Journal of King Saud University – Engineering Sciences (2019) 31, 19–25

King Saud University

Journal of King Saud University – Engineering Sciences

www.ksu.edu.sa
www.sciencedirect.com

ORIGINAL ARTICLE

Evaluation of splitting tensile and compressive strength relationship of self-compacting concrete

Mutiu A. Akinpelu [a], **Samson O. Odeyemi** [a], **Oladipupo S. Olafusi** [b,*], **Fatimah Z. Muhammed** [a]

[a] *Department of Civil Engineering, College of Engineering and Technology, Kwara State University, P.M.B. 1530, Ilorin, Kwara State, Nigeria*
[b] *Civil Engineering Department, College of Engineering, Federal University of Agriculture, Abeokuta, Nigeria*

Received 18 October 2016; accepted 3 January 2017
Available online 28 January 2017

KEYWORDS

Vibrated concrete;
Self-compacting concrete;
Compressive strength;
Splitting tensile strength

Abstract Research findings have reported a behavioural relationship between the splitting tensile strength and compressive strength of concretes. This work studied both the experimental and analytical relationships that exist between splitting tensile strength and compressive strength of both vibrated concrete (VC) and self compacting concrete (SCC) of similar grades. Both concrete types were designed to achieve target compressive strength of 20 N/mm^2, 30 N/mm^2 and 40 N/mm^2 at 28 days. The compressive and splitting tensile properties were measured on cylindrical concrete specimens of 150 mm diameter × 300 mm length at 28-days using a compression testing machine. The analytical work tested seven different reported models relating the two measured parameters for VC on SCC, while the Welch 2 sample *t*-test statistical technique was adopted to check the normality and equality of variance of the results. Experimental findings revealed that the ratio of the splitting tensile to compressive strengths for VC and SCC decreases with increasing compressive strength, and the analytical study revealed that similar analytical model could be adopted for both concrete types as there is no statistically detectable difference between their results.
© 2017 The Authors. Production and hosting by Elsevier B.V. on behalf of King Saud University. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Self-compacting concrete was developed in Japan in 1983 to overcome the problem of achieving durability of concrete structures due to shortage of skilled labour. It is an innovative concrete that is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement without segregation (Okamura and Ouchi, 2003). It has proved beneficial economically because of a number of factors, including: faster construction, reduction in site manpower, better surface finishes,

* Corresponding author.
E-mail address: olafusidipo@yahoo.com (O.S. Olafusi).
Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jksues.2017.01.002
1018-3639 © 2017 The Authors. Production and hosting by Elsevier B.V. on behalf of King Saud University.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Table 1 Mix proportions for VC.

Mixes	Target compressive strength (N/mm^2)	W/C	Cement (kg/m^3)	Sand (kg/m^3)	Crushed granite (kg/m^3)
VC-1	20	0.50	369	1107	1476
VC-2	30	0.45	369	738	554
VC-3	40	0.40	369	369	369

easier placing, improved durability, greater freedom in the design of thinner concrete sections, reduced noise levels, absence of vibration and safer working environment. To achieve the required workability necessary for self-consolidation in fresh state, SCC requires high powder volumes at relatively low water/powder ratios with significant quantities of admixtures such as high range water reducing superplasticizers and sometimes supplemented by viscosity modifying agents. The powder generally consists of a combination of Portland cement with one or more additions. The additions might be inert such as granite dust or reactive such as fly ash and silica fume (EFNARC, 2002). SCC typically contains lesser amount and smaller sizes of coarse aggregates when compared with the conventional vibrated concrete (VC); and thus significantly influences its mechanical properties (Krishna et al., 2010).

Compressive and tensile strengths of concrete are important parameters utilised in the analysis and design of concrete members. Although, classification of concrete in most national and international design codes are often based on the compressive strength, while other mechanical properties such as tensile strength, modulus of elasticity and compressive strain are expressed as a function of the compressive strength; several theoretical and empirical models have been developed to predict the splitting tensile strength of concrete based on its compressive strength (Yan et al., 2013). American Concrete Institute (ACI) model recommends square root relationship between the splitting tensile strength and cylinder compressive strength. Recent studies have also showed that the relationship is not most appropriate (SeshaPhani et al., 2013; Arıoglu et al., 2006; Lavanya and Jegan, 2015; Gajendran et al., 2015). The power of compressive strength varies between 0.6 and 0.8 (SeshaPhani et al., 2013). The ratio of tensile strength to compressive strength also decreases as the compressive strength increases (Arıoglu et al., 2006; Lavanya and Jegan, 2015). It is worthy to emphasize that most of the relationships have been developed based on studies on the conventional vibrated concrete (VC). However, the thrust of this research was to assess the relationship between the hardened properties of VC and SCC of similar compressive strength and to validate the applicability of the existing models connecting compressive strength and splitting tensile strength on self-compacting concrete (SCC).



