Relationship between splitting tensile and compressive strengths for self-compacting concrete containing nano- and micro silica

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Abstract. This paper describes the relationship between splitting tensile strength and compressive strength of self-consolidating concrete using data collected from laboratory specimens tested at standard conditions. The results were then compared with some expressions published in international literature. The investigated variables included: type of cement, percentage of nanosilica and percentage of microsilica as a cement replacement by weight. In spite of concrete not being designed to resist direct tension the knowledge of tensile strength is needed to estimate the cracking load. In the absence of test results an estimate of the tensile strength may be obtained by using the relationship proposed. The verification of the proposed formula based on experimental data was estimated by means of the integral absolute error (IAE). The output of this study has provided a better understanding of the correlation between splitting and compressive strengths of SCCs and the effect of some related variables on the resultant behavior, which has therefore, helped to generate new expression with better accuracy.

1 Introduction

Compressive strength is the main measure of structural quality of concrete. Structural design depends mainly on the compressive strength for some purposes the tensile strength is of interest. In the design of highway and airfield slabs, shear strength, and resistance to cracking requires information about the tensile strength. The compressive and splitting tensile strength are closely related depending on the nature strength of concrete. Concrete is not normally designed to resist direct tension; the knowledge of tensile strength is used to estimate the load under which cracking will develop. This is due to its influence on the formation of cracks and their propagation to the tension side of reinforced concrete flexural member. There is no direct relation between the compressive and the splitting tensile strengths. It was noticed that with the increased compressive strength, the tensile splitting strength is also increased but at a decreasing rate [1][2].

The test process of splitting tensile strength involves loading the cylinder specimens to induce transverse tension. Two strong parallel plates distribute and apply a stress in two diametrically opposite points on the cylinder diameter leading to the propagation of cracks through the paste, due to high tensile stresses that cause splitting of the specimen along the vertical plane [2 & 3].

The equation that was used to calculate the splitting tensile stress (fspt) which causes the failure of the specimen according to ASTM C496 / C496M-11 [3] is:

$$fspt = \frac{2F}{\pi DL} \tag{1}$$

where: (F) the applied force; (D) the diameter of the sample; and (L) the sample length. The empirical formula relating $(fspt)$ and (fc') had been suggested by researchers (see Table I) having the following type:

$$fspt = k\,(fc')^{n} \tag{2}$$

where: (k) and (n) are constant coefficients; and (fc′) is the compressive strength of concrete cylinder. The values of (n) between (0.5) and (0.85) have been suggested. The former value is used by the ACI 318-2014 [4], different values of the experimental coefficients (k) and (n) were proposed by other researchers which are indicated in Table 1. Table 1 shows the experimental parameters (k) and (n) proposed by various concrete design codes.

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Table 1. Values of the constant coefficients (k) and (n)

Sources	k	n
ACI 318 [4]	0.56	0.5
ACI 363R [5]	0.59	0.5
Gardner [6]	0.47	0.59
Nihal [7]	0.387	0.63
JCI [8]	0.13	0.85
JSCE [9]	0.23	0.67
CEB-FIB [10]	0.3	0.67
Raphael [11]	0.313	0.667
Ahmad and Shah [12]	0.462	0.55
Oluokun et al. [13]	0.294	0.69

Some studies suggest that ACI 318-2014 [4] coefficients underestimate the splitting tensile strength for high strength concrete and overestimate it for low strength concrete [14]. Other research findings have consistently indicated that the 0.5 power relation adopted in ACI 318-2014 [4] does not agree particularly well with the test results. Consequently, researchers have proposed several alternative relations.

2 Research significance

This investigation was intended to present a relationship between compressive strength and splitting tensile strength for SCC containing nanosilica and microsilica as a cement replacement by weight and cast using two types of cement (type I and V). Two ages (28 and 90 days) were studied in this analysis to predict the constant coefficients (k) and (n) using regression analysis. For this purpose, the existing relationship between the compressive strength and splitting tensile strength of concrete was examined.

The evaluation of the constant coefficients (k & n) and the derived constant coefficients from regression analysis models were estimated through the use of Integral Absolute Error (IAE) described by:

$$\mathrm{IAE} = \frac{\sum[(Q_i - P_i)^2]^{0.5}}{\sum Q_i} \tag{3}$$

where: (Oi) the experimental splitting tensile strength; and (Pi) the predicted splitting tensile strength from regression analysis.

