SPLITTING TENSILE STRENGTH AND COMPRESSIVE STRENGTH RATIOS AND RELATIONS FOR CONCRETE MADE WITH DIFFERENT GRADES OF NIGERIAN PORTLAND LIMESTONE CEMENT (PLC)

Supported by tetfund

Christopher A. Fapohunda*, Blessing A. Adigo and Babatunde I. Famodimu
Department of Civil Engineering, Federal University, Oye-Ekiti, Ekiti State, Nigeria
*Corresponding author: christopher.fapohunda@fuoye.edu.ng

Received: July 14, 2020 **Accepted:** November 02, 2020

Abstract: The results of splitting tensile strength and compressive strength ratios, as well the expression relating splitting tensile strength and compressive strength of concrete produced with Portland limestone cement are presented in this paper. Portland limestone cement grades 32.5R and 42.5R were used for this work. Concrete cube specimens 150 x 150 x 150 mm were used to measure the compressive strength while 150 x 300 mm cylindrical concrete specimens were used to assess the splitting tensile strength. Both strengths were measured at 7, 14, 21, 28, 60 and 90 days of curing. Experimental findings show that the 28-day ratios of the splitting tensile strength to the compressive strength for concrete produced with grade of cement 32.5 R are found to be higher than the specimens produced with grade 42.5R, both at the early and latter days. The results of analytical and experimental relationship indicate that the usual power expression, relating tensile to compressive strength, though popular in other brands of cement, may not be applicable to splitting tensile strength and compressive strength of concrete produced with all the grades of Portland limestone cement. The results show that logarithmic trend equation in the form f_t = 2.3529ln(f_c) - 4.8642, with R^2 values of 0.76 and above, because of its simplicity, is reliable in expressing the relationship between the splitting tensile strength and compressive strength of concrete produced with all the grades of Portland limestone cement.

Keywords: Compressive strength, strength ratios, strength relations, splitting tensile strength

Introduction

In structural concrete structures, the compressive strength is what is used for design purposes and often times, is an indication of the quality of concrete. However, in certain applications, tensile strength of concrete is important. For example, tensile strength of concrete, rather than the compressive strength is the deciding factor in highway pavements and airfield slabs. Such structures are design on the principle that rests on the flexural strength of concrete.

Furthermore, the knowledge of tensile strength is useful to estimate the load under which cracking will develop (Neville, 2011). This is due to the influence of tensile stress on the formation of cracks and its propagation in the tension region of reinforced concrete flexural member. Shear, torsion and other actions also produce tensile stresses to the particular section of concrete member. In structural concrete, assessment of concrete strength in tension is usually determined in three ways, namely: direct tension test, flexure test, and splitting tension test. Direct tension test, though accurate, is rarely used because of difficulty of keeping the specimen free of eccentricity. The flexure test, on the other hand, is not convenient for control or compliance purposes because the test specimens are heavy and are easily damaged (Neville, 2011). In the case of the splitting test, it is simple to perform and gives more uniform results than other tension tests. The strength determined in the splitting test is believed to be close to the direct tensile strength of concrete, being 5 to 12 per cent higher. However, for the purpose of field control and compliance, assessing the tensile strength either from the modulus of rupture or splitting test is difficult (Oluokun *et al.*, 1991).

On the other hand, compressive strength is easy to measure. Thus, an indirect means of assessing the flexural strength (obtained as modulus of rupture) or the splitting tensile strengths of concrete is usually through the compressive strength. This is made possible through the establishment of mathematical relationship between the tensile strength (splitting and modulus of rupture) and compressive strength. The ratios and expressions between splitting tensile strength and the compressive strength for concrete is the concern of this work. It is an accepted fact among practicing engineers that the splitting tensile strength of concrete is about one tenth of the compressive strength while the modulus of rupture is about 15% of the compressive strength (Raphael, 1984; Shetty, 2009; Neville, 2011; Gambhir, 2013). There are also relationships between the splitting tensile strength and compressive strength for concrete. These relationships, developed by many researchers between splitting tensile strength (f_t) and the compressive strength (f_t) in concrete, are usually expressed in the form of:

$$f_t = \beta f_c^{\kappa} \quad \textbf{(1)}$$

Where: f_t = tensile strength, f_c = compressive strength. The terms β and κ are constants.

The summary of constants for different authors are as shown in Table 1.

But most of these expressions and relationships between tensile strength and compressive strength of concrete were developed by the researchers using ordinary Portland cement. Also, the ratio of the splitting tensile to compressive strength were obtained as a function of the cylinder compressive strength. It is already established that size and shape of specimens affects the results of strength tests (Heilmann, 1969; Neville, 2011). Thus, the results of relationship derived from cylinder specimens may not be applicable to cube specimens (Ros and Shima, 2013). In the same vein, for concrete produced with cement that fall into the category of Portland-composite cement, classified as CEM II in which the clinker has been replaced by suitable supplementary cement materials (SCM), there is paucity of literature on the ratios and relationship between the splitting tensile strength and the compressive strength. It is already well-established in the literature that the type of cement is one of the major factors affecting relationship between the tensile strength and compressive strength (Heilmann, 1969; Rüsch, 1975; Raphael, 1984). There is also dearth of information on the sufficiency or otherwise of the applicability of equations developed for concrete made from other types and grades cements for concrete made with Portland limestone cement.

