0.2514	22029.9068	-0.00368176	0.00184088	0.00030681	1753.97347
0.251323	22548.0799	-0.00375876	0.00187938	0.00031323	1795.22929
0.251215	23093.4093	-0.00386676	0.00193338	0.00032223	1838.64724
0.251107	23610.8484	-0.00397476	0.00198738	0.00033123	1879.84462
0.25103	23948.4682	-0.00405176	0.00202588	0.00033765	1906.72518
0.250922	24745.5446	-0.00415976	0.00207988	0.00034665	1970.18667
0.250814	25118.3943	-0.00426776	0.00213388	0.00035565	1999.87216
0.250721	25596.1998	-0.00436076	0.00218038	0.0003634	2037.914
0.250613	26109.9691	-0.00446876	0.00223438	0.0003724	2078.8192
0.250521	26765.392	-0.00456076	0.00228038	0.00038006	2131.00255
0.250397	27279.1613	-0.00468476	0.00234238	0.0003904	2171.90775
0.250335	27796.6004	-0.00474676	0.00237338	0.00039556	2213.10513
0.250212	28418.2612	-0.00486976	0.00243488	0.00040581	2262.60042
0.250104	28970.1963	-0.00497776	0.00248888	0.00041481	2306.54429
0.249996	29413.5058	-0.00508576	0.00254288	0.00042381	2341.83963
0.249872	30141.5903	-0.00520976	0.00260488	0.00043415	2399.80815
0.24978	30657.5615	-0.00530176	0.00265088	0.00044181	2440.88865
0.249656	31352.618	-0.00542576	0.00271288	0.00045215	2496.22755
0.249533	31831.8914	-0.00554876	0.00277438	0.0004624	2534.38625

0.249441	32455.0201	-0.00564076	0.00282038	0.00047006	2583.99842
0.249333	33077.415	-0.00574876	0.00287438	0.00047906	2633.55215
0.249224	33522.1924	-0.00585776	0.00292888	0.00048815	2668.96436
0.249101	34143.8533	-0.00598076	0.00299038	0.0004984	2718.45966
0.248978	34729.5503	-0.00610376	0.00305188	0.00050865	2765.09158
0.24887	35134.6941	-0.00621176	0.00310588	0.00051765	2797.34826
0.248761	35906.082	-0.00632076	0.00316038	0.00052673	2858.76449
0.248623	36566.6426	-0.00645876	0.00322938	0.00053823	2911.35689
0.24853	37079.6779	-0.00655176	0.00327588	0.00054598	2952.20366
0.248376	37633.0809	-0.00670576	0.00335288	0.00055881	2996.2644
0.248283	38256.2096	-0.00679876	0.00339938	0.00056656	3045.87656
0.24816	38843.3746	-0.00692176	0.00346088	0.00057681	3092.62536
0.248021	39464.3015	-0.00706076	0.00353038	0.0005884	3142.06222
0.247898	40160.8259	-0.00718376	0.00359188	0.00059865	3197.51798
0.247774	40822.8543	-0.00730776	0.00365388	0.00060898	3250.22726
0.247651	41371.8536	-0.00743076	0.00371538	0.00061923	3293.93738
0.247527	42036.0839	-0.00755476	0.00377738	0.00062956	3346.82197
0.247404	42476.4576	-0.00767776	0.00383888	0.00063981	3381.88357
0.247265	43170.7801	-0.00781676	0.00390838	0.0006514	3437.16402
0.247172	43833.5425	-0.00790976	0.00395488	0.00065915	3489.93173
0.247018	44494.1031	-0.00806376	0.00403188	0.00067198	3542.52413
0.246894	45047.506	-0.00818776	0.00409388	0.00068231	3586.58487
0.24674	45885.684	-0.00834176	0.00417088	0.00069515	3653.31879
0.246632	46293.7636	-0.00844976	0.00422488	0.00070415	3685.8092
0.246478	46913.9565	-0.00860376	0.00430188	0.00071698	3735.18762
0.246339	47755.8043	-0.00874276	0.00437138	0.00072856	3802.21371
0.2462	48417.8327	-0.00888176	0.00444088	0.00074015	3854.92299
0.246046	48932.336	-0.00903576	0.00451788	0.00075298	3895.88662
0.245922	49593.6305	-0.00915976	0.00457988	0.00076331	3948.53746
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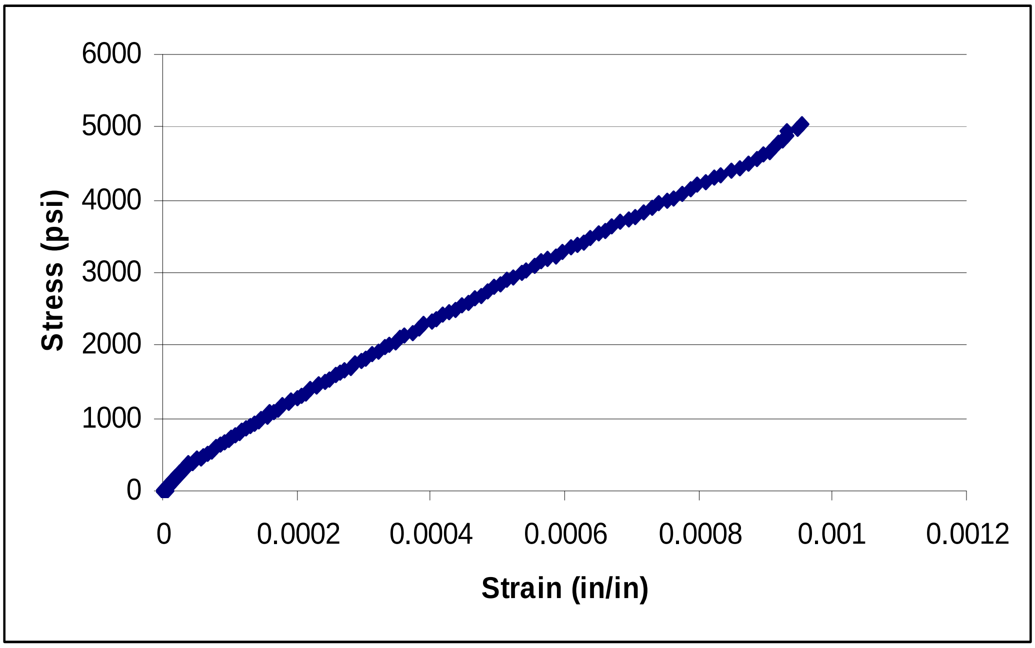