3 Materials and experimental program

3.1 Materials

Two types of Commercial Iraqi cements were used. The first was Ordinary Portland Cement (OPC Type I) and the second was Sulfate Resisting Portland cement (SRPC Type V). Both of them conform to ASTM C150/C150M-15 [15] and Iraqi Specification No. 5/1984 [16]. Two types of silica were considered:

- Densified microsilica (mS) MEYCO MS 610 conforming to ASTM C 1240-15 [17], supplied by BASF, with density of 2.2 g/cm^3 and SiO_2 content more than 90%.
- Colloidal nanosilica (nS) produced by Jinan Yinfeng Silicon Products Company, with slight blue and transparence, pH value of 9.55 and density 1.204 g/cm^3.

Local natural fine (FA) and crushed coarse aggregate (CA) were used, they were within the requirements of ASTM C33/C33M-13 [18] and also conform to the Iraqi Specification No. 45/1984 [19]. The specific gravity and bulk density were 2.65 and 1670 kg/m^3 for fine aggregate, 2.63 and 1685 kg/m^3 for coarse aggregate, respectively. A constant amount of 100 kg/m^3 ground limestone powder (LP) was applied as filler for all SCCs mixes.

Superplasticizer (SP) was used to increase the workability of SCC for this work, unique polycarboxylic ether with long lateral chains based SP with the specific gravity of 1.07 was used as a high range water reducer (GLENIUM 54 produced by BASF company and conforming to ASTM C494/C494-15 Type F [20] depending on the dosages used) to improve the performance of SCC. Table 2 describes the various physical and chemical characteristics of the cement types and each mineral admixture used in this study.

Table 2. Chemical composition and physical properties of cement and admixtures

Oxides	Percent chemical composition (%)				
	Cement type I	Cement type V	Micro-silica	Nano-silica	Lime stone filler
CaO	66.11	63.32	0.92	---	65.32
SiO_2	21.93	21.95	95.14	30.1	1.02
Al_2O_3	4.98	3.76	0.71	---	0.61
Fe_2O_3	3.10	4.66	0.46	---	0.32
SO_3	2.25	1.10	0.95	---	0.12
MgO	2.00	2.15	---	---	0.31
Insoluble material	1.29	0.49	---	---	
Loss on ignition	2.39	1.93	1.41	---	31.5
Lime saturation factor	0.93	0.85	---	---	
Physical properties					
Specific gravity	3.12	3.08	2.2	1.204	2.7
Surface area- cm^2/g	3760	3400	20750	50000	3900

3.2 Experimental program

3.2.1 Properties of fresh SCC

Fresh state properties such as filling ability, viscosity and passing ability of concrete, Slump Flow and T50 cm, V-Funnel and V-Funnel at T5 minutes, J-Ring and L-Box Tests, were conducted according to European

Federation of National Associations (EFNARC) for SCC specifications [21].

Using the provided materials, fourteen SCC mixes were casted according to the mix proportions listed in Table 3. A total time of mixing was 5 minute in a compulsory mixer; fresh properties according to EFNARC were done.

3.2.2 Properties of hardened SCC

Three specimens (cubes, 100 mm side length) were cast for each mix of SCC to determine the compressive strength.

Table 3. Mixture proportions of the investigated concretes.

Mix*	Cement kg/m^3	mS kg/m^3	nS kg/m^3	FA kg/m^3	CA kg/m^3	LP kg/m^3	Water L/m^3	SP L/m^3	W/Cem	W/P
SCC Ref. I	400	0	0	850	850	100	152	5	0.38	0.3
SCC 3% mSI	388	12	0	850	850	100	152	5.4	0.38	0.3
SCC 4.5 % mSI	382	18	0	850	850	100	152	5.8	0.38	0.3
SCC 6% mSI	376	24	0	850	850	100	152	6.4	0.38	0.3
SCC 3% nSI	388	0	12	850	850	100	152	11.82	0.38	0.3
SCC 4.5 % nSI	382	0	18	850	850	100	152	15.21	0.38	0.3
SCC 6% nSI	376	0	24	850	850	100	152	18.74	0.38	0.3
SCC Ref. V	400	0	0	850	850	100	152	5	0.38	0.3
SCC 3% mSV	388	12	0	850	850	100	152	5.4	0.38	0.3
SCC 4.5% mSV	382	18	0	850	850	100	152	5.8	0.38	0.3
SCC 6% mSV	376	24	0	850	850	100	152	6.4	0.38	0.3
SCC 3% nSV	388	0	12	850	850	100	152	11.82	0.38	0.3
SCC 4.5% nSV	382	0	18	850	850	100	152	15.21	0.38	0.3
SCC 6% nSV	376	0	24	850	850	100	152	18.74	0.38	0.3