Table 1: Splitting tensile and compressive strengths relations equation

Authors	β	κ	Comments
Carino and Lew (1982)	0.272	0.710	
Raphael (1984)	0.313	0.667	1. Ordinary Portland cement was used for concrete was used for the investigation 2. Value of κ proposed for all ages of concrete 3. Based on 150 x 300 mm cylindrical specimens
Gardener (1990)	0.330	0.667	1. CEM II cement with fly-ash was used for the investigation 2. Value of κ proposed for all ages of concrete
CEB-FIB (1991)	0.300	0.660	1. Value of κ proposed for all ages of concrete
Oluokun *et al*. (1991)	0.294	0.790	1. Normal weight concrete 2. Value of κ proposed for the early age of concrete
Arioglu *et al.* (2006)	0.387	0.630	1. Cement + silica fume concrete
JSCE (2007)	0.230	0.667	1. Value of κ proposed for all ages of concrete
JCI (2008)	0.130	0.850	
Selim (2008)	0.106	0.948	
ACI Committee 318 (2014)	0.560	0.500	1. Value of κ proposed for all ages of concrete 2. Based on 150 x 300 mm cylindrical specimens
Lavanya and Jegan (2015)	0.249	0.772	1. High calcium fly ash based geopolymer concrete was used for the investigation.

Thus, the aim of this work is to determine the strength ratios and strength relations between the splitting tensile strength and cube compressive strength of concrete produced with Portland limestone cement. The specific objectives include determination of cube compressive strength and splitting tensile strength of concrete produced with grade 32.5 R and 42.5 R Portland limestone cement, being the grades available in the open market. This work does not attempt to analyze the relationship between the splitting tensile and the compressive strengths of concrete produced with 32.5R and 42.5R cement based on tests results of others, because of paucity of data. It will however attempt to predict the relationship between the spitting tensile and compressive strengths from the experimental data from this investigation.

Materials and Method

Materials and mix proportions

The materials used for this investigation are: cement, fine aggregate and coarse aggregate and water. The cement was Portland limestone cement (PLC) produced to conform to the requirement of BS EN 197-1 (2000) and CEM II of NIS 444 (2014. Two grades: 32.5 R and 42.5 R were used. These two grades are the only one available in the market. For the fine aggregate, river sand obtained from a river running adjacent to the Ikole-Ekiti Campus of the Federal University Oye-Ekiti, Ikole-Ekiti was used. The river sand was sun-dried and sieved. The fraction of the material passing through sieve BS no 4 (4.75 mm) but retained on sieve no BS 200 (75 μm) was collected. The collected portion was bagged and stored in a cool place. The quarry site located in Ikole-Ekiti, where the University of the authors was located, served as the source of crushed stone that was used as the coarse aggregate for this work. The maximum size of the coarse aggregate was limited to 20 mm, in line with the recommendation of with BS 8110 (1997) in relation to coarse aggregate for structural concrete. Portable water from the University borehole, that is suitable for drinking, was used for the investigation. In order to achieve the set objectives for this investigation, a concrete mix of 1:2:4 and water/cement ratios of 0.4, 0.5 and 0.6, as well as having work abilities of 20 – 50, according to recommendations of COTEN (2017) were adopted. On the basis of this mix proportion, the fractions of concrete ingredient for one cubic meter (1 m^3) of concrete was obtained and presented in Table 2.

Table 2: Mix proportion for the investigation

Grade	W/C Ratio	Mix Designation	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)
32.5	0.4	M_{14}	343	686	1372	137
	0.5	M_{15}	343	686	1372	172
	0.6	M_{16}	343	686	1372	206
42.5	0.4	M_{24}	343	686	1372	137
	0.5	M_{25}	343	686	1372	172
	0.6	M_{26}	343	686	1372	206

Production of concrete was accomplished by batching the ingredients by weight. The ingredients were thoroughly mixed according to the procedures suggested Gambhir (2013). The concrete was then cast into 150 x 150 x 150 mm cube moulds for compressive specimens and into 150 x 300 mm cylinder moulds for splitting tensile strength specimens. The cast concrete was then given adequate compaction. The concrete specimens were demoulded after 24 h and then moist-cured until the date of testing. Both the compression and tensile specimens were tested after 7, 14, 21, 28, 60 and 90 days of curing. Three specimens were tested at each curing days for each of the properties (that is compressive strength and the splitting tensile strength).