Figure 1 Slump flow test.



Figure 2 V-funnel test.

2. Materials and methods

2.1. Materials

The materials used in the investigation of VC and SCC specimen were: portable water conforming to ASTM 1602 (2012), ordinary Portland cement of grade 42.5 conforming to BS 12 (1996), naturally occurring river sands as fine aggregates,

Table 2 Mix proportions for SCC.

Mixes	Target compressive strength (N/mm^2)	W/C	Cement (kg/m^3)	Granite dust (kg/m^3)	Sand (kg/m^3)	Crushed granite (kg/m^3)	Superplasticizer (L/100 kg of cement)
SCC-1	20	0.50	450	135	960	813	1.5
SCC-2	30	0.45	500	100	960	813	1.5
SCC-3	40	0.40	553	80	960	813	1.5



Figure 3 L-box test.

crushed granite stones passing sieve size 20 mm and retained on 10 mm as coarse aggregate and conforms to the specifications of ASTM C 33 (1999). Although, granite powder passing sieve 0.09 mm and a sulphated naphthalene polymer based admixture were added to SCC mixes as inert additions and as superplasticizer respectively to improve its flowability.

As there is currently no standardised mix design procedure for SCC, the guideline given by EFNARC (2002) was adopted for the study. Several trial mixes were made to achieve the target compressive strengths. Both the VC and SCC specimens were designed to achieve 28 day cylindrical compressive strength (f'_c) of 20 N/mm^2, 30 N/mm^2 and 40 N/mm^2. Tables 1 and 2 gives the final mix proportion adopted for VC and SCC respectively.

2.2. Fresh properties of the VC and SCC mixes

The workability of the VC specimens were evaluated by the slump test while the rheological properties that categorise a concrete as SCC; flowability, passing ability and segregation resistance were evaluated by slump cone, L-box, V-funnel apparatuses respectively according to EFNARC standards (EFNARC, 2002) as shown in Figs. 1–3.

2.3. Hardened properties of VC and SCC mixes

The hardened properties of concretes considered relevant to this study were the compressive strength and the splitting tensile at 28 days. A total of thirty-six (36) cylindrical specimen (150 mm diameter by 300 mm length) were evaluated for both compressive strength and tensile strength as per ASTM C39 (2014) and ASTM C496 (2004) respectively for both concrete types. The samples were prepared under Standard laboratory conditions (except that the SCC specimens were not vibrated), water-cured by immersion and tested after 28 days using a compression testing machine of 1500 KN capacity. The reported strengths were the average of three specimens.

2.4. Statistical test

To determine whether or not, on average, there is no statistically detectable difference between accuracies of experimental measured values of splitting tensile strength and computed values from existing models (Table 6), the Welch two sample *t*-test procedure was adopted (Shapiro and Wilk, 1965). Seven different null hypotheses (H0) of no statistically detectable difference were tested at 5% critical rejection level ($\alpha = 0.05$) using the *t*-test function in the *stats* library of the version 3.3.1 of R software for statistical computing and graphics (R Core Team, 2016).

Because inferences based on 2-sample *t*-test, as found in literature, are known to be reliable only if samples have equal variances and they assume normal distribution (Welch, 1951) the normality assumption was checked on the sample datasets by testing the null hypothesis of normal samples using Shapiro–Wilk normality test (Royston, 1982a,b, 1995) at 5% critical rejection level. The Shapiro–Wilk method is reported to be more appropriate for small sample sizes (< 50 samples), but can also handle sample sizes as large as 2000. It is the most powerful normality test available and is able to detect small departures from normality (Shapiro et al., 1968; D'Agostino and Stephens, 1986). Visual inspection of the distribution of the dataset may be used for assessing normality, although this approach is usually unreliable and does not guarantee that the distribution is normal (Field, 2009; Altman and Bland, 1995). Examples of the visual inspection methods for checking normality are the frequency distribution (histogram), P–P plot (Probability–Probability plot), and Q–Q plot (Quantile–Quantile plot).

