

EVALUATION OF MECHANICAL PROPERTIES OF SELF CONSOLIDATING CONCRETE

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ملخص البحث

حديثاً يعتبر استخدام الخرسانة ذاتية الدمك عالمياً كأحد الحلول الهامة للوصول إلى خرسانة ذات جودة عالية. تقدم هذه الدراسة برنامجاً عملياً يتكون من 15 خلطة من الخرسانة ذاتية الدمك حيث يهدف هذا البرنامج البحثي إلى دراسة الخواص الميكانيكية للخرسانة ذاتية الدمك. اشتمل البحث على أربعة متغيرات أساسية هي: استخدام بودرة الحجر الجيري كإضافة و استخدام غبار السيليكا باستبداله بجزء من الأسمنت و مقاس الركام الكبير (10 mm, 20 mm) و كذلك نسبة الركام الكبير إلى الركام الكلى. تم إنشاء مجموعة من العلاقات بين الخواص التي تم دراستها في هذا البحث و مقارنتها بالنماذج الإحصائية المقترحة للخرسانات العادية في المواصفات الدولية المختلفة.

و قد تبين من هذه الدراسة أن النسبة المثلى لإستخدام بودرة الحجر الجيري هي 20% على الرغم من النقص الهامشي لقيم مقاومة الضغط للخرسانة. كما أشارت الدراسة إلى أن استبدال 10% من محتوى الأسمنت بغبار السيليكا أدى إلى تحسن ملحوظ في كل الخواص التي درست في هذا البحث. كما تبين أن استخدام الركام ذو مقاس (10 mm.) في الخرسانة ذاتية الدمك أدى إلى تحسن في الأداء و الخواص الميكانيكية لهذا النوع من الخرسانة. كما استنتج من هذه الدراسة أن النماذج الإحصائية المقترحة في بعض المواصفات الدولية المستخدمة في هذه الدراسة و الخاصة بالخرسانات العادية تعطي قيماً أقل من القيم الحقيقية- لمقاومة الشد المستنتجة من مقاومة الضغط- عند تطبيقها على الخرسانة ذاتية الدمك. وعلى العكس من ذلك فإن النموذج الإحصائي في المواصفة الأوروبية CEB-FIP يعطي قيماً أكبر من القيم الحقيقية لمقاومة الشد المستنتجة من مقاومة الإنحناء عند تطبيق هذا النموذج على نتائج الخرسانة ذاتية الدمك. تم اقتراح عدة نماذج إحصائية في هذا البحث ولكنها تحتاج إلى تحقيق أكثر للنتائج.

ABSTRACT

Recently, all over the world, one of the main solutions for achieving higher quality concrete is the use of Self Consolidating Concrete (SCC). This investigation introduces an experimental program, consisting of 15 different SCC mixtures, aiming at studying the mechanical properties of SCC through compressive strength, splitting tensile strength, and the flexural strength. The main parameters investigated in this study were: lime stone powder as an addition, silica fume as a replacement of the cement content, coarse aggregate size, and coarse to total aggregate ratio. The relationships between the studied properties were suggested in this study and compared to the other models suggested by international codes to enhance our understanding of the behavior of SCC.

The results indicated that the optimal percent of lime stone powder to be used in SCC is 20% though it might introduce some slight reduction in cube compressive strength. It is also found that the replacement of 10% of cement content by silica fume greatly enhanced the mechanical properties examined in this investigation. The use of smaller sized coarse aggregate (10 mm) produced better performance than the larger coarse aggregate (20 mm). Moreover it was concluded that the international codes studied here underestimate the tensile strength calculated from the corresponding compressive strength when applied to the SCC. However, the CEB-FIP model to estimate the tensile strength from the flexural strength for normal concrete overestimates the tensile strength for SCC. Different models were suggested in this investigation but need further validation.

KEY WORDS

Self-Consolidating Concrete (SCC), Admixture, Compressive Strength, Splitting Tensile Strength, Flexure Strength.

1. HISTORICAL BACKGROUND

The problem of the durability of concrete structures was a major topic of interest in Japan for several years, beginning in 1983. Sufficient compaction by skilled workers is required in order to realize durable concrete structures. One solution for the achievement of durable concrete structures independent of the quality of construction work is using of self-consolidating concrete, which can be compacted into every corner of a formwork, purely by means of its own weight and without the need for vibrating compaction [Okamura et al., 2003]. Okamura proposed the necessity of this type of concrete in 1986. At first, it was thought that it would be easy to create this new concrete because anti-washout underwater concrete was already in practical use. Anti-washout underwater concrete is cast underwater and segregation was strictly inhibited by adding a large amount of a viscous agent made of water-soluble polymer. However, it was found that anti-washout underwater concrete was not applicable for structures in air for two reasons. First, entrapped air bubbles could not be eliminated due to the high viscosity, and second, compaction in the confined areas of reinforcing bars was difficult [Okamura, 2004].

In the summer of 1988, Ozawa succeeded in developing self-compacting concrete for the first time. And with the increasing use of congested reinforcements in mat foundations and moment-resisting reinforced concrete structures, a growing interest in specifying highly flowable concrete has occurred.

The year after that, an open experiment on this new concrete was held at the University of Tokyo. As a result, intensive research began in many places, especially in the research institutes of large construction companies and the University of Tokyo.

In the early 1990's there was limited public knowledge about the SCC, mainly in Japan, the fundamental and practical know-how was kept secret by the large corporations to maintain commercial advantage. The SCC was used under trade names, such as the Non-vibrated concrete (NVC), Super quality concrete (SQC) [Okamura et al., 2003].

Research into self-consolidating concrete, or as it was first called in Sweden, vibrating-free concrete, began in Sweden in 1993. Swedish businesses, universities, research institutes and authorities have concentrated heavily on the development of self-compacting concrete for both buildings and civil engineering structures. Europe's first bridge built of self-consolidating concrete was Swedish. The strong position of Sweden in self-consolidating concrete was quite evident at the first international conference within the field, a RILEM conference held in Stockholm in the autumn of 1999 [Ravindrarajah et al., 2003].

Several European countries were interested in exploring the significance and potentials of SCC developed in Japan. These European countries formed a large consortium in 1996 to embark on a project aimed at developing SCC for practical applications in Europe. In the last six years, a number of SCC bridges, walls and tunnel linings have been constructed in Europe [Ravindrarajah et al., 2003].

In the United States, SCC is beginning to gain interest, especially by the precast concrete industry and admixture manufacturers. The precast concrete industry is beginning to apply the technology to commercial projects when specifications permit. The applications range from architectural concrete to complex private bridges [Ghezal et al. 2002].

2. DEVELOPMENT OF CONCRETE STRENGTH WITH TIME

2.1. COMPRESSIVE STRENGTH

The compressive strength, which is one of the most important properties of hardened concrete, is in general the characteristic material value for the classification of concrete in national and international codes. For this reason, it is of interest whether the differences in the mixture composition and positive dissimilarities in the microstructure affect the short and long term load-bearing behavior. Accordingly, clarification is still necessary to determine whether the hardening process and the ultimate strengths of SCC and conventional concrete differ. After 28 days the reached compressive strength of SCC and normal vibrated concrete of similar composition does not differ significantly in the majority of the published test results [Holschemacher et al. 2002]. Individual cases, however, showed that at the same water cement ratios slightly higher compressive strengths were reached for SCC. At the current time there is insufficient research to result in generalized conclusions with this fact [Holschemacher et al. 2002 and Petal et al., 2004].

The comparison of hardening processes shows that the strength development of SCC and conventional concrete is similar. Some of the published test results show that an increase of the cement content and a reduction of filler content at the same time increase

the initial concrete strength and the ultimate concrete strength. For early aged SCC up to 7 days the relative compressive strength spreads to a greater extent, whereas higher values as well as lower ones are reached. Especially if limestone powder is used higher compressive strengths are noticeable at the beginning of the hardening process. There is no difficulty in producing SCC with compressive strengths up to 60Mpa [Sonebi, 2004 and Lachemi et al., 2003].

2.2. SPLITTING TENSILE STRENGTH

All parameters which influence the characteristics of the microstructure of the cement matrix and of the interfacial transition zone are of decisive importance in respect of the tensile load bearing behavior. Most results of the measured splitting tensile strength values are in the range of valid regulations for normal vibrated concrete with the same compressive strength [Okamura et al., 2003].

Hence, it appears that the tendency of a higher splitting tensile strength of SCC. Likely as not, 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. Further on, denser cement matrix is present due to the higher content of ultra fines. 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 [Holschemacher et al. 2002].

3. EXPERIMENTAL DETAILS

3.1. EXPERIMENTAL PROGRAM

To investigate the hardened properties of self compacting concrete, an experimental program was designed using 15 concrete mixtures. Four parameters were studied in this experimental program: coarse to total aggregate ratio (0.5, 0.47 and 0.44); percent of lime stone powder added (20 % and 40 % by weight of cement) as a replacement of part of the coarse aggregate; coarse aggregate size (10 mm and 20 mm); and finally the percent of silica fume replacement (10 % of cement weight). For all the mixes, the water to binder ratio was constant along with the free water content but the HRWR was added and changed from one mix to the other to reach a final goal of a slump flow diameter between 60 and 75 cm and other fresh properties were measured [Eldarwish, 2006]. All the fresh properties of the 15 mixes agree with the EFNARK [2002] guidelines.