*SCC 3% nSV means self-consolidating concrete with 3% nanosilica as a replacement of cement type V; W/Cem, ratio of water to cementitious materials; W/P, ratio of water to powder materials.

The cubes were cured sealed for the first day, demoulded after 24 hours and cured in water till the age test (28 and 90 days). The average of three cubes was used to calculate the compressive strength. The compressive strength test was performed according to B.S 1881: Part 116: 1989 [22] (BS EN 12390-3:2009). Cylinders conforming to the ASTM C 496/C 496M – 11 [3] were cast to calculate the splitting tensile strength after 28 and 90 days.

4 Test results and discussion

4.1 Results of fresh SCC

Preliminary results given in Table 4, concern fresh concrete properties. The experimental results show that, type of cement has no significant effect on fresh properties. The SCCs mix presents a good filling ability (slump-flow ranged from 695 to 740 mm and T50 from 2.8 to 3.6 second and V-funnel flow times were between 7.4 to 9.1 second) and an acceptable passing ability (L-box results ranged between 0.86 and 0.95 and J-ring 695 to 720 mm). Therefore, fresh SCC properties complied well with EFNARC guidelines, which is an indication of a good workability. The mix with colloidal nanosilica gave closer flow result to the lower limit. The plasticizer content was changed (as indicated in Table 3) to stay within the limit of fresh tests specified standards. The supper plasticizer dosage depends on the surface area and the mineralogy and the fine-ness of particles. The supper plasticizer requirement is rather related to changes in the surface area of the mix than to the concentration (by weight) of the nanosilica addition, as presented by Sobolev et al. [23][24].

Test results of fresh SCC mixes with different percentages of different SiO_2 indicated that, there is a remarkable reduction in slump flow for both types of cement when using micro or nanosilica. Consequently, it could be caused by higher surface area for both macro and nanosilica that require higher w/c. Also, the reduction by microsilica was less than nanosilica for the same added percent.

Test results for V-funnel time are presented in Table 4 and indicate that using different percentages of SiO_2 has less/no effect on the results. Besides, test results of L-box for all SCC mixes, clarify that using nanosilica cause an increase in the flowability and viscosity of the mixes as compared to micro silica.

4.2 Results of hardened SCC

4.2.1 Compressive strength

The cube specimens were cured and tested at 28 and 90 days' age, they gave an indication to an enhancement that occurred as a result of SiO_2 nano particles incorporation on all SCC mixes and the influence of the cement type, which are presented in Table 5. The results of cube compressive strength (fcu) listed in Table IV were equated by cylinder (fc') using factor equal (0.8) multiplying by (fcu) [22].

The cylinder compressive strength (fc') presented in Fig. 1 displayed an improvement in SCCs mix with OPC and SRPC using nS and mS. It was indicated that using nS developed higher strength than mS for specimens with two types of cement and both ages 28 and 90 days, but the improvement for specimens with OPC were higher than specimens with SRPC. The behavior of collided SiO_2 nano particles was responsible for the enhancement in the strength due to acting as nucleus sites to tightly bond with C-S-H gel particles, resulting in more intensified microstructure. During the development of hydration process with time, the mix contained colloidal nanosilica indicated higher increase in the compressive strength. Several investigations in concrete containing nanosilica concluded that the pore structure was denser and lower coarse capillary pores than Portland cement concretes [25][26].