Table 3 Physical properties of the aggregates used in the study.

Materials	Specific gravity	Absorption (%)	Silt content (%)	Maximum size (mm)
Fine aggregate	2.6	1.8	7.4	4.0
Coarse aggregate	2.6	0.3	–	20.0

3. Result and discussions

3.1. Physical properties of materials

The physical properties of the aggregates used in this study are reported in Table 3.

3.2. Fresh concrete properties of VC and SCC

The results of rheological property tests on SCC are presented in Table 4. As seen in the table, all the three concrete mixes satisfied EFNARC (2002) standard specifications for SCC.

3.3. Hardened concrete properties of VC and SCC

The result of compression and splitting tensile test carried out on both VC and SCC cylindrical specimen is presented in Table 5. Each reported result as presented in the table was obtained as the average value of three tested specimens. The results of compressive strength for both VC and SCC for all

the mixes fall within the acceptable allowance limit for the target compressive strength of 20 N/mm^2, 30 N/mm^2 and 40 N/mm^2 for this study. Although, the compressive and splitting tensile strengths of the SCC mixes were lower than those of the VC for the same concrete grade despite the higher paste volume in the SCC. The lower coarse aggregate content may have been responsible for the reduced compressive and splitting tensile strength, and according to Olafusi et al. (2015); the compressive strength of SCC mix at 28 days is in the range of 85–95% of VC, but shows a potential of greater compressive strength at 90 days and beyond.

Fig. 4 revealed that there was no significant difference in the relationship between splitting tensile strength and the compressive strengths of both VC and SCC. The splitting tensile strengths for both concrete types increased with increasing compressive strength in similar trend. This was in line with the findings of Haranki (2009) on vibrated concrete; where he also concluded that splitting tensile strength of concrete is directly proportional to the product of the square root of its compressive strength and the coefficient derived from the regression analysis. Fig. 5 also revealed that the ratio of the splitting tensile to the compressive strengths for both VC and SCC were mostly influenced by their compressive strengths, as the ratio decreased with increasing compressive strength; which justifies the findings of Arıoglu et al. (2006), Lavanya and Jegan (2015); where the ratio of splitting tensile strength to compressive strength decreases with increases in compressive strength and varies between 0.07 and 0.17. Although, the difference between their ratios ranged between 0.01 and 0.002 at compressive strengths up to 32 MPa, and remained at 0.002 afterwards. This indicates that the difference between rate of splitting tensile and compressive strength for both VC and SCC for compressive strengths of 32 MPa and above is negligible.

3.4. Statistical analysis

The result of the predicted splitting tensile strengths of concrete for the models considered in this study is presented in Table 6. From the Shapiro–Wilk normality test results, there is enough data evidence that all samples have normal distribution since their *p*-values, as seen in Table 7, are higher than 0.05. It is also clear that variance of Experimental sample differs from those of models F1 through F7. Hence, we adjusted the *t*-test procedures in R by indicating that variances are not equal for necessary adjustment using alternative statistic that accommodates such violation of variance equality assumption. With the assumptions of the 2-sample *t*-test procedure met, the test was performed on each pair of experimental and model samples.

The results presented in Table 8 reveals that there is enough data evidence to conclude that at 5% critical rejection level, difference between accuracy of experimental method and all models is not different from zero except F2. The implication here is that only F2 (That is CEB-FIB, 1991) has a statistically detectable difference (SDD) from the experimental method at $\alpha = 0.05$.

These inferences are further supported by the boxplot and line graphs in Figs. 6 and 7, respectively. Graph of models F3 through F7 are like the left plot in Fig. 6.

The figure on the left shows the measured tensile strength is not significantly different from ACI Committee 318 (2014) model since the median accuracy in ACI Committee 318 (2014) is overlapping with the box of measured values of split tensile strength; while that on the right shows the measured tensile strength is significantly different from CEB-FIB model since the median accuracy in CEB-FIB is not overlapping with the box of measured values.

Table 4 Test results of fresh properties for SCC.