A total of 225 specimens were tested during this experimental program in compressive strength, flexural strength and splitting tensile strength. The compressive strength was measured at ages of 7, 28 and 90 days. The flexural strength was measured at 28 days. The tensile strength was also measured using the splitting tensile test at 28 days age for each mix. Each test result is the average of the results of three samples.

The cement content for all mixtures was 450 kg/m³. The lime stone powder was used as an additive. Silica fume was used as partial replacement of cement (10% by weight). The water to binder materials ratio was kept constant through the whole investigation at 0.33. Table 1 shows the control concrete mixtures constituents while Tables 2, 3 and 4 present the constituents of concrete mixtures for different studied parameters, lime stone powder, silica fume and coarse aggregate size respectively.

Table 1: Control concrete mixtures constituents

Mix No	Coarse/Total*	Dosage of HRWR % **	Cement	Water	Fine Aggregate	Coarse Aggregate
C-1	0.5	4.0	450	150	889	889
C-2	0.47	4.0	450	150	936	842
C-3	0.44	4.0	450	150	988	790

- All the constituent amounts are in kg/m³. * Coarse to total aggregate ratio
- Coarse aggregate size 10 mms.

** HRWR Dosage is a percent by weight of cement to get a final goal of slump flow 60 to 75 cm.

Table 2: Constituents of concrete mixtures with lime stone powder

Mix No	Dosage of HRWR % **	Cement	Water	Lime Stone Powder	Fine Aggregate	Coarse Aggregate
L20-1	4.0	450	150	90	889	799
L40-1	5.0	450	150	180	889	709
L20-2	4.0	450	150	90	936	752
L40-2	5.0	450	150	180	936	662
L20-3	4.0	450	150	90	988	700
L40-3	5.0	450	150	180	988	610

- All the constituent amounts are in kg/m³. • Coarse aggregate size 10 mms.

** HRWR Dosage is a percent by weight of cement to get a final goal of slump flow 60 to 75 cm.

Table 3: Silica fume concrete mixtures constituents

Mix No	SF	Dosage of HRWR % **	Cement	Water	Fine Aggregate	Coarse Aggregate
S-1	45	2.5	405	150	909	909
S-2	45	3.0	405	150	956	862
S-3	45	3.0	405	150	1008	810

- All the constituent amounts are in kg/m³. • Coarse aggregate size 10 mms

** HRWR Dosage is a percent by weight of cement to get a final goal of slump flow 60 to 75 cm.

Table 4: Constituents of concrete mixtures using coarse aggregate size of 20 mm.

Mix No	Dosage of HRWR % **	AGG Size (mm)	Cement	Water	Fine Aggregate	Coarse Aggregate
G-1	3.5	20	450	150	889	889
G-2	3.5	20	450	150	936	842
G-3	4.0	20	450	150	988	790

- All the constituent amounts are in kg/m³.

** HRWR Dosage is a percent by weight of cement to get a final goal of slump flow 60 to 75 cm.

3.2. MATERIALS

The type of coarse aggregate used in this study is the pink lime stone. The two sizes used in this study (10 mm and 20 mm) complied with the grading requirements of ECS 203-2001. The properties of the two sizes of the coarse aggregate are presented in Table 5. Natural siliceous sand, free of clay, silt and organic materials was used as fine aggregate in this investigation with fineness modulus of 2.6. The fine aggregate grading complied with ECS 203-2001 requirements (Zone 3). Other properties of the fine aggregate used in this investigation are listed in Table 5.

Table 5: Properties of the aggregates used in this study.

Aggregate	Specific Gravity	Dry Unit Weight (t/m ³)	Absorption (%)
Fine	2.65	1.72	-
Coarse (10mm)	2.46	1.48	1.30
Coarse (20 mm)	2.45	1.45	2.00

The cement used in this investigation was Ordinary Portland cement (type1) which complies with the requirements of ECS 203-[2001]. Silica fume was used in one concrete mixture with 10% replacement of the cement content by weight. Tap water was used for all concrete mixes. The high range water reducer used in this study is ASTM type F polymer type, brown in color, with no chloride content and a density of 1.2 kg/lit,

3.3. TESTING PROCEDURES

The mechanical properties of self consolidating concrete were experimentally evaluated by performing the cube compressive strength, splitting tensile strength and flexural strength. Compressive Strength test was carried out on cubes 100 x 100 x 100 mm. Nine cubes were cast for each mixture and tested at ages 7, 14 and 28 days, respectively. Splitting Tensile Strength test was carried out on cylinders 75 x 150 mm at age of 28 days according to ECS 203 [2001] procedure. Three cylinders were cast and tested for each mix. Center point loading was used to measure the flexural strength, at age of 28 days. For each mixture, three beams, 75 x 75 x 250 mm, were cast. The span used for testing the flexural specimens was 225 mm resulting in a span to depth ratio of 3: 1. The testing and curing procedures used in this investigation were performed in accordance with the Egyptian Code ECS 203 [2001] procedures.

4. RESULTS AND DISCUSSION

4.1. COMPRESSIVE STRENGTH OF SCC

Figures 1 and 2 show the effect of adding 20 % and 40% lime stone powder, respectively, (as a percentage of cement content) on cube compressive strength of SCC, while Figure 3 represent a comparison between the effect of adding 20% and 40% lime stone powder on cube compressive strength of SCC. at 7,28 and 90 days. It can be seen from Figures 1 and 2 that using lime stone powder as a replacement of part of the coarse aggregate resulted in a reduction in the cube compressive strength at all concrete ages when compared to the control mixtures. This is due to the reduction in coarse aggregate content in SCC. It can also be seen that the cube compressive strength increases with age however, a slight increase takes place after 28 days.

Two sizes of pink lime stone coarse aggregate (10 mm and 20 mm) were used in this study. The effect of the size of coarse aggregate on cube compressive strength at different ages is presented in Figure 4. It can be observed that all SCC mixtures containing coarse aggregate of size 10 mm showed greater compressive strength than the SCC mixtures containing 20 mm size coarse aggregate. It was noted that SCC with 10 mm coarse aggregate had a better filling and flow ability. This might be the main reason for this increase in the compressive strength. It was also observed, during the mixing and casting processes that some segregation was noticed for the mixes

containing the 20 mm coarse aggregate size which may have an adverse effect on the compressive strength.

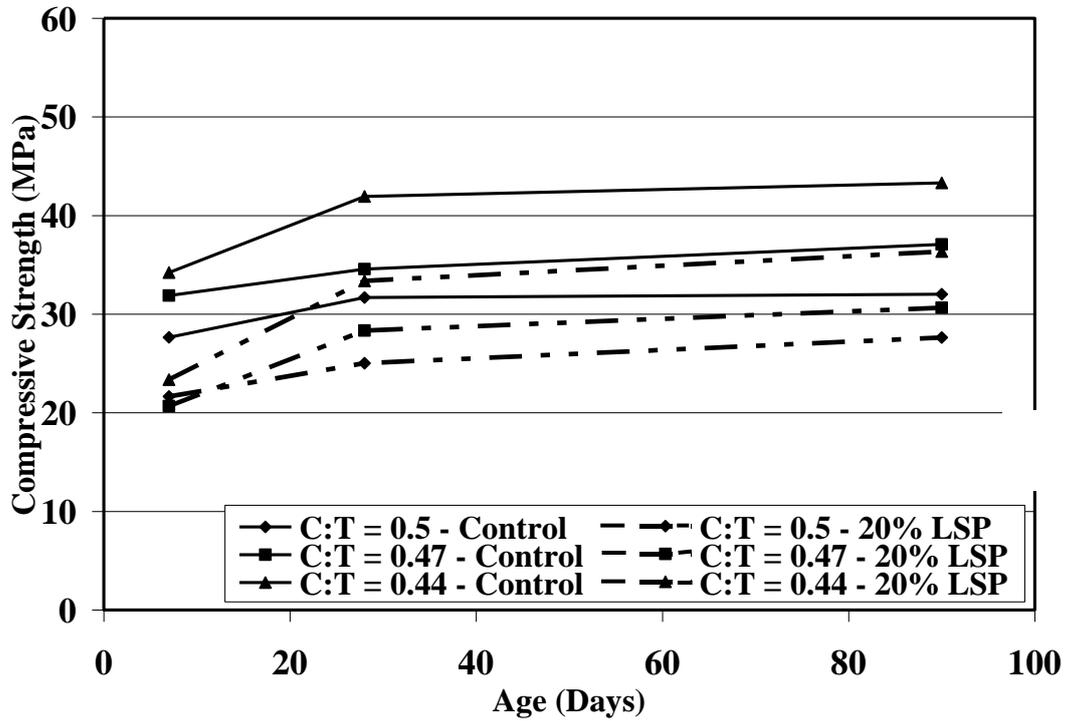


Figure 1: Effect of adding 20% Lime Stone Powder on Cube Compressive Strength of SCC [Coarse Aggregate Size =10 mms]