Table 4. Concrete properties in fresh stat

Mix description	Slump flow (mm)	Flow time (sec.)	J-ring (mm)	L-box (H_2/H_1)	V-funnel (sec.)
EFNARC requirements[21]	650 - 800	2- 5	600 –750	0.8 -1.0	6 -12
SCC Ref. I	740	3.5	695	0.95	8.0
SCC 3% mSI	717	3.6	703	0.94	8.5
SCC 4.5 % mSI	710	3.2	696	0.93	9.0
SCC 6% mSI	705	2.9	702	0.91	9.4
SCC 3% nSI	705	3.2	710	0.93	8.7
SCC 4.5 % nSI	700	2.9	698	0.92	9.3
SCC 6% nSI	695	3.5	716	0.90	9.8
SCC Ref. V	735	3.4	704	0.94	8.2
SCC 3% mSV	720	3.2	720	0.93	8.8
SCC 4.5% mSV	710	2.9	713	0.92	9.0
SCC 6% mSV	706	3.0	699	0.90	9.2
SCC 3% nSV	710	3.3	717	0.92	9.0
SCC 4.5% nSV	705	3.5	722	0.91	9.3
SCC 6% nSV	700	2.8	690	0.89	9.7

Table 5. Concrete properties in hardened state

Mix description	Compressive Strength (MPa)				Tensile Splitting Strength (MPa)	
	28 days		90 days		28 days	90 days
	fcu	fc'	fcu	fc'	fc'	f c'
SCC Ref. I	52.3	41.84	55.4	44.32	4.12	4.92
SCC 3% mSI	55.9	44.72	58.8	47.04	4.63	5.24
SCC 4.5 % mSI	57.8	46.24	60.3	48.24	4.36	5.11
SCC 6% mSI	58.3	46.64	61.5	49.2	4.14	4.96
SCC 3% nSI	63.9	51.12	66.1	52.88	4.96	5.53
SCC 4.5 % nSI	67.8	54.24	69.7	55.76	4.59	5.48
SCC 6% nSI	68.1	54.48	71.2	56.96	4.21	5.28
SCC Ref. V	45.6	36.48	47.8	38.24	3.91	4.50
SCC3% mSV	50.2	40.16	53.1	42.48	4.45	4.93
SCC4.5%mSV	55.3	44.24	58.5	46.8	4.25	4.88
SCC 6% mSV	55.8	44.64	58.9	47.12	4.01	4.64
SCC 3% nSV	57.6	46.08	60.5	48.4	4.81	5.41
SCC 4.5% nSV	62.2	49.76	66.3	53.04	4.65	5.22
SCC 6% nSV	63.1	50.48	67.5	54	4.23	5.12

4.2.2 *Tensile splitting strength*

The average 28 and 90 days' age tensile splitting strength results are presented in Table V and plotted in Fig. 2. It was indicated that the reference specimens with OPC gave higher tensile splitting strength than SRPC, however, the improvement in using nS and mS for SRPC was higher than OPC. The results of specimens with nS gave higher splitting strength than specimen with mS for both types of cement. The higher splitting tensile strength was for SCC specimens with 3% mS and nS for both ages as indicated in Fig.2. This was due to the stronger bond between the hardened paste and the aggregate. Mixes containing nanosilica produce an enhancement in the quality of the interfacial zone (ITZ), this is due to precipitation of smaller and stronger (higher stiffness) C–S–H gel and an accelerated rate of hydration of the paste, as reported by K. Audenaert and G. De Schutter [25].

This study was presented to investigate the applicability of existing relationships between the compressive strength and splitting tensile strength for SCC mixes containing mS and nS. The applicability of existing relationships shown in Table 6 between the two strengths were examined to estimate the Integral Absolute Error (IAE) and listed in Table 6. The results indicated that the relation presented by Gardner [6] and Nihal [7] gave approximately the smaller values of (IAE%) for both ages.

The Nonlinear relationships between the experimental results and predicted splitting tensile strength from all relations indicated in Table 1 for all SCCs specimens are shown in Figs. 3 to 6. In view of the numerous factors influencing the relationships of the strengths of concrete, it is not surprising that no simple exact relation is applicable. However, these correlations are felt to be representative in lieu of specific testing for concrete design and evaluation.