Experimental investigations

Characterization of the materials

For the purpose of characterizing the materials used, some preliminary investigation was conducted to determine the physical properties of aggregate such as the density, specific gravity, water absorption, moisture content, and particle size distribution, for both the fine and coarse aggregate. Chemical analysis was also carried on the grades of the Portland limestone cement (32.5R and 42.5R) to determine the oxides composition.

Compressive strength tests

The compressive strengths of the concrete samples were determined using 150 x 150 x 150 mm cube specimens in accordance to the provisions of BS EN 12390-3 (2009). The equipment used for the test was a 2000KN WAW-2000B computerized electrohydraulic servo universal testing machine. The machine has an accuracy of ± 1% of test force. At each testing age, three specimens were tested, and the average used to evaluate the mean strength.

Splitting tensile strength

Concrete cylinder specimens with dimensions 150 x 300 mm were used in the determination of the splitting tensile strength of concrete samples. The splitting tensile strength test was conducted in accordance to the provision of BS 12390: Part 6 (2009) using 2000KN WAW-2000B computerized electrohydraulic servo universal testing machine with accuracy of ± 1% of test force. In order to obtain the splitting tensile strength (Ts), the expression in equation 2 was used.

$$T_s = \frac{2P}{\pi l d} \quad \textbf{(2)}$$

Where: *Ts* is the splitting tensile strength (N/mm^2), P is the maximum applied load (in Newtons) by the testing machine, *l* is the length of the specimen (mm), and d is the diameter of the specimen (mm).

Results and Discussions

Characterization of materials

Some of the observed properties of the aggregates are shown in Table 3. The values of the specific gravities of sand and gravel are 2.64 and 2.68, respectively as can be observed from Table 4. These values placed the aggregates in the category of natural aggregate. According to Gambhir (2013), the average specific gravity of majority of natural aggregate have been found to lie between 2.5 and 2.8. Further, the bulk density, water absorption and the moisture content of both the sand and gravel fell between the ranges recommended for normal concrete (ACI, 1999). These values are 1280 to 1920 kg/m^3 for density; 0 to 8% for water absorption, and moisture content of 0 – 2% for sand and 0 – 10% for gravel. Also, the coefficient of curvature for both are close to 1; thus indicating that both are well-graded, while the coefficient of uniformity of less than or equal to 4 recorded for both sand and gravel suggest that both are uniformly graded (Iowa, 2020). Overall conclusion of all of these is that the materials are good for concrete production.

Table 3: Some physical properties of the aggregates

Properties	Sand	Gravel
Specific Gravity	2.64	2.68
Bulk Density (kg/m^3)	1668.67	1643.67
Water Absorption (%)	2.01	2.08
Moisture Content (%)	0.00	0.00
Coefficient of curvature (Cc)	0.89	0.99
Coefficient of uniformity (Cu)	3.05	2.44

Table 4: Oxides composition and compounds of grades of cement

Oxides	32.5R (%)	42.5R (%)
CaO	63.90	61.55
SiO_2	19.10	17.89
Al_2O_3	4.91	4.78
F_2O_3	3.24	4.18
MgO	0.93	0.88
Na_2O	0.18	0.31
K_2O	0.41	0.41
Mn_2O	0.01	0.01
SO_3	2.31	2.27
LOI	2.02	1.99
Insoluble Residue	0.34	0.30

Chemical analysis

The oxides composition, resulting from the chemical analysis of the Portland limestone cement of grade 32.5 R and 42. 5 R are shown in Table 4.

From the Table 4, it can be observed that both 32. 5 R and 42. 5 R have high CaO in relation to other oxides. The overall oxides composition is in line with similar limestone Portland cement reported by Tosun *et al*. (2009). In addition, the chemical compositions met the requirements of BS 12 (1996) and BS EN 197-1 (2000) for the followings, namely: the quantity of SO_3 is less than 4.0%; loss on ignition was found to be less than 5% and insoluble of less than 5.0%.

Compressive strength

The results of the cube compressive strength tests of the concrete specimens for the grades of cement at the water/cement ratios of 0.40, 0.50 and 0.60 are presented in Tables 5.

From the Table 5, the followings pattern can be observed: (i) at all the water/cement ratios for the two cement grades, the compressive strength increased with curing days, (ii) the compressive strengths of the specimens increased with water/cement ratios, and (iii) concrete specimens produced with grace 42.5 R developed higher compressive strength than the concrete specimens produced with grade 32.5R, at all the water/cement ratios. The fact that concrete specimens produced with Portland cement grade 42.5R developed higher compressive strengths than those produced with Portland cement grade 32.5R are consistent with findings of other researchers (Adewole *et al*., 2015; Joel and Mbapuun, 2016).