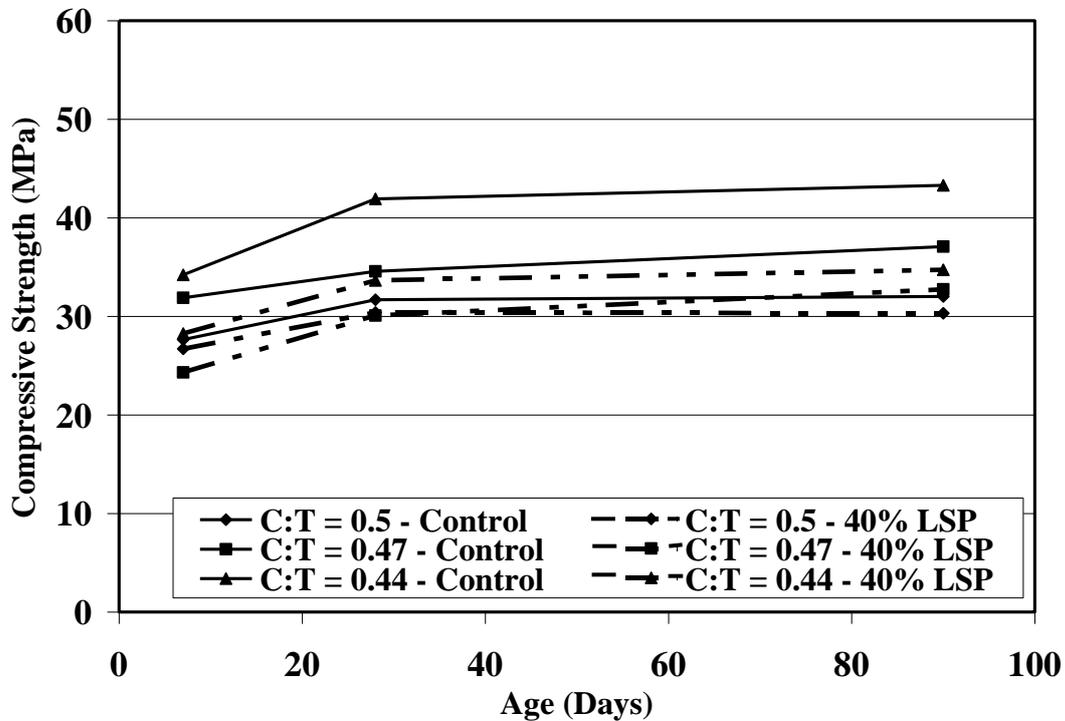


Figure 2: Effect of adding 40% Lime Stone Powder on Cube Compressive Strength of SCC [Coarse Aggregate Size =10 mms]

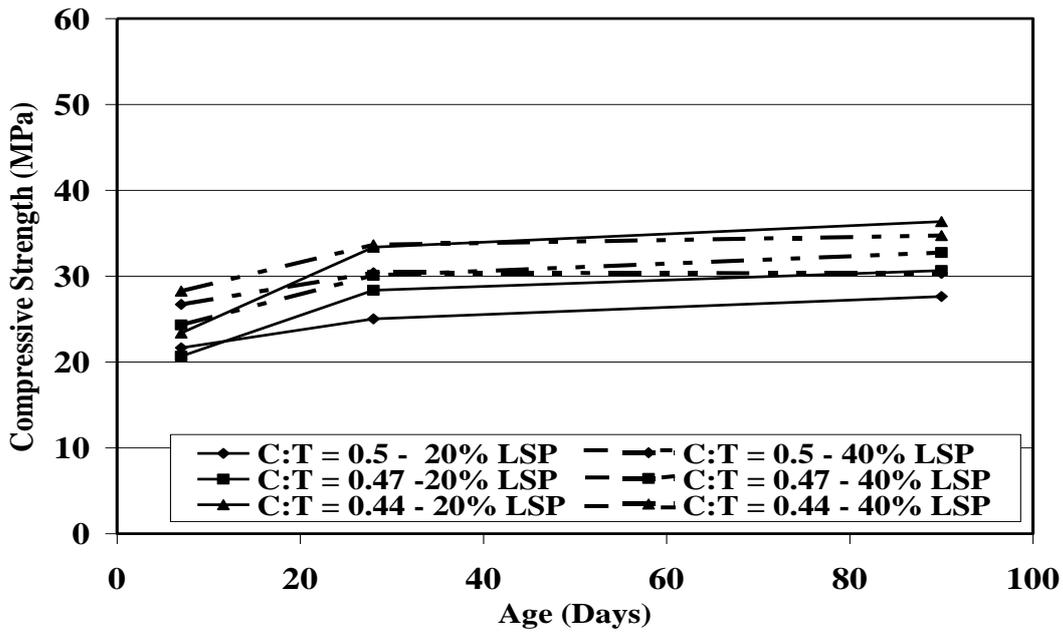


Figure 3: Comparison between the effect of adding 20% and 40% Lime Stone Powder on Cube Compressive Strength of SCC [Coarse Aggregate Size =10 mms].

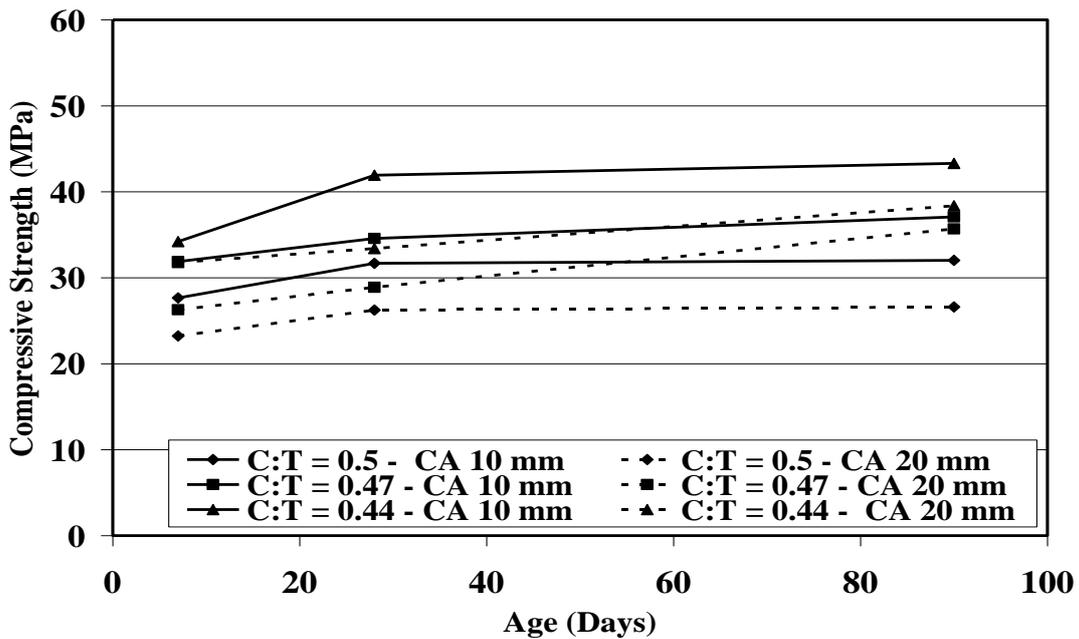


Figure 4: Effect of Coarse Aggregate Size on Cube Compressive Strength of SCC

The results of compressive strength of concrete mixes containing silica fume along with their control mixes at ages 7, 28 and 90 days are presented in Figure 5. It can be seen that replacing 10 % of the cement content resulted in an increase in cube compressive strength for all mixes and at all ages. This is due to the plugging effect of the small silica fume particles to the small pores in cement paste structure of SCC. It is also due to the high pozzolanic action of the silica fume in partial replacement of the cement content and its effect in the reaction with the lime, produced from hydration process, resulting in formation of more calcium silicate hydrate (C-S-H) which enhances the bonding effect of the hydrated cement. It is also noticed from Figure 5 that a slight increase took place by replacing 10 % of the SCC cement content with silica fume at early age, 7 days, but a larger effect is noticed at later ages (28 days and 90 days ages

compressive strength). This is due to the slow reaction of the silica fume which leads to a delayed effect at the start of the hydration reaction and its effect is slight at early ages.