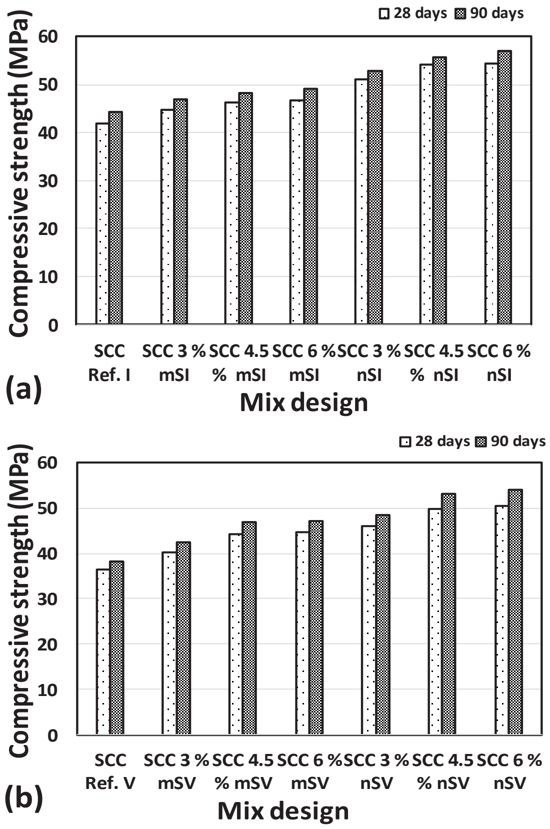


Fig. 1 Average compressive strength for SCCs at 28 and 90 days, (a) Ordinary Portland cement and (b) Sulfate Resisting Portland cement.

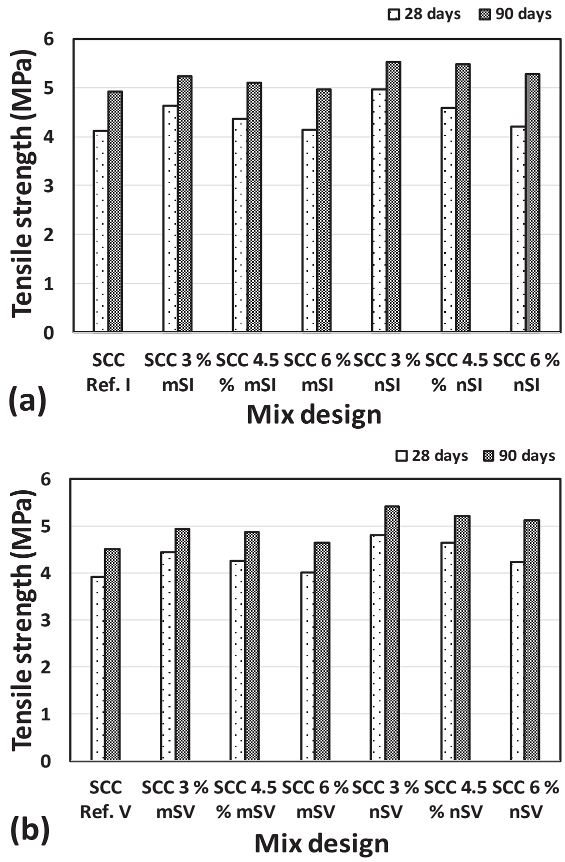


Fig. 2. Average tensile splitting strength for SCCs at 28 and 90 days, (a) Ordinary Portland cement and (b) Sulfate Resisting Portland cement.

All theoretical study presented above gave higher values for splitting strength (when applying their relations), the reason for this is that they ignore flaws, and all materials contain flaws.

Based on this research, the relationship between the compressive and splitting tensile strengths of SCCs mixes containing nano and micro silica for 28 and 90 days was studied. A new equation was predicted by regression analysis, in which for simplicity a square root was used as given in most research and ACI-318-2014 [4]:

$$fspt = 0.65 * \sqrt{(f'c)} \quad (4)$$

Using equation (4) to calculate the values of splitting tensile strength and IAE% as presented in Table VI, it complements well with experiment results and gave lesser values for IAE%.

5 Conclusions

Experimental results of SCC mixes made with both types of cement, OPC and SRPC and replacements of cement with (3-6) % of micro silica or nano silica increased concretes compressive strength compared to the reference SCC mixes. The enhancement in strength was more visible in concretes made with OPC.

As previously stated, there is little information in the literature concerning the accuracy and validity of the equations used for the purpose of estimating splitting tensile strength from compressive strength. This is especially true for normal strength concrete without any fiber or additives. To assess the accuracy of other power function relationships, the IAE concept was used for the experimental data reported by the various researchers.

The relationship between the compressive and splitting tensile strengths of SCCs mixes used in this research containing nano and micro silica for 28 and 90 days was found to be $fspt = 0.65 * \sqrt{f'c}$. The IAE results for 28 and 90 days results were between 5 % and 10.8% respectively, which were almost the lesser value.