Specimen	Slump flow (mm)	V-funnel at T_{5min} (sec)	L-box
SCC 1	670	10	0.82
SCC 2	655	11	0.89
SCC 3	665	11	0.91
EFNARC limit	650–800	6–15	0.8–1.0

Table 5 Test results of hardened concrete properties of VC and SCC specimens.

Concrete mix	Compressive strength, f'_c (N/mm^2)	Tensile strength, f_t (N/mm^2)
VC-1	19.9	2.9
VC-2	31.5	4.5
VC-3	40.5	5.8
SCC-1	18.1	2.8
SCC-2	30.1	4.4
SCC-3	39.2	5.7

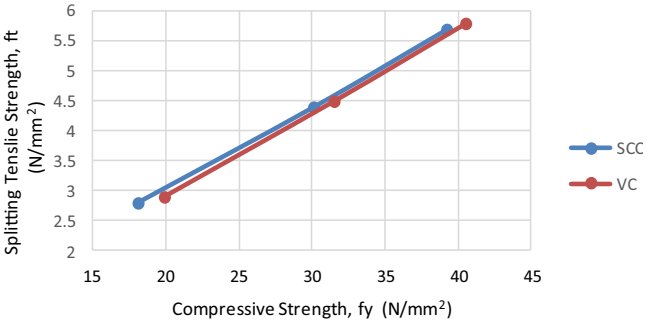


Figure 4 Splitting tensile strength versus compressive strength of SCC and VC.

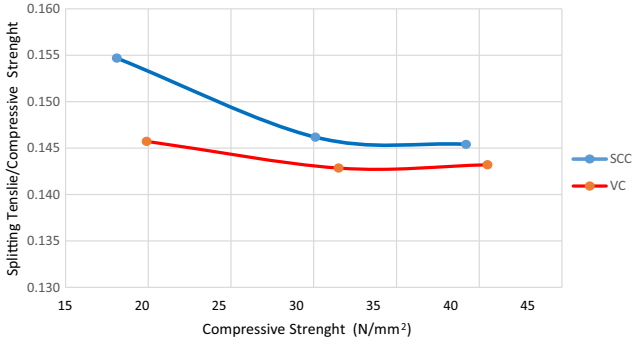


Figure 5 Ratio of splitting tensile to compressive strength vs compressive strength of VC and SCC.

Table 6 Predicted splitting tensile strength of concrete from different models.

Compressive strength (N/mm^2)	Split tensile strength (N/mm^2)							
	Measured value	ACI Committee 318 (2014)	CEB-FIB (1991)	Carino and Lew (1982)	Oluokun et al. (1991)	Arıoglu et al. (2006)	Lavanya and Jegan (2015)	Gardner (1990)
		F1 = $0.56f'^{0.5}_c$	F2 = $0.3f'^{0.66}_c$	F3 = $0.272f'^{0.71}_c$	F4 = $0.294f'^{0.69}_c$	F5 = $0.387f'^{0.63}_c$	F6 = $0.249f'^{0.772}_c$	F7 = $0.33f'^{0.667}_c$
18.1	2.8	2.4	2.0	2.1	2.2	2.4	2.3	2.3
30.1	4.4	3.1	2.8	3.1	3.1	3.3	3.4	3.2
39.2	5.7	3.5	3.4	3.7	3.7	3.9	4.2	3.8
19.9	2.9	2.5	2.2	2.3	2.3	2.5	2.5	2.4
31.5	4.5	3.1	2.9	3.2	3.2	3.4	3.6	3.3
40.5	5.8	3.6	3.5	3.8	3.8	4.0	4.3	3.9

Table 7 Checking variance and normality assumptions on the sample datasets.

Sample	Variances	Test *p*-value	Decision
Experimental	1.6910	0.2575	Observations in sample have normal distribution
F1	0.2467	0.3611	Observations in sample have normal distribution
F2	0.3720	0.5260	Observations in sample have normal distribution
F3	0.4947	0.3950	Observations in sample have normal distribution
F4	0.4590	0.3274	Observations in sample have normal distribution
F5	0.4690	0.3274	Observations in sample have normal distribution
F6	0.7017	0.3976	Observations in sample have normal distribution
F7	0.4590	0.3274	Observations in sample have normal distribution

Table 8 Welch's 2-sample *t*-test.