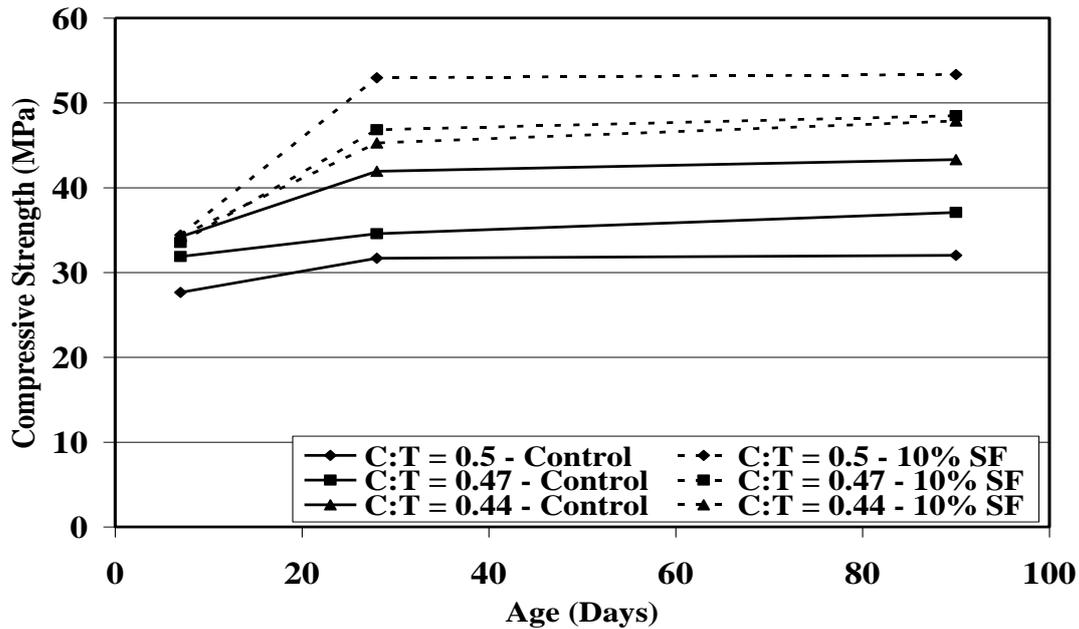


Figure 5: Effect of Silica Fume Replacement percentage on cube Compressive Strength of SCC [Coarse Aggregate Size =10 mms]

Three different sets of mixtures using different coarse to total aggregate ratios (0.5, 0.47 and 0.44) were used in this study. Figure 6 shows the effect of coarse to total aggregate ratio on the 28 days compressive strength. It can be noticed that the reduction in the coarse aggregate content, with constant water to binder ratio and constant binder content shows a slight increase in the 28 days compressive strength. Mixtures containing silica fume behaved conversely. The reduction of the coarse aggregate content resulted in a reduction in the 28 days compressive strength. This is due to the increase of the surface area of the aggregate with the replacement of part of the coarse aggregate with the fine particles.

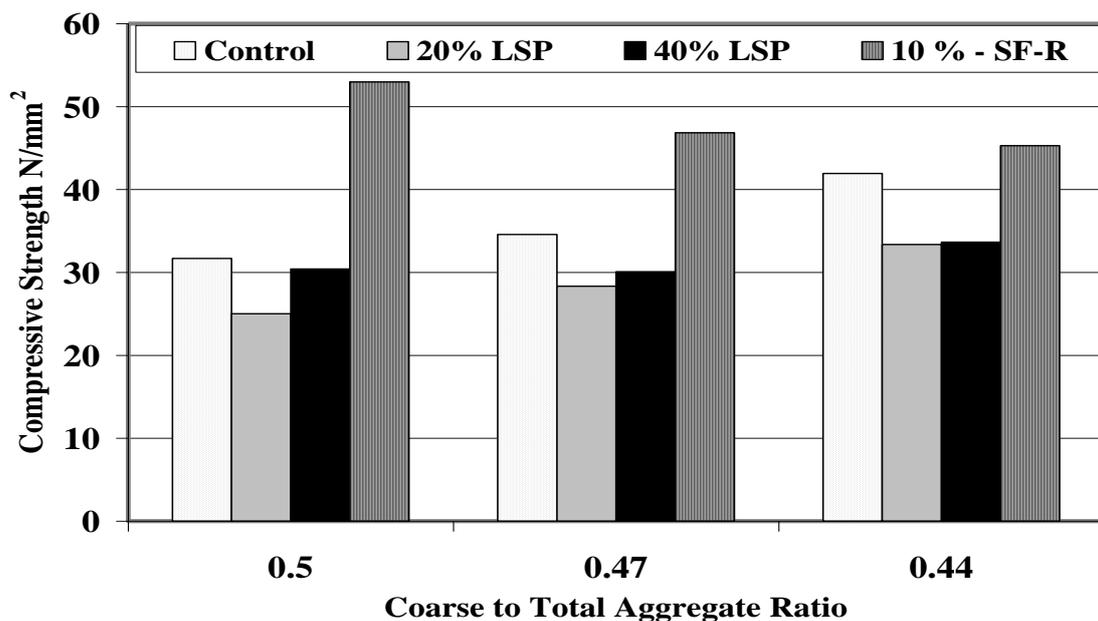


Figure 6: Effect of Coarse to Total Aggregate Ratio on Cube Compressive Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms].

4.2. SPLITTING TENSILE STRENGTH OF SCC

Figure 7 shows the effect of Lime Stone Powder Percentage on Splitting Tensile Strength of SCC at 28 days. It can be seen that the addition of Lime stone powder as a replacement for a part of the coarse aggregate slightly reduces the splitting tensile strength at 28 days. This reduction in tensile strength is a result of the reduction in the coarse aggregate content by replacing a part with the lime stone powder.

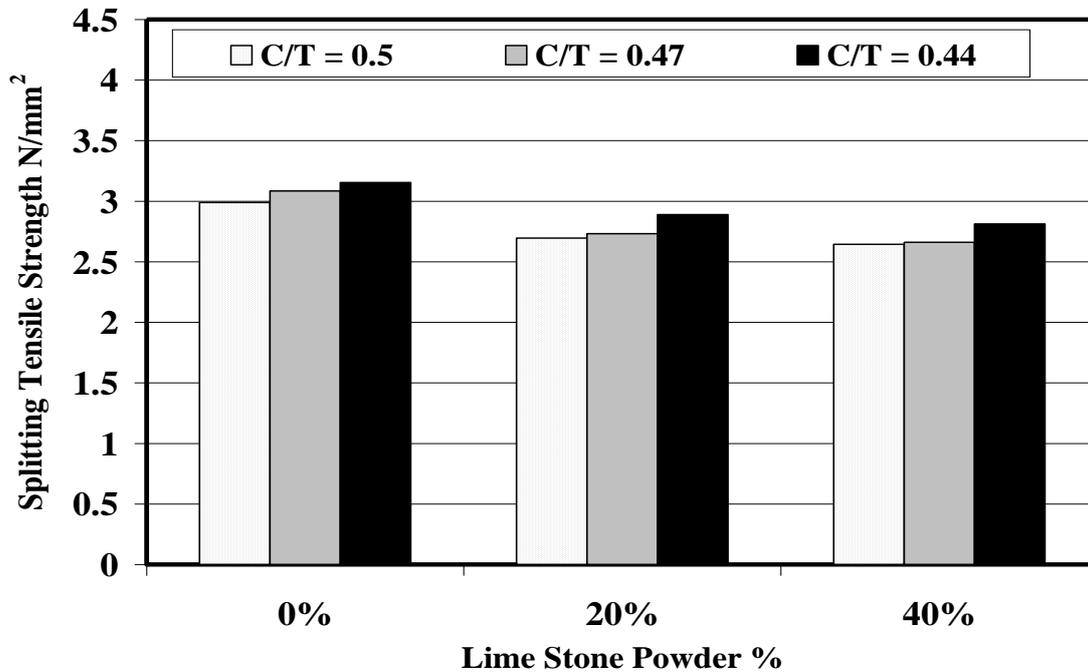


Figure 7: Effect of Lime Stone Powder Percentage on Splitting Tensile Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms].

Figure 8 shows the effect of replacing 10 percent of the cement content with silica fume by weight on the splitting tensile strength after 28 days. It can be noticed that the silica fume replacement generally increases the splitting tensile strength at 28 days for all the coarse to total aggregate ratios used in this study. This conclusion is attributed to the pozzolanic effect of the silica fume and its effect on tensile strength.

The effect of the coarse aggregate size on the splitting tensile strength of SCC at 28 days is presented in Figure 9. It can be seen that, for the same coarse to total aggregate ratio, SCC containing smaller coarse aggregate (10 mm) produced slightly higher splitting tensile strength than mixtures containing larger coarse aggregates (20mm). The slight increase can be attributed to the improving the transition zone between the cement paste and the coarse aggregate. Figure 10 shows the effect of coarse to fine aggregate ratio on the splitting tensile strength of SCC at 28 days. From Figure 10 it can be seen that when reducing the coarse to total aggregate ratio a slight increase of the splitting tensile strength takes place. Mixtures containing silica fume show better increase in the tensile strength than all of the other mixtures.