Table 5: Cube compressive strength for the concrete specimens

Curing Age (days)	Cube Compressive Strength f_t (N/mm^2)					
	32.5 R			42.5 R		
	0.40	0.50	0.60	0.40	0.50	0.60
7	11.76±0.21	17.05± 0.56	16.51± 0.75	12.30± 0.56	16.70± 0.34	20.22± 0.43
14	12.46± 0.23	17.20± 0.56	20.40± 0.23	12.30± 0.45	17.96± 0.32	20.30± 0.42
21	15.44± 0.45	21.35± 0.54	24.15± 0.34	14.14± 0.58	23.23± 0.45	24.07± 0.43
28	16.04± 0.34	23.99± 0.45	26.40± 0.43	15.02± 0.36	31.67± 0.34	30.76± 0.44
60	17.01± 0.33	32.33± 0.34	34.88± 0.56	16.32± 0.67	34.61± 0.45	32.73± 0.56
90	17.28± 0.32	35.01± 0.34	37.56± 0.67	19.81± 0.56	34.93± 0.44	36.93± 0.52

Table 6: Splitting tensile strength of the concrete specimens

Curing Age (days)	Splitting tensile Strength f_t (N/mm^2)					
	32.5 R			42.5 R		
	0.40	0.50	0.60	0.40	0.50	0.60
7	0.90± 0.06	2.20± 0.02	1.62± 0.06	0.55± 0.04	2.11± 0.09	1.29± 0.02
14	1.17± 0.05	2.22± 0.03	1.89± 0.07	0.95± 0.03	2.32± 0.05	1.95± 0.02
21	1.49± 0.06	2.52± 0.06	2.24± 0.06	1.09± 0.01	2.55± 0.06	2.40± 0.03
28	1.54± 0.04	2.82± 0.05	2.34± 0.08	1.39± 0.03	2.85± 0.06	2.43± 0.03
60	1.80± 0.05	2.96± 0.03	2.88± 0.05	1.48± 0.04	2.98± 0.07	2.76± 0.03
90	1.99± 0.04	3.22± 0.04	3.06± 0.06	1.55± 0.02	3.23± 0.06	2.91± 0.06

Splitting tensile strength

The results of the splitting tensile strength of the concrete specimens for the grades of cement at the water/cement ratios of 0.40, 0.50 and 0.60 are presented in Tables 6.

The pattern of the splitting tensile strength development for concrete made with grade 42.5 R is similar to that of the compressive strength. However, for concrete specimens made with 32.5 R grade, the splitting tensile strength increased with curing ages. Also, the splitting tensile strength at the water/cement ratio of 0.50 are higher than those of 0.40. The splitting tensile strength at the water ratio of 0.60 were lower.

Strength ratios

The ratios of the splitting tensile strength and the cube compressive strength are presented in Tables 7 – 9, respectively for water/cement ratios of 0.40, 0.50 and 0.60 for the two grades of Portland limestone cement used. Looking at the Tables critically, some patterns are observable.

Table 7: Ratio of splitting tensile strength to compressive strength (W/C = 0.40)

Curing Days	Compressive Strength, f_c (N/mm^2)		Splitting tensile Strength f_t (N/mm^2)		Ratio, $\alpha = \frac{f_t}{f_c}$	
	32.5 R	42.5 R	32.5 R	42.5 R	32.5R	42.5R
7	11.76	12.30	0.90	0.55	0.077	0.045
14	12.46	12.30	1.17	0.95	0.094	0.077
21	15.44	14.14	1.49	1.09	0.097	0.077
28	16.04	15.02	1.54	1.39	**0.103**	**0.093**
60	17.01	16.32	1.80	1.48	0.106	0.091
90	17.28	19.81	1.99	1.55	0.115	0.078

Table 8: Ratio of splitting tensile strength to compressive strength (W/C = 0.50)

Curing Days	Compressive Strength, f_c (N/mm^2)		Splitting tensile Strength f_t (N/mm^2)		Ratio, $\alpha = \frac{f_t}{f_c}$	
	32.5 R	42.5 R	32.5 R	42.5 R	32.5R	42.5R
7	17.05	16.70	2.20	2.11	0.129	0.126
14	17.20	17.96	2.22	2.32	0.129	0.129
21	21.35	23.23	2.52	2.55	0.118	0.110
28	23.99	31.67	2.82	2.85	**0.118**	**0.090**
60	32.33	34.61	2.96	2.98	0.092	0.086
90	35.01	37.56	3.22	3.23	0.092	0.086

Table 9: Ratio of splitting tensile strength to compressive strength (W/C = 0.60)

Curing Days	Compressive Strength, f_c (N/mm^2)		Splitting tensile Strength f_t (N/mm^2)		Ratio, $\alpha = \frac{f_t}{f_c}$	
	32.5 R	42.5 R	32.5 R	42.5 R	32.5R	42.5R
7	16.51	20.22	1.62	1.29	0.098	0.064
14	20.40	20.30	1.89	1.95	0.093	0.096
21	24.15	24.07	2.24	2.40	0.093	0.100
28	26.40	30.76	2.34	2.43	**0.090**	**0.079**
60	32.73	36.49	2.88	2.76	0.088	0.079
90	34.97	36.93	3.06	2.91	0.088	0.079