Data	SDD	*t*-Statistics	*p*-value	Decision
Exp. and F1	6.4283	2.3169	0.05686	On average, samples are not significantly different
Exp. and F2	7.0983	2.6434	0.03284	On average, samples are significantly different
Exp. and F3	7.6947	2.1815	0.06204	On average, samples are not significantly different
Exp. and F4	7.5281	2.1717	0.06375	On average, samples are not significantly different
Exp. and F5	7.5281	1.8376	0.10580	On average, samples are not significantly different
Exp. and F6	8.5399	1.5308	0.16200	On average, samples are not significantly different
Exp. and F7	7.5281	2.0046	0.08217	On average, samples are not significantly different

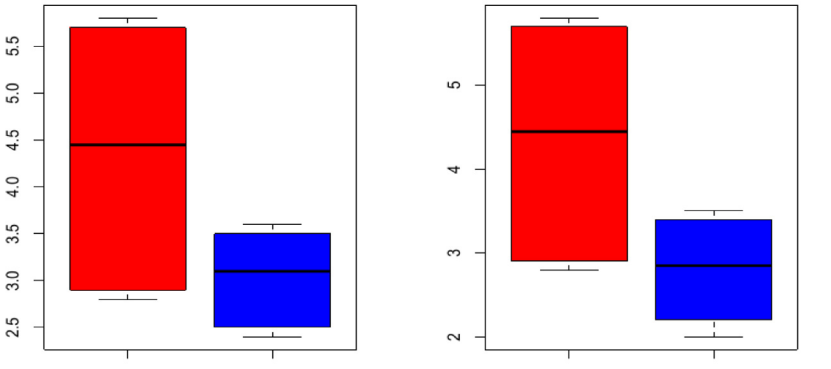


Figure 6 Boxplot showing median accuracies over 6 observations.

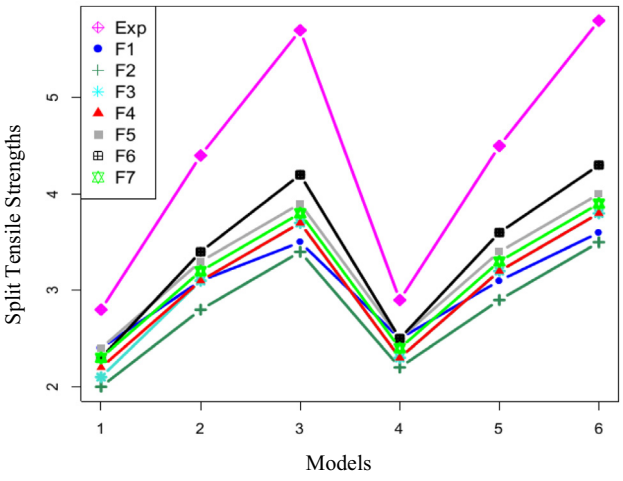


Figure 7 Line plot of split tensile strength measurement by the models.

4. Conclusions

The following conclusions were drawn from this study:

1. The higher powder content and lower coarse aggregate in SCC do not influence its mechanical properties, contrary to the opinion of Krishna et al. (2010); as the relationship between splitting tensile strength and compressive strength was similar for both VC and SCC. Therefore, the same model can be applied to both concrete types.
2. The ratio of the splitting tensile strength to compressive strengths of both concrete types is influenced by the level of concrete strength. The ratio decreases with increasing compressive strength.
3. The accuracy of all the models examined in this study seems to decrease with increasing compressive strength of concrete.
4. Based on the results of statistical analysis, predicted values of splitting tensile strength were not significantly different from the experimental values for all the tested models except for CEB-FIB (1991) model.
5. The model of Lavanya and Jegan (2015) gives splitting tensile strengths that is closest to the experimental value for the range of concrete compressive strengths (20–40 N/mm^2) considered in this research.

References

ACI Committee 318, 2014. Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, Farmington Hills, MI, pp. 107.

Altman, D.G., Bland, J.M., 1995. Statistics notes: the normal distribution. BMJ 310 (6975), 298.

Arıoglu, N., Girgin, Z.C., Arıoglu, E., 2006. Evaluation of ratio between splitting tensile strength and compressive strength for concretes up to 120 MPa and its application in strength criterion. ACI Mater. J. 103 (1), 18–24.