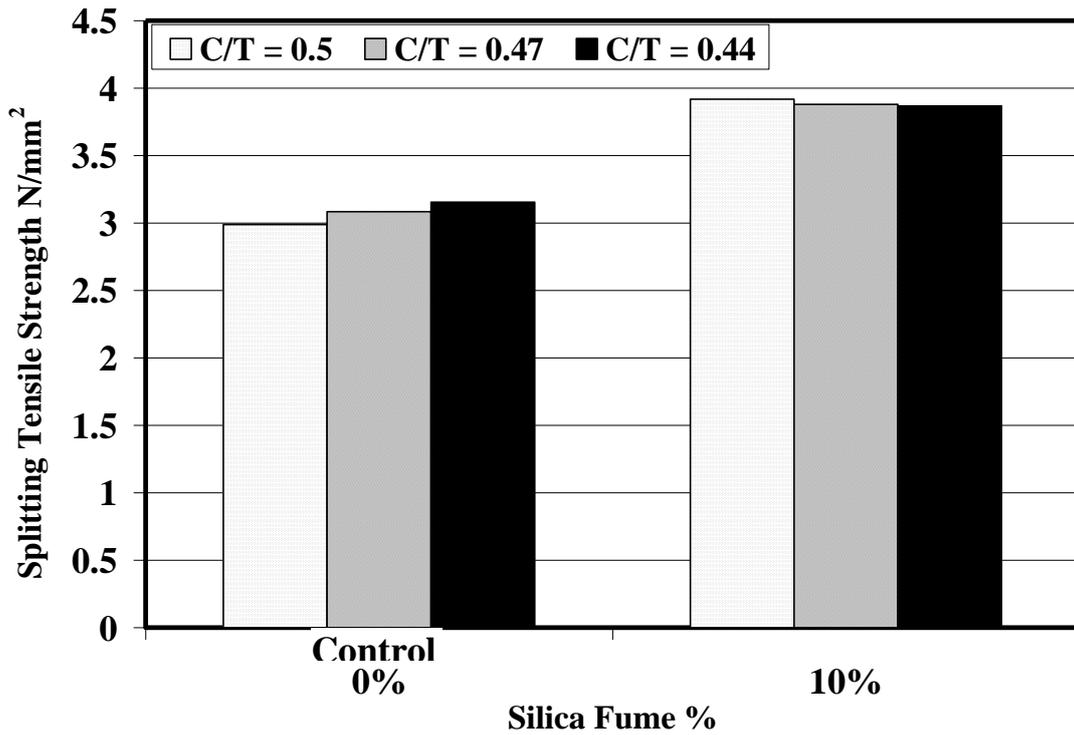


Figure 8: Effect of Silica Fume Percentage Replacement on Splitting Tensile Strength of SCC at 28 Days [Coarse Aggregate Size =10 mms].

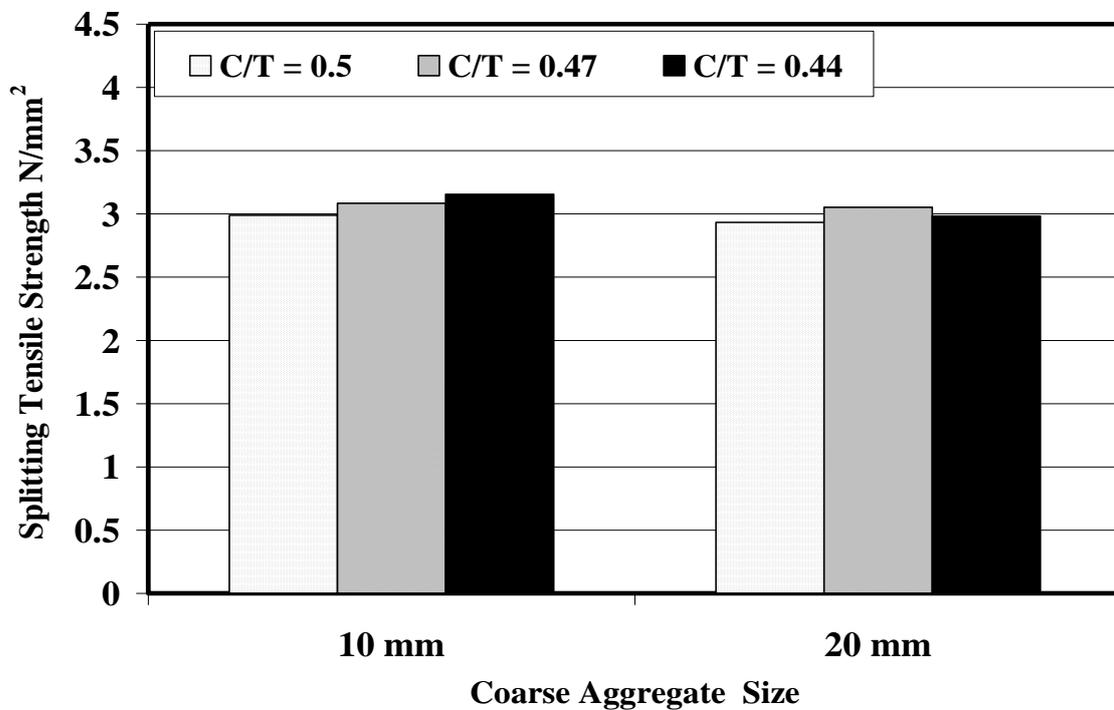


Figure 9: Effect of Coarse Aggregate Size on Splitting Tensile Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms].

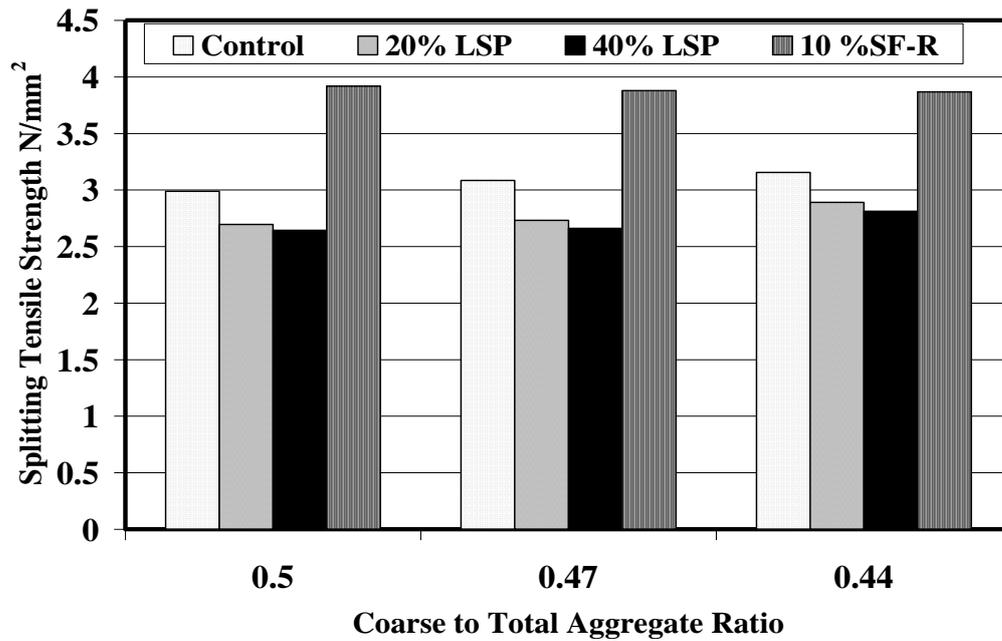


Figure 10: Effect of Coarse to Total Aggregate Ratio on Splitting Tensile Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms].

4.3. FLEXURAL STRENGTH OF SCC

Figure 11 shows effect of lime stone powder percentage on flexural strength of SCC at 28 days age. Generally it can be seen that using lime stone powder as a replacement of part of the coarse aggregate, slightly reduces the flexural strength for different coarse to total aggregate ratios when compared to the control mixtures. It is also observed that no significant difference was noticed between the concrete mixtures containing 20% and 40% lime stone powder. This is also observed for the three coarse to total aggregate ratios investigated.

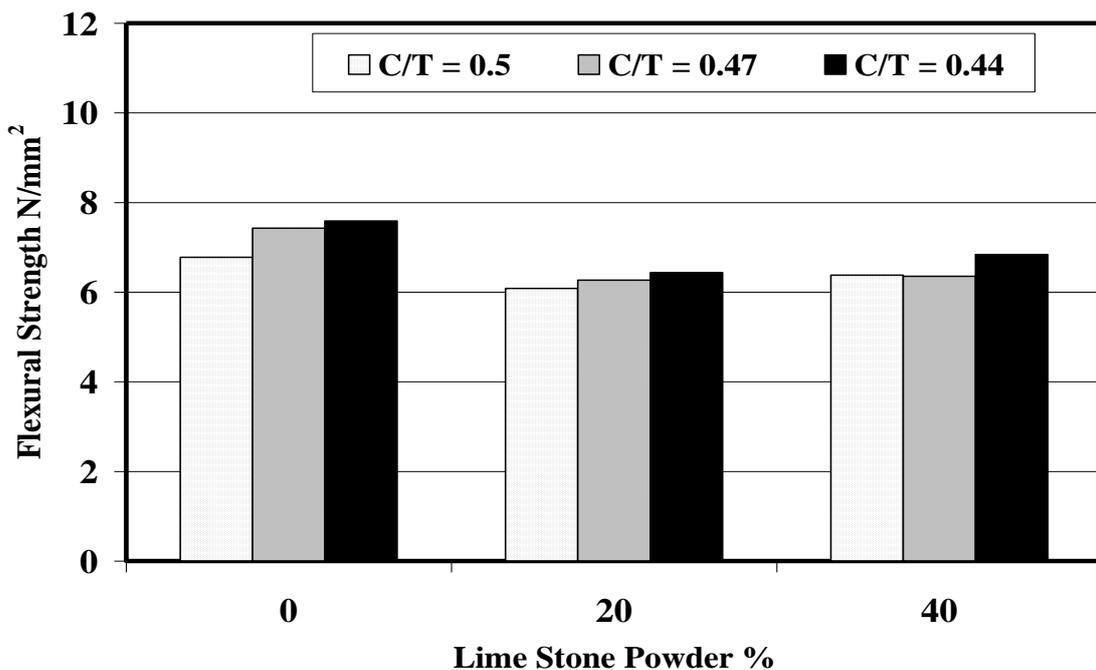


Figure 11: Effect of Lime Stone Powder Percentage on Flexural Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms]

