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Tensile/Compressive/Flexural Strength Relationships for Concrete using Kgale Aggregates with Botchem as Binder

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Abstract— The present investigation is concerned with the development of empirical relationships between the split tensile and compressive strengths as well as the flexural tensile and compressive strengths of concrete manufactured using BOTCHEM cement as a binder. In these regards, a total of thirty six 100 mm cubes, twenty four 150 mm x 300 mm cylinders and twenty four 100 mm x 100 mm x 400 mm beams were cast and tested for the determination of the compressive, split tensile and flexural tensile strengths of concrete in that order. Four different characteristic strengths of concrete ranging from 20 to 50 MPa were chosen for the current study, and the aforementioned mechanical properties were assessed at 7, 14 and 28 days after casting. Using regression analysis, a power series equation $f_r = 0.234(f_c')^{2/3}$ is proposed to express the relationship between the flexural tensile and compressive strengths. The connection between the split tensile and compressive strengths for the specimens tested is best represented by the formula $f_t = 0.533(f_c')^{0.5}$. However, while these relationships are deemed accurate for the range of characteristic strengths employed in the present study, they may be unsatistactory for the overall range of concrete strengths used in engineering practice. Furthermore there is some disparity between the current test results and the relationships proposed in the literature; the inconsistency is more prominent in the case of the flexural tensile strength. It is suggested that additional studies are required on BOTCHEM concrete in order to account for other parameters not included in the present study, such as the effect of aggregate sizes and curing methods, amongst others.

Index Terms— Compressive, flexural tensile, split tensile, strength, relationship, concrete..

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1 INTRODUCTION

THE relationship between the tensile, compressive and flexural tensile strengths have always been of great interest in concrete technology practice, since they are important for the analysis, design and construction of structures. The compressive strength of the concrete is the mechanical property of most concern in the design of structures, but in some instances, the tensile strength is of interest, as it is this characteristic that primarily enables the concreteto resist bending, or forms the basis of its flexural strength [1]. With appropriate water-cement ratios and carefully controlled time and quality of curing, compressive strengths of up to about 100 MPa can be achieved. However commercially, strengths in the range 20 to 80 MPa are quite feasible, although for the greater majority of cast-in-place buildings, 20 to 45 MPa range is considered quite normal. For precast and prestressed concrete applications, the corresponding range is 35 to 65 MPa.

Although concrete is very rarely subject to direct tension, notwithstanding, an understanding of its tensile behaviour or characteristic is often utilized to estimate the loading at which cracking commences. This is on account of its influence on the initiation and development of cracks on the tension face of reinforced concrete flexural members [2]. Also in punching shear situations, it is generally accepted that the tensile strength influences the behaviour of the structure in several ways including the strength in diagonal tension, resistance to shear, the cracking levels and crack patterns, the effective stiffness of the structure and the degree of non-linearity in response to load [3]. Hence not surprisingly, the tensile strength of concrete is likewise considered in the design of a concrete member. This strength is of importance in the design of highway and runway slabs since shear strengths and resistance to cracking are critical in the sustainance of the design loadings [4].

The flexural tensile strength or the transverse rupture strength test is frequently carried out using a three point flexural test technique on a specimen of rectangular cross-section. For a homogeneous material the flexural strength should have the same value as the direct tensile strength. However since concrete is not homogeneous, it is quite obvious that the flexural tensile strength can be higher than the strength of concrete in direct tension. In civil engineering construction technology, the accurate assessment of flexural strength is important because it provides a means of judging the quality of the concrete being utilized as well as a basis to predict both the resistance and durability of the material. More importantly, the flexural strength aids in designing structural elements such as beams and cantilevers amongst others. It further provides a useful tool for the development of stronger and higher performance concrete. Indeed the cracking and deflection behaviour of concrete structures under flexure and the minimum flexural reinforcement of concrete members depend on the flexural tensile strength to some degree.

In general the relationship between the mechanical properties of concrete is well documented and is described in detail in several design standards and codes. The tensile strength of concrete is moderately low, approximately 10 % to 15 % of the compressive strength, and very rarely up to 20 % [5]. It has been stated however that there is no direct proportionality between the two properties, but generally when the compressive strength increases, the tensile strength also increases, but in a reducing manner [1]. Similarly it has been asserted that the flexural strength is generally about 10 % of the compressive strength [6] although the relationship is not a linear one. The ratio may rise to about 30 % for concretes with lower compressive strength [4]. However it is important to note that the ratio is greatly influenced by the composition of the concrete, aggregate type, and the curing and testing conditions [7]. The empirical relationships between the mechanical properties of concrete for various design standards and codes are summarized in Table 1. Here f_t, f_r, f_c and f_c' represent the tensile or split tensile, flexural tensile, cube compressive and cylinder compressive strengths respectively of concrete at 28 days, in MPa.