ASTM C 1602, 2012. Standard Specification for Mixing Water Used in the production of Hydraulic Cement Concrete. ASTM International, West Conshohocken, PA.

ASTM C 33, 1999. Standard Specification for Concrete Aggregates. ASTM International, West Conshohocken, PA.

ASTM C39/C39M, 2014. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.

ASTM C496/C496M, 2004. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.

BS 12, 1996. Specification for Portland Cement. British Standard Institution, London, United Kingdom.

Carino, N.J., Lew, H.S., 1982. Re-examination of the relation between splitting tensile and compressive strength of normal weight concrete. ACI Mater. J. 79 (3), 214–219.

CEB-FIB Model Code for Concrete Structures, 1991. Evaluation of the Time Dependent Behaviour of Concrete. Bulletin d'Information No. 199, Comite European du Béton/Fédération Internationale de la Precontrainte, Lausanne, pp. 201.

D'Agostino, R.B., Stephens, M.A., 1986. Goodness-of-Fit Techniques. Marcel Dekker Inc, New York.

EFNARC: European Federation Dedicated to Specialist Construction Chemicals and Concrete Systems, 2002. Specifications and Guidelines for Self-Compacting Concrete. Surrey, U.K.

Field, A., 2009. Discovering Statistics Using SPSS. SAGE publications Ltd, London, p. 822.

Gajendran, K.A., Anuradha, R., Venkatasubramani, G.S., 2015. Studies on relationship between compressive and splitting tensile strength of high performance concrete. ARPN J. Eng. Appl. Sci. 10 (14), 6151–6156.

Gardner, N.J., 1990. Effect of temperature on the early age properties of type I, type III, and type I/Fly ash concretes. ACI Mater. J. 87 (1), 68–78.

Haranki, B., 2009. Strength, Modulus of Elasticity, Creep and Shrinkage of concrete used in Florida (Master of engineering thesis). University Of Florida.

Krishna, A.V., Rao, Krishna, Rajagopal, A., 2010. Effect of different sizes of coarse aggregate on the properties of NCC and SCC. Int. J. Eng. Technol. 2 (10), 5959–5965.

Lavanya, G., Jegan, J., 2015. Evaluation of relationship between split tensile strength and compressive strength for geopolymer concrete of varying grades and molarity. Int. J. Appl. Eng. Res. 10 (15), 35523–35527.

Okamura, H., Ouchi, M., 2003. Self-compacting concrete. J. Adv. Concr. Technol. 1 (1), 5–15.

Olafusi, O.S., Adewuyi, A.P., Otunla, A.I., Babalola, A.O., 2015. Evaluation of fresh and hardened properties of self-compacting concrete. Open J. Civil Eng. 5, 1–7. http://dx.doi.org/10.4236/ojce.2015.51001.

Oluokun, F.A., Burdette, E.G., Deatherage, J.H., 1991. Splitting tensile strength and compressive strength relationships at earl y ages. ACI Mater. J. 88 (2), 115–121.

R Development Core Team, 2016. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0. URL: http://www.R-project.org.

Royston, Patrick, 1982a. Algorithm AS 181: the W test for normality. Appl. Stat. 31, 176–180.

Royston, Patrick, 1982b. An extension of Shapiro and Wilk's W test for normality to large samples. Appl. Stat. 31, 115–124.

Royston, Patrick, 1995. Remark AS R94: a remark on algorithm AS 181: the W test for normality. Appl. Stat. 44, 547–551.

SeshaPhani, A., Seshadri, S.T., Srinivasa, R.S., 2013. Evaluation of relationship between mechanical properties of high strength self compacting concrete. Am. J. Eng. Res. 2 (4), 67–71.

Shapiro, S.S., Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591.
Shapiro, S.S., Wilk, M.B., Chan, H.J., 1968. A comparative study of various tests for normality. JASA 63, 324.
Welch, B.L., 1951. On the comparison of several mean values: an alternative approach. Biometrika 38, 330–336.
Yan, Kezhen, Hongbing, Xu, Shen, Guanghui, Liu, Pei, 2013. Prediction of splitting tensile strength from cylinder compressive strength of concrete by support vector machine. Adv. Mater. Sci. Eng. 2013, 1–13. Article ID 597257.