The effect of replacing part of cement content by silica fume on the flexural strength of SCC at 28 days age is shown in Figure 12. It can be seen that replacing 10 % (by weight) of the cement by silica fume increase the flexural strength at 28 days age for all the mixtures using silica fume. Figure 13, presents the effect of coarse aggregate size on flexural strength of SCC at 28 days, it demonstrates that the use of 10 mm coarse aggregate size showed slightly higher flexural strength than those mixtures using 20 mm coarse aggregate size. The effect of coarse to total aggregate ratio on the flexural strength of SCC is presented in Figure 14. No notable effect on flexural strength at 28 days age is shown with the change of the coarse to fine aggregate ratio. Mixtures containing silica fume show better increase in the flexural strength than all other mixtures.

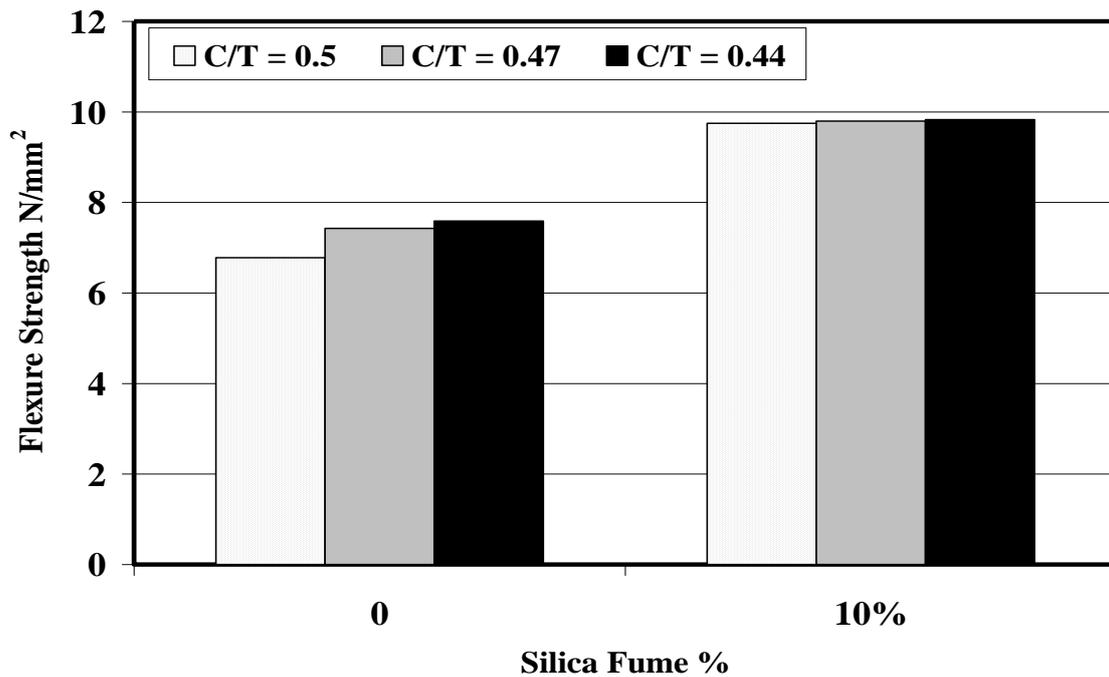


Figure 12: Effect of Silica Fume Percentage Replacement on Flexural Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms].

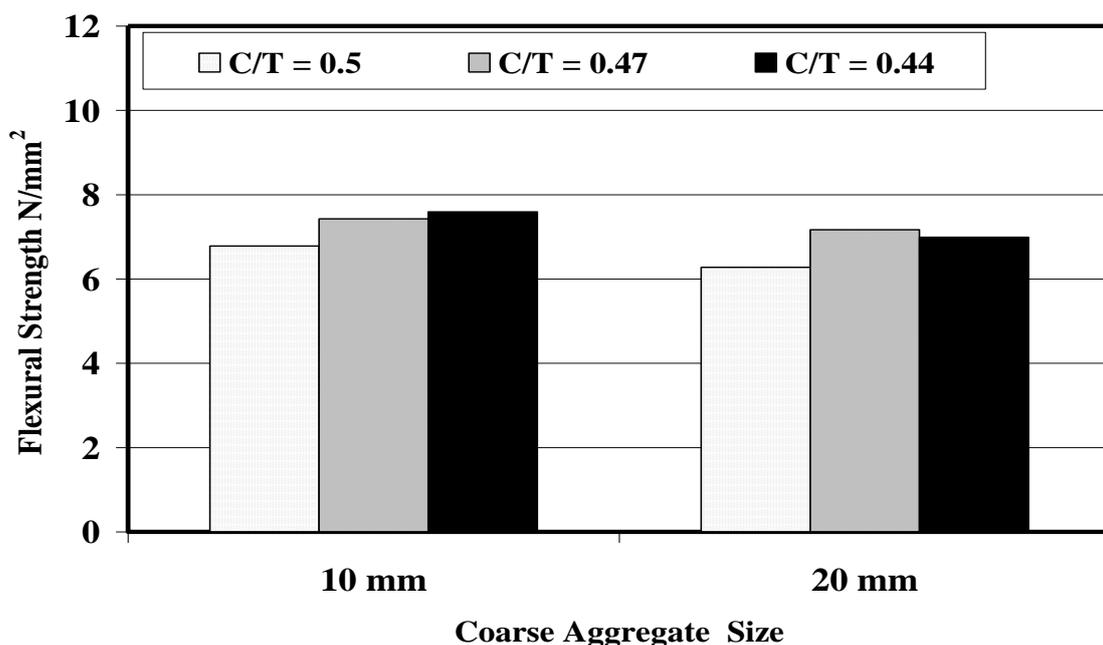


Figure 13: Effect of Coarse Aggregate Size on Flexural Strength of SCC at 28 Days Age.

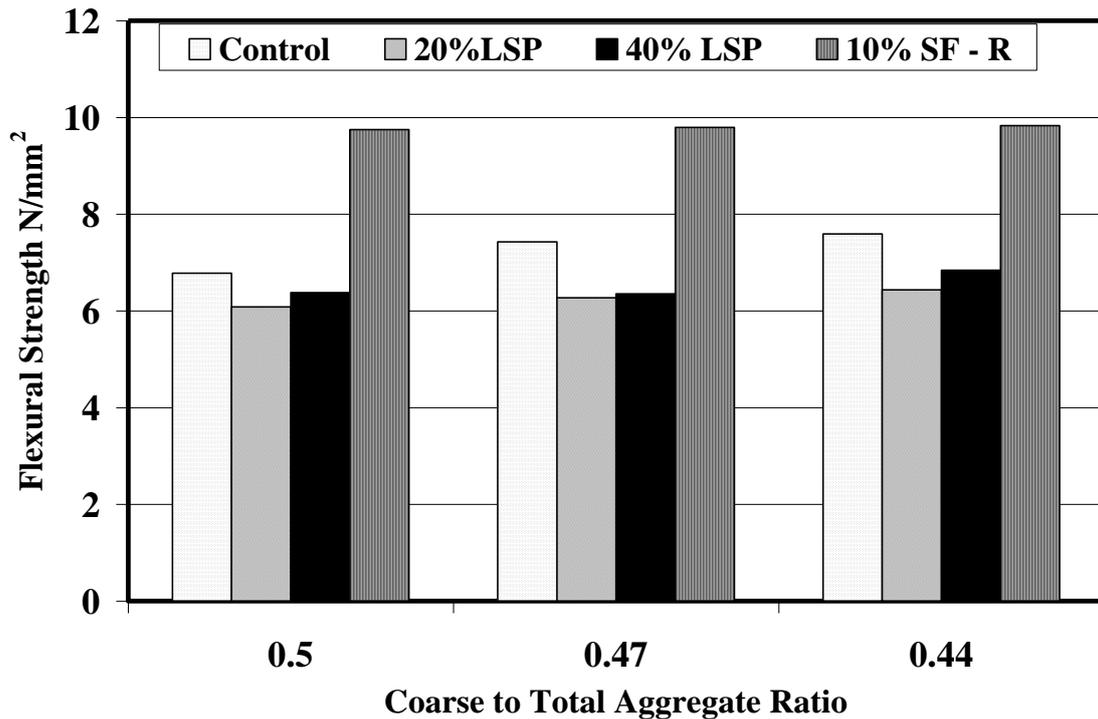


Figure 14: Effect of Coarse to Total Aggregate Ratio on Flexural Strength of SCC at 28 Days Age [Coarse Aggregate Size =10 mms].