At all the water/cement ratios, the ratios of the splitting tensile strength to the compressive strength for concrete produced with grade of cement 32.5 R are found to be higher than the specimens produced with grade 42.5R, both at the early and latter days. This is obviously due to the fact that the compressive strengths of the grade 32.5R specimens increased more slowly, in relation to grade 42.4R specimens, than the splitting tensile strengths (Arioglu *et al*., 2006; Neville, 2011). For concrete produced with grade 32.5R, the following observations can be made. First, at the water/cement ratio of 0.40, the ratio increased with curing ages. This means that, with curing ages, the compressive strength increased more slowly than the splitting tensile strength. Secondly, at the water/cement ratios of 0.50 and 0.60, the ratio decreased with curing ages. This is because the splitting tensile strength increases more slowly than the compressive strength so that the ratio *ft*/*fc* decreases with time (Neville, 2011). In a similar vein, the concrete specimens produced with grade 42.5R shows two distinct characteristics. First, the specimens produced at the water/cement ratios 0.40 and 0.60, the ratio increased with curing age (at early ages) up to 28 days of curing and then decreased (or remain constant) at the latter ages. This means that the compressive strengths of the specimens increased more slowly than the splitting tensile strength at early ages, but at the latter ages, the reversal is the case. Secondly, for specimens produced with water/cement ratio of 0.50, the ratios reduced with curing ages. This means that the splitting tensile strength increased more slowly than the compressive strength with curing age. However, the 28-day ratio varied between 0.090 and 0.118 for concrete specimens produced with grade 32.5R cement, while the range is between 0.079 and 0.093 for specimens produced with grade 42.5R cement.

Strength relations

A statistical model of the power form in equation 1 (reproduced below) was adopted to evaluate the relationship between the splitting tensile strength and the compressive strength.

$$f_t = \beta f_c^{\kappa} \quad \textbf{(1)}$$

In equation 1; f_t is the tensile strength, f_c is the compressive strength, while β and κ are non-dimensional coefficients. As can be observed in Table 1, most of the expressions relating tensile strength to compressive strength are in this form, and will thus allow comparison of results. Representing the data for the splitting tensile and compressive strengths values in Tables 7 – 9, for the cement grades 32.5R and 42.5R at the water/cement ratios of 0.40, 0.50 and 0.60 and the curing age of 7, 14, 21, 28, 60 and 90 days in scattered plots shown in Fig. 1, for the purpose of conducting regression analysis, the equations 3 – 8 were obtained.

$f_t = 0.0135 f_c^{1.7295}$ $R^2 = 0.9459$ (32.5R, w/c = 0.40) **(3)**
$f_t = 0.0101 f_c^{1.7439}$ $R^2 = 0.6595$ (42.5R, w/c = 0.40) **(4)**
$f_t = 0.5465 f_c^{0.4974}$ $R^2 = 0.9527$ (32.5R, w/c = 0.50) **(5)**
$f_t = 0.5716 f_c^{0.4738}$ $R^2 = 0.9544$ (42.5R, w/c = 0.50) **(6)**
$f_t = 0.1236 f_c^{0.8899}$ $R^2 = 0.8710$ (32.5R, w/c = 0.60) **(7)**
$f_t = 0.0883 f_c^{0.9803}$ $R^2 = 0.7101$ (42.5R, w/c = 0.60) **(8)**