Fig. 3. Comparison of the relationship for splitting tensile strength and compressive strength for SCCs mixes with OPC at 28 days, (a) with mS and (b) with nS.

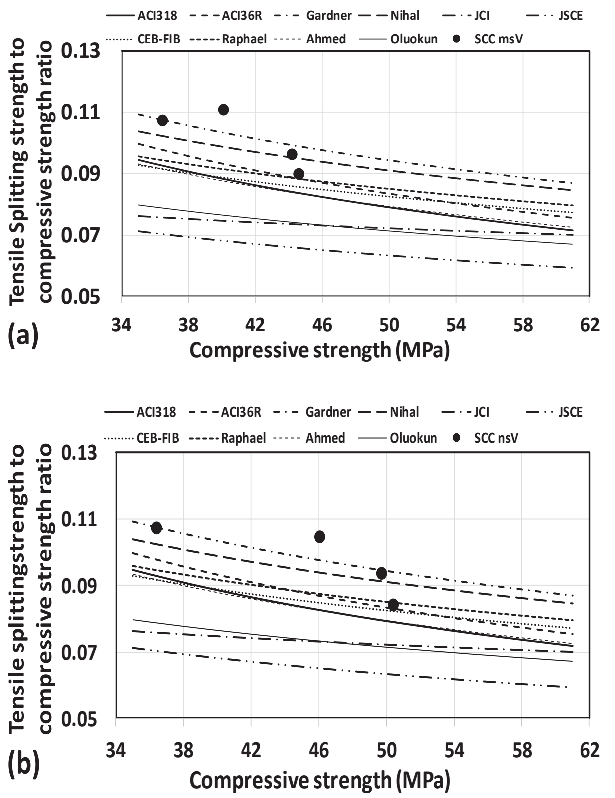
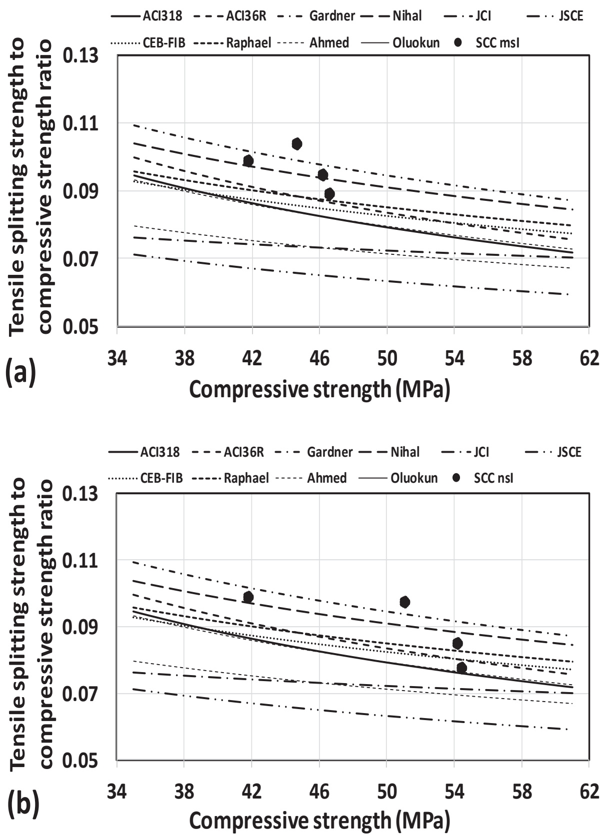


Fig. 4. Comparison of the relationship for splitting tensile strength and compressive strength for SCC mixes with SRPC at 28 days, (a) with mS and (b) with nS.