4.4. RELATIONS BETWEEN SCC HARDENED PROPERTIES

The relationships between the different hardened properties of SCC, investigated in this study, are constructed aiming for a better understanding of the hardened behavior of the SCC. A model equation linking each two parameters is developed and presented using statistical regression. Although the data given in this study may seem not enough for constructing a new model but it can help in better grasp of knowledge and explanation of the mechanical behavior of SCC. The model equations and its represented behavior are then compared to different models found in different international codes and specifications as will be shown in the following figures. [CEB-FIP (1990) and BS 8007: 1987]

4.4.1. RELATIONSHIP BETWEEN CUBE COMPRESSIVE STRENGTH AND SPLITTING TENSILE STRENGTH

A relationship is constructed between the cube compressive strength and splitting tensile strength, MPa, for SCC at 28 days. Different models were previously proposed to represent the relationship between the tensile strength and the compressive strength but only two representative models were used regarding the relationship between compressive and tensile strength. The first model is the CEB-FIP model Code [1990] which recommends a lower and upper bound values for the characteristic mean direct tensile strength expressed as a function of the characteristic cylinder compressive strength.

As explained earlier, the compressive strength data in this study is the result of performing the compressive strength test on cube specimens while the CEB-FIP model [1990] uses the cylinder compressive strength as a basis for the model. The well established relation between the cube compressive strength and the cylinder

compressive strength, as recognized by the British Standards BS 1881: Part 120: 1983, is that the strength of cylinder is equal to 0.8 the strength of cube. This relation is used when applying the CEB-FIP model by replacing f_{ck} with $0.8 f_C$ as in Figure 15, where f_C is the cube compressive strength.

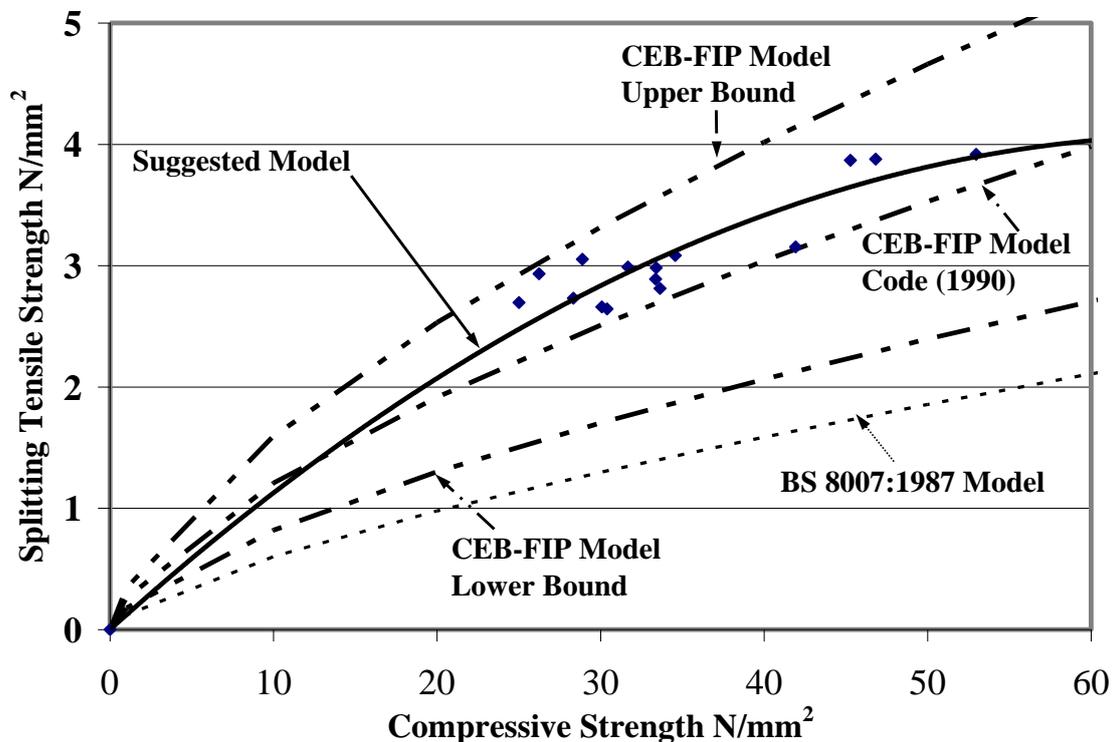


Figure 15: Relation between Splitting Tensile Strength and Cube Compressive Strength at 28 days Age

The second model used in Figure 15 is the expression used by the British Code of Practice [BS 8007: 1987]. In addition, a suggested model for the relationship between cube compressive and splitting tensile strength of SCC is presented in Figure 15 and is as follows:

$$f_t = -0.0009(f_C)^2 + 0.1218(f_C)$$

where

f_C is the cube compressive strength at 28 days age (in MPa)

f_t is the splitting tensile strength at 28 days age (in MPa)

The proposed model showed a good agreement with the experimental results. However, the suggested model, which is presented in Figure 15, can be applied only in the range of cube compressive strength ranging from 25 to 55 MPa. The proposed model agrees well with the experimental results obtained in this study and compares well with CEB-FIP model. Moreover, all data points tend to be near to the upper bound and above the mean value of the model. It can be seen also that the suggested model better capture the behavior than the CEB-FIP model [1990].

Figure 15 shows that the BS 8007: [1987] model underestimate the value of the tensile strength and gives lower values when compared to the results data of SCC and also when compared with the CEB-FIP model [1990] values of tensile strength. The BS 8007: [1987] model gives values of tensile strength lower than the lower bound values suggested by CEB-FIP model. From this discussion it can be seen that the suggested

model gives better estimation of the tensile strength of SCC than other models that under estimate its value. For better understanding and comparison between the up mentioned models, Figure 16 is constructed. Figure 16 represents the relation between the actual measured splitting tensile strength and the predicted splitting tensile strength using the three discussed models (CEB-FIP model [1990], BS 8007: [1987] model and the suggested model) at 28 days age for SCC. From the figure it can be seen that the model which best capture the relation between compressive strength and tensile strength by predicting the tensile strength for SCC is the suggested model. This is true as the best fit line representing the relation between actual tensile strength and the predicted tensile strength using the suggested model gives line with a slope of almost 1: 1 which means that in general the predicted tensile strength equal to the actual tensile strength. Other models give a value for the slope of 0.89 and 0.46 for the CEB-FIP model [1990] and BS 8007: [1987], respectively. This further proves that the suggested model is better for capturing the compressive-tensile behavior of SCC.

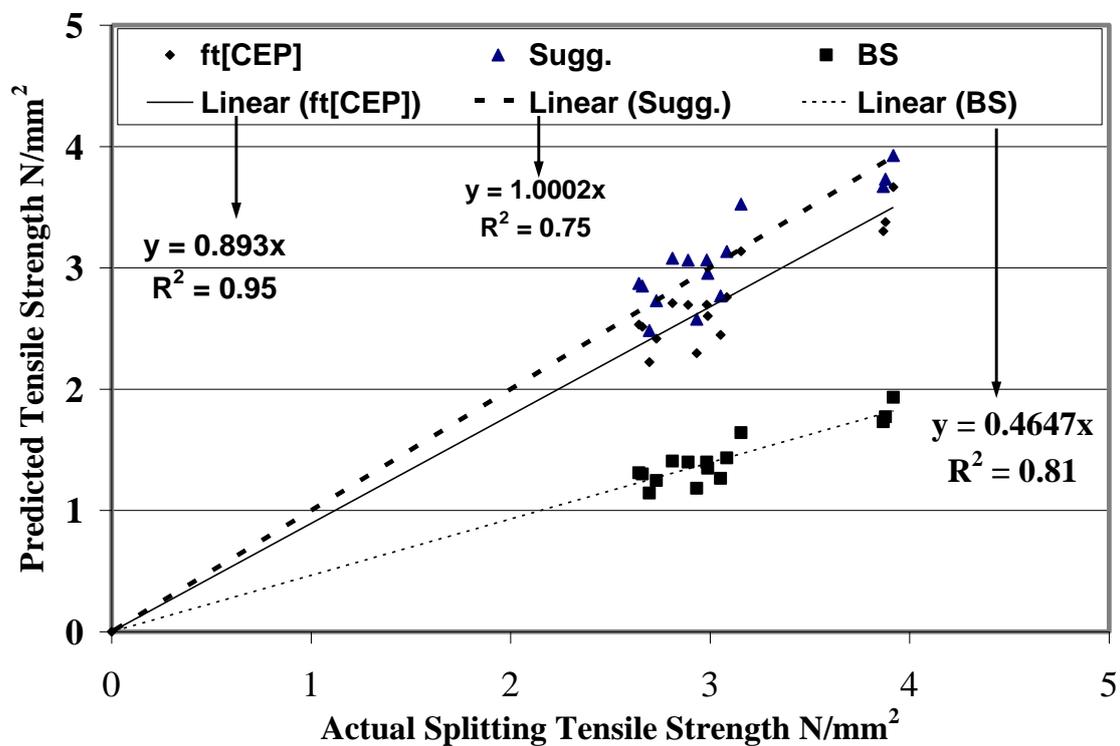


Figure 16: Relation between the Predicted Splitting Tensile Strength and Actual Splitting Tensile Strength at 28 days Age for SCC.