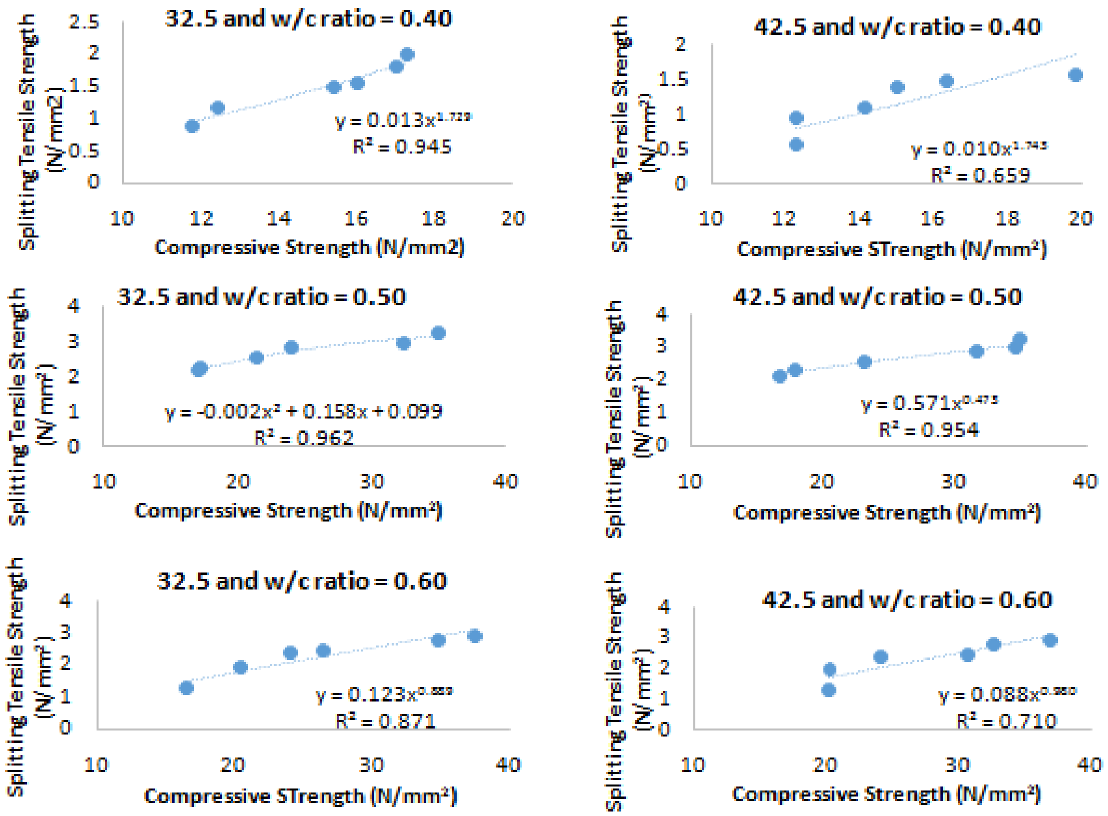

Fig. 1: Relationship between the splitting tensile and compresive strengths of portland limestone cement of Grade 32.5 and 42.5 at the considered water/cement ratios

Careful observation of equations 2 – 7 shows that the values of the coefficeint of determination R^2 obtained from the regresion analysis are quite large (least being 0.8710) for concrete made with cement grade 32.5R at all the water cement ratios. That is, approximately 87% and above of the test data correlated to the regression equations. This suggest a strong relationships of the models for concrete made with grade 32.5R at all the water/cement raios. However, in comparison to concrete made with cement grade 32.5%, the values of R^2 obtained for grade 42.5R cement grade are lower, that is, 0.6595 at 0.40 water/cement ratio and 0.7101 at water/cement ratio of 0.60. Only the concrete prodcuced with water/cement ratio of 0.5 had high R^2 value of 0.9544. What this suggests is that, the power equation may not adequately cater for all grades of concrete produced with portland limestone cement at all the water/cement ratios.In order to confirm this deduction, relaibility test was conducted by evaluating the errors associated with the regression equations (Arioglu *et al.*, 2006). This is assessed through the integral absolute error (IAE, %), which is a method employed by many researchers (Gardner, 1990; Oluokun, 1991; Arioglu *et al.*, 2006) to assess the goodness of fit of any proposed relationship. In this case, the proposed regression equations 3 – 8. The IAE is computed from equation 9

$$IAE = \Sigma \frac{\sqrt{[(O_i - P_i)^2]}}{\Sigma O_i} \, x \, 100 \quad \textbf{(9)}$$

In equation 9, *Oi* is the observed value, and *Pi* is the predicted value from the regression equation. According to Arioglu *et al.* (2006), the IAE measures the relative deviations of data from the regression equation. They averred that when the IAE is zero, the predicted values from the regression equation are equal to the observed values; this situation rarely occurs. They further stated that when comparing different equations, the regression equation having the smallest value of the IAE can be judged as the most reliable, with a range of IAE from 0 to 10% being regarded as the limits for an acceptable regression equation. The values of the experimental splitting tensile strength and the calculated splitting tensile strengths (in N/mm^2) using the obtained regression equations, are presented in Tables 10 – 12. These values were used in equation 9 to obtain the IAE values presented in Table 13. From the values of IAE obtained as presented in Table 13, it can be concluded that the regression equations will produce reliable results for concrete made with grade 32.5R.

Table 10: Experimental and predicted splitting tensile strengths at W/C ratio 0.40

Curing Age (days)	Grade 32.5R			Grade 42.5R		
	Compressive Strength	Splitting Tensile Strength		Compressive Strength	Splitting Tensile Strength	
		Experimental	Model		Experimental	Model
7	11.76	0.90	0.96	12.30	0.55	0.81
14	12.46	1.17	1.06	12.30	0.95	0.81
21	15.44	1.49	1.52	14.14	1.09	1.03
28	16.04	1.54	1.64	15.02	1.39	1.14
60	17.01	1.80	1.82	16.32	1.48	1.32
90	17.28	1.99	1.87	19.81	1.55	1.85

Table 11: Experimental and predicted splitting tensile strengths at W/C ratio 0.50