Figure B-2 Strain –stress diagram for one of the tested cylinders in SCC 15

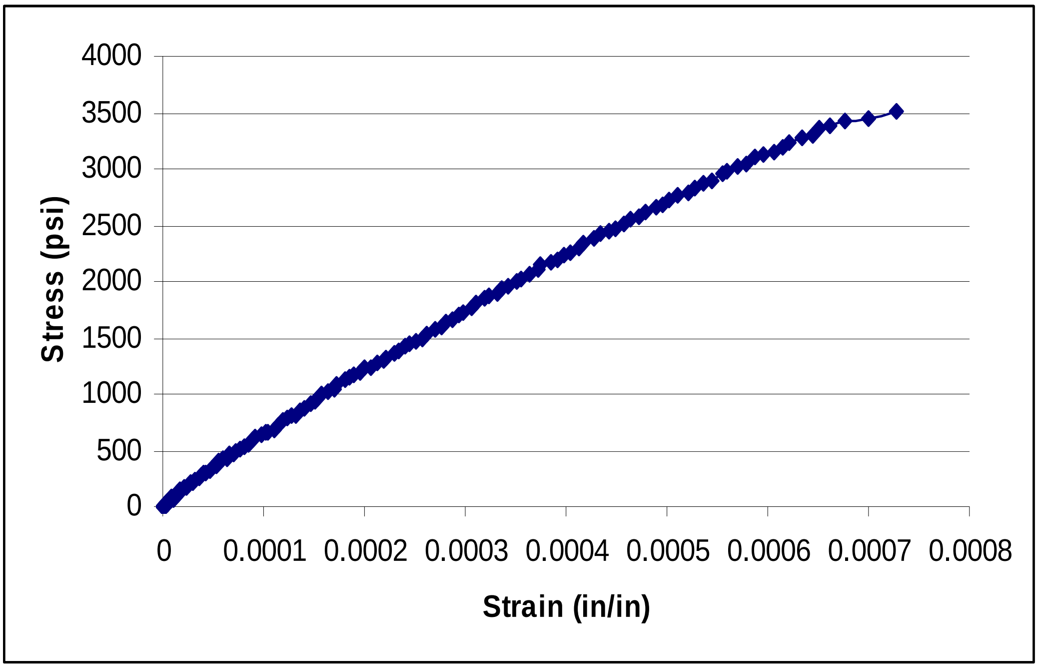

Figure B-3 Strain-Stress diagram for one of the tested cylinders in SCC 37