4.4.2. RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND FLEXURAL STRENGTH

A relationship between the cube compressive strength and flexural strength, in MPa, of SCC at 28 days is presented in Figure 17. A proposed equation relating these two parameters is presented as follow:

$$f_b = -0.0013(f_c)^2 + 0.2583 (f_c)$$

where

f_c is cube compressive strength at 28 days age (in MPa)

f_b is flexural strength at 28 days age (in MPa)

From Figure 17 it can be seen that the proposed equation shows a good agreement with the presented data. However, the proposed equation is validated only for a range of compressive strength between 25 and 55 MPa.

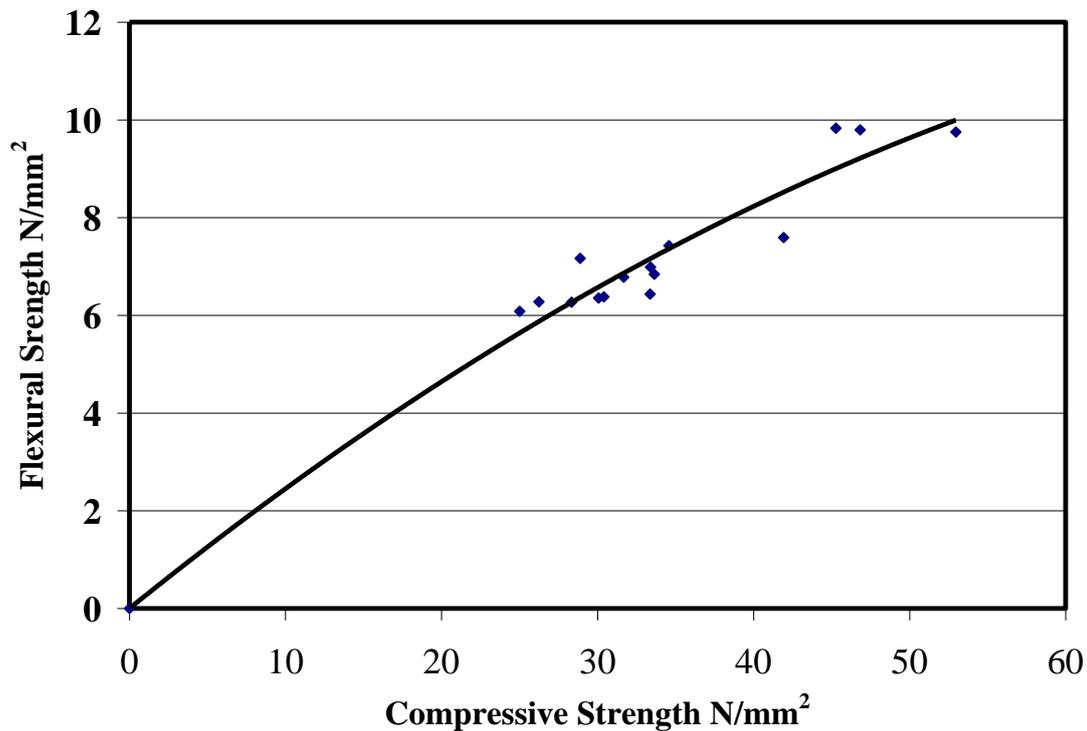


Figure 17: Relation between Center Point Flexural Strength and Cube Compressive Strength at 28 days Age for Self Consolidated Concrete

4.4.3. RELATIONSHIP BETWEEN SPLITTING TENSILE STRENGTH AND FLEXURAL STRENGTH

The relationship between the flexural strength and the splitting tensile strength of SCC at 28 days is developed from the results in this study. This relation is presented in Figure 18 along with the CEB-FIP model [1990] representing the same relation.

It can be noticed that the relation between the splitting tensile strength and the flexural strength is directly proportioned with a good correlation between the two. A proposed model equation representing the relationship between these two parameters is developed as follows (figure 18):

$$f_t = 0.418 f_b$$

where

f_t is the splitting tensile strength at 28 days age (in MPa)

f_b is the flexural strength at 28 days age (in MPa)

However, the suggested relation between the splitting tensile strength and the flexural strength is validated only in a range of flexural strength between 6 and 10 MPa. From Figure 18 it can be seen that the CEB-FIP Model Code [1990] over estimates the values of the splitting tensile strength of SCC. It can also be seen that the suggested model better represents the behavior of SCC with a ratio between the tensile strength and the flexural strength of 0.418 instead of a ratio value of 0.62 as presented in the CEB-FIP Model Code [1990].

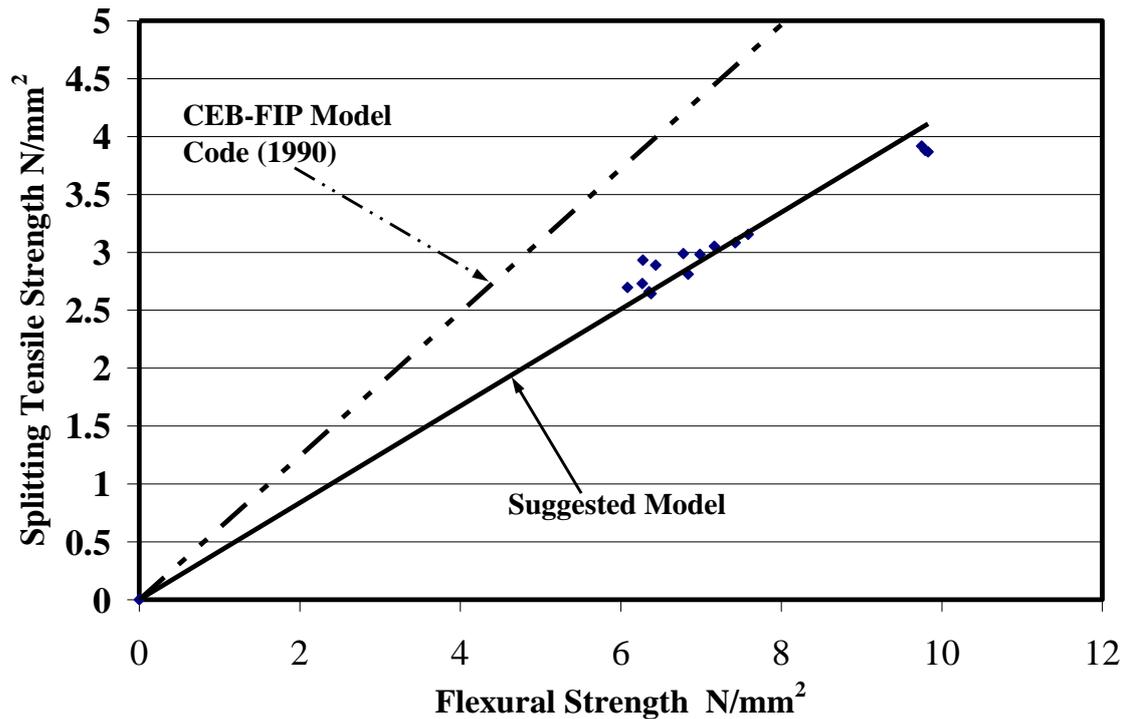


Figure 18: Relation between Splitting Tensile Strength and Flexural Strength at 28 days Age

5. CONCLUSIONS

From the results of this research, it can be concluded that

- a) For a constant cement content and water to cement ratio, adding 20 % or 40 % (by weight of cement) lime stone powder to SCC slightly reduced the cube compressive strength, the tensile strength and the flexural strength at all the tested ages (7, 28 and 90 days).
- b) 20% lime stone powder seems to be the efficient (optimum) percentage compared to 40% in the production of SCC.
- c) Using the smaller size of coarse aggregate (10 mm) showed higher cube compressive strength at all tested ages (7, 28 and 90 days) and a slight increase in the splitting tensile strength and the flexural strength of SCC.
- d) Replacing 10 % of the cement content by the silica fume obviously increased all properties including the cube compressive strength, the splitting tensile strength and the flexural strength of SCC.
- e) The reduction of the coarse to total aggregate ratio increases the cube compressive strength (in the range of 20%) however the effect is not generally obvious for the other measured properties.
- f) The models used to estimate the tensile strength of normal concrete from the compressive strength seems to under-estimate the true value of the splitting tensile strength of SCC. A model for SCC is suggested but although it need further investigation.

- g) A model to relate the flexural strength and compressive strength is suggested in this study.
- h) The model estimating the splitting tensile strength from the flexural strength [CEB-FIP model code 1990] for normal concrete over-estimates the actual value of the splitting tensile strength when applied to SCC. Another model is suggested in this study.
- i) The models suggested in this investigation needs further research due to the limited number of data available.

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