Curing Age (days)	Grade 32.5R			Grade 42.5R		
	Compressive Strength	Splitting Tensile Strength		Compressive Strength	Splitting Tensile Strength	
		Experimental	Model		Experimental	Model
7	17.05	2.20	2.24	16.70	2.11	2.17
14	17.20	2.22	2.25	17.96	2.32	2.25
21	21.35	2.52	2.51	23.23	2.55	2.54
28	23.99	2.82	2.66	31.67	2.85	2.94
60	32.33	2.96	3.08	34.61	2.98	3.07
90	35.01	3.22	3.20	37.56	3.23	3.19

Table 12: Experimental and predicted splitting tensile strengths at W/C ratio 0.60

Curing Age (days)	Grade 32.5R			Grade 42.5R		
	Compressive Strength	Splitting Tensile Strength		Compressive Strength	Splitting tensile strength	
		Experimental	Model		Experimental	Model
7	16.51	1.62	1.50	20.22	1.29	1.62
14	20.40	1.89	1.81	20.30	1.95	1.69
21	24.15	2.24	2.10	24.07	2.40	2.00
28	26.40	2.34	2.28	30.76	2.43	2.54
60	32.73	2.88	2.76	36.49	2.76	3.00
90	34.97	3.06	2.92	36.93	2.91	3.04

This is because the IAE values are less than 10% at all the w/c ratios. But the ability to give a reliable splitting tensile strength for concrete made with grade 42.5R is suspect. Only the samples with w/c ratio of 0.50 has IAE values of less than 10%.

In order to obtain expression that is capable of prediction reliable results between splitting tensile strength and compressive strength of concrete made with the grades of Portland limestone cement, a number of other trend lines models were evaluated. These trend lines models expressions of the form of equations 10 – 13 were evaluated for adequacy to give reliable relationship between the splitting tensile strength and the compressive strength of concrete produced with the available grades of Portland limestone cement.

$$f_t = 0.2336e^{0.1209f_c} \quad \text{(Exponential)} \quad \textbf{(10)}$$

$$f_t = 0.1653f_c - 0.9974 \quad \text{(Linear)} \quad \textbf{(11)}$$

$$f_t = 2.3529\ln(f_c) - 4.8642 \quad \text{(Logarithmic)} \quad \textbf{(12)}$$

$$f_t = 0.0046f_c^4 - 0.2418f_c^3 + 4.6911f_c^2 - 39.408f_c + 121.18 \quad \text{(4th order Polynomial)} \quad \textbf{(13)}$$

The coefficient of determination resulting from the regression analysis (following the procedures that produced Fig. 1), for the grades 32.5R and 42.5R at the w/c ratios of 0.40, 0.50 and 0.60, using these trend line equations 10 – 13 are presented in Table 14. The values earlier obtained for the power functions are also included to capture all the patterns. Careful perusal of the values shows that, in addition to power model, linear and exponential models will not be able to express the relationship between the splitting tensile strength and the compressive strengths reliably for concrete made with the grades of Portland limestone cement. It was earlier shown in Table 13 that the coefficient of determination R^2 values for concrete specimens produced with cement grade 42.5R at water/cement ratio of 0.40 and 0.60 resulted in unacceptable IAE.

Table 13: The IAE for the regression analysis of equations 3 – 8

W/C Ratio	Grade of Concrete	R^2	IAE
0.40	32.5	0.9459	4.95
	42.5	0.6595	16.69
0.50	32.5	0.9527	2.38
	42.5	0.9544	2.24
0.60	32.5	0.8710	4.70
	42.5	0.7101	10.69

Table 14: Coefficient of determination for trend lines models

Trend Lines Models	W/C Ratio	R^2 Cement grade 32.5R	R^2 Cement grade 42.5R
Power	0.4	0.9459	0.6595
	0.5	0.9527	0.9544
	0.6	0.8710	0.7101
Linear	0.4	0.9393	0.7161
	0.5	0.9346	0.9472
	0.6	0.8691	0.7686
Exponential	0.4	0.9473	0.6095
	0.5	0.9204	0.9494
	0.6	0.7862	0.6810
Logarithm	0.4	0.9294	0.7648
	0.5	0.9584	0.9448
	0.6	0.9347	0.7915
Polynomial (order 4)	0.4	0.9994	0.8901
	0.5	0.9996	0.9725
	0.6	0.9969	0.8934

For the same reason, the linear models yield R^2 that is in the domain of unacceptable integral absolute error (IAE) for concrete specimens made with grade 42.5R at water/cement ratio of 0.40. The model will thus not be suitable for concrete produced with the available grades of cement. Similarly, exponential trend lines, with lower R^2 for concrete specimens produced with grade 42.5R at the water/cement ratios of 0.40 and 0.60 also fell in the domain of unacceptable IAE. The power, linear and exponential trend lines will thus not be acceptable. However, the coefficient of determination (R^2) values obtained for logarithmic and polynomial of order 4, for all the concrete samples produced with the grades of Portland limestone cement, at all the water/cement ratios considered, are sufficiently large (more than 0.76). In relation to Table 13, the logarithmic and polynomial of order 4 will yield acceptable IAE. However, for simplicity, however, the logarithmic should be preferred.