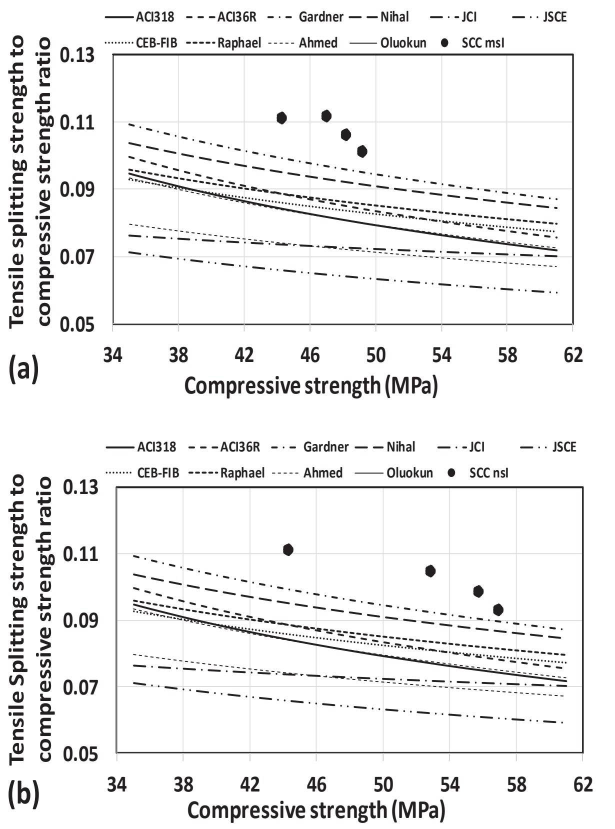
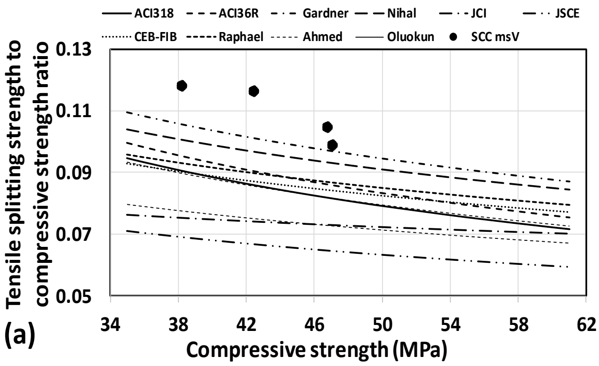


Fig. 5. Comparison of the relationship for splitting tensile strength and compressive strength for SCC mixes with OPC at 90 days, (a) with mS and (b) with nS.



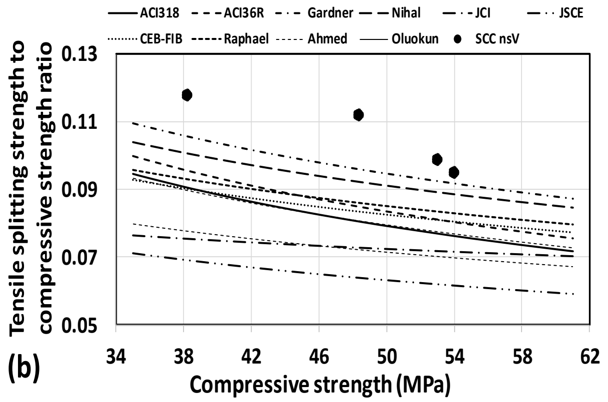


Fig. 6. Comparison of the relationship for splitting tensile strength and compressive strength for SCC mixes with SRC at 90 days, (a) with mS and (b) with nS.

Table 6. Values of the integral absolute error (IAE)

Sources	IAE % (28 days)				IAE % (90 days)			
	OPC		SRPC		OPC		SRPC	
	msI	nsI	msV	nsV	msI	nsI	msV	nsV
ACI 318 [4]	13.04	11.47	13.00	14.36	27.06	27.70	23.59	26.34
ACI 363R [5]	8.39	8.26	8.49	9.69	22.45	22.89	19.09	21.67
Gardner [6]	5.15	8.30	5.03	5.25	10.92	9.79	8.54	9.69
Nihal [7]	3.97	6.90	5.43	6.52	14.94	13.53	12.71	13.63
JCI [8]	23.57	19.09	25.26	24.32	36.07	33.87	34.35	34.53
JSCE [9]	31.82	29.73	32.09	32.95	45.02	45.11	41.96	44.16
CEB-FIB [10]	11.07	9.33	12.27	12.06	24.31	23.04	22.03	23.05
Raphael [11]	8.27	7.93	9.57	9.83	21.53	20.11	19.33	20.23
Ahmad and Shah [12]	13.24	11.13	13.53	14.46	27.02	27.16	23.87	26.16
Oluokun et al. [13]	6.27	7.12	7.91	8.85	19.11	17.28	17.16	17.68
Proposed Equation	4.21	6.61	4.53	4.92	11.71	11.29	9.42	10.85

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