Conclusions and Recommendations

Conclusions

From the analysis of the results generated in the course of this work, the following conclusions can be made.

i. At all the water/cement ratios, the 28-day ratios of the splitting tensile strength to the compressive strength for concrete produced with grade of cement 32.5 R are found to be higher than the specimens produced with grade 42.5R, both at the early and latter days.
ii. The power expression relating the splitting tensile strength to the compressive strength may not be adequate for all the grades of Portland limestone cement.
iii. The logarithmic and polynomial trends lines of order 4 can be accepted to reliably express the relationship between the splitting tensile strength and compressive strength of concrete samples produced with Portland cement grades 32.5R and 42.5R at all the water/cement ratios considered.

Recommendations

It was earlier observed in the introduction that there is dearth of literature documenting the relationship between the splitting tensile strength and compressive strength of concrete produced with Portland limestone cement. Although, this work has attempted to investigate this issue, more research work still needs to be done, so as to generate a sufficiently large base of data that can be later use to carry out statistical analysis for accuracy of prediction. This is hereby recommended.

Acknowledgment

The technical assistance provided by the Technologists in the Concrete Laboratory of the Civil Engineering Department, Federal University, Oye-Ekiti, Nigeria are sincerely acknowledged by the authors.

Conflict of Interest

Authors have declared that there is no conflict of interest reported in this work.

References

ACI 1999. Aggregates for Concrete. ACI Education Bulletin – E1-99. *American Concrete Institute*, Farmington Hills, Michigan.

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

Adewole KK, Ajagbe WO & Arasi IA 2015. Determination of appropriate mix ratios for concrete grades using Nigerian Portland-limestone grades 32.5 and 42.5. *Leonardo Electr. J. Practices and Techn.*, 26: 79 – 88.

Arıoglu N, Girgin ZC & 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 Materials Journal*, 103(1): 18–24.

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

BS 8110 1997. Structural Use of Concrete – Code of Practice for Design and Construction. *British Standard Institution*, London.

BS EN 197-1 2000. Cement, Composition, Specification and Conformity Criteria for Common Cements. *British Standard Institution,* London.

BS EN 12390-3 2009. Testing Hardened Concrete: Compressive Strength of Test Specimens. *British Standard Institution,* London.

BS 12390: Part 5 2009. Testing Hardened Concrete: Tensile Splitting Strength of Test Specimens. *British Standard Institution*, London.

Carino NJ & Lew HS 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 Be´ton/Fe´de´rationInternationale de la Precontrainte,* Lausanne, p. 201.

COREN 2017. Concrete Mix Design Manual. *Special Publication No. COREN/2017/016/RC*, 1st Edition.

Gambhir ML 2013. Concrete Technology – Theory and Practice. 5th Edition, McGraw Hill Education Private Limited, New Delhi, India, pp. 149 – 161.

Gardner NJ 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.

Heilmann HG 1969. Beziehungenzwischen Zug- und Druckfestigkeit des Betons. *Beton,* 19(2): 68–70.

Iowa 2020. Class Notes: C.C. Swan, University of Iowa: Lecture 2: Grain Size Distributions and Soil Particle Characteristics. Available online at: http://user.engineering.uiowa.edu/~swan/courses/53030/notes/gsd.pdf. Assessed on January, 2020.

Joel M & Mbapuun ID 2016. Comparative analysis of the properties of concrete produced with Portland Limestone Cement (Plc) Grade 32.5N and 42.5R For Use in Rigid Pavement Work. *Global J. Engr. Res.*, 15: 17 - 25.

JSCE 2007. Standard specifications for concrete structures-2007, Materials and Construction, *Japan Society of Civil Engineers*, Japan.

JCI 2008. Guidelines for Control of Cracking of Mass Concrete, *Japan Concrete Institute*, Japan.

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.

Neville AM 2011. Properties of Concrete. 5th Edition, Pearson International, London, UK.

NIS 444-1 2014. Cement – Part I: Composition and Conformity Criteria for Common Cements. *Standard Organisation of Nigeria*, Abuja Nigeria.

Oluokun FA 1991. Prediction of concrete tensile strength from its compressive strength: evaluation of existing relationship for normal weight concrete. *ACI Materials Journal,* 88(3): 302–309.

Raphael JM 1984. Tensile strength of concrete. *J. Am. Concrete Institute,* 81(2): 158 -165.

Ros S & Shima H 2013. Relationship between splitting tensile strength and compressive strength of concrete at early age with different types of cements and curing temperature histories. *Concrete Institute Proceedings,* 35: 427 – 432

Selim P 2008. Experimental investigation of tensile behavior of high strength concrete. *Indian J. Engr. and Mat. Sci.*, 15(6): 467 - 472.

Shetty MS 2009. Concrete Technology. Multi-color Edition, S. Chand and Company Ltd, New Delhi.