TABLE 1
RECOMMENDED TENSILE-COMPRESSIVE AND FLEXURAL-COMPRESSIVE EMPIRICAL RELATIONSHIPS

Design standards or codes	Relationship
BS 8007 [8]	$f_t = 0.12(f_c)^{0.7}$
ACI 318-99 [9]	$f_t = 0.56(f_c')^{0.5}$
CEB-FIP Model Code (1990) [10]	$f_{tk} = 1.40(f_{ck}/f_{cko})^{2/3}$
IS 456-2000 [11]	$f_r = 0.626(f_c')^{0.5}$
ACI 318 (2002) [12]	$f_r = 0.62(f_c')^{0.5}$
NZS-3101 [13]	$f_r = 0.60(f_c')^{0.5}$
CAN/CSA A23.3-04 (2007) [14]	$f_r = 0.60\lambda(f_c')^{0.5}$ where $\lambda = 1.0$ for normal weight concrete

With reference to the relationship between the tensile and compressive strength of concrete, it is commonly accepted that this should be of the form 1 where k_1 and n_1 are coefficients. Mindess et al. [2] based on statistical analysis of available data proposed the expression$f_t = 0.3(f_c)^{2/3}$. They however observed that this relationship had a higher degree of variability of up to$\pm 30\ \%$. Raphael [15] based on an examination of numerous individual test resultssuggested the relationship $f_t = 0.313(f_c)^{2/3}$. Gardener [16] studied the effects of temperature on the early age properties of various types of cements and proposed the relationship $f_t = 0.33(f_c')^{2/3}$ for Types I and III cements and fly ash concrete. Oluokun [17] opined that the then existing ACI 318 building code requirements for structural concrete did not adequately predict the tensile strength of concrete at early ages, and subsequently, he proposed the relationship $f_t = 0.294(f_c')^{0.69}$ for normal weight concretes based on an examination of over 500 test data [18]. Freyne et al. [19] in their comparative study on different cements in high performance concrete stated that the cement type influences the tensile strength characteristics to a greater degree than the compressive strength, and consequently, the applicability of the existing empirical relationships should be confirmed for different cement types. They also concluded that the ACI 363R–1992 [20] equation appears to overestimate the tensile strength. Selim [21] conducted an experimental investigation on high strength concrete and proposed the relationship $f_t = 0.106(f_c)^{0.948}$. Chhorn et al. [22] in their study on roller-compacted concrete concluded that age was not a significant factor in predicting the tensile strength; for their limited test results they suggested the equation $f_t = 0.47(f_c')^{0.511}$. It should be borne in mind at this stage that in most of the aforementioned investigations, the tensile strength of concrete has been based on measurement of the splitting tensile strength.

Regarding the relationship between the flexural tensile strength or modulus of rupture and the compressive strength of concrete, it is also commonly agreed just as for the case of the tensile strength that the relationship should be of the form $f_r = k_2(f_c)^{n_2}$ where k_2 and n_2 are coefficients. Ahmed et al. [23] in their study on lateral response of RCC buildings stated that values of modulus of rupture reported by various researchers were in the range $0.33(f_c')^{0.5}$ to$1.0(f_c')^{0.5}$. This suggests a wide variability in the f_r values. Ahmed et al. [6] proposed three equations$f_r = 1.055(f_c)^{0.5}$, $f_r = 0.45(f_c)^{2/3}$ and$f_r = 0.827(h)^{-0.1}(f_c)^{2/3}$, where h is the depth of the beam. They concluded that previous empirical relationships in the literature clearly overestimate the flexural tensile strength and have low validity range of compressive strength; furthermore no account had been taken of the depth of the concrete member. Additionally they pointed out that the two-third power model was more accurate than the square root model and more applicable to the wider range of concrete compressive strengths existing in practice. In a further study, Ahmed et al. [7] proposed the relationship $f_r = \lambda_1 \lambda_2 0.45(f_c)^{2/3}$ where λ_1 and λ_2 are factors to account for the age and confinement conditions of the concrete. They also suggested that further work was required to realistically account for larger member sizes.

The influence of aggregate characteristics on the flexural strength of high strength mortar has been investigated by Knab et al. [24] who found that the aggregate shape and roughness appeared to affect the flexural strength. Beushausen and Dittmer [25] undertook a study of two common South African aggregate types, namely andesite and granite on the compressive, split tensile and flexural tensile strengths as well as the elastic modulus. Concrete strengths ranged from 30 MPa to 120 MPa. The granite concrete was found to have a higher compressive strength, while the stiffer andesite aggregate produced concrete with significantly higher elastic modulus. However there was no discernible trend observed for the influence of aggregate type on the split tensile and flexural tensile strengths.

From a review of the work of all the investigators cited above, it is evident that most of the flexural/compressive strength relationships proposed are generally applicable to narrow ranges of concrete strengths and specimen sizes.In addition it would appear that the the work of Beushausen and Dittmer [25] notwithstanding, there may be the need to assess more closely the influence if any of aggregate type on the flexural/compressive strength relationship. It is evident that there is no clear consensus on the estimation of the value of this relationship. Consequently there is a need for a deliberate investigation of the tensile and flexural strengths over a wide range of concrete compressive strengths and utilizing statistical procedures to survey or inquire into the reliabilityof the anticipated values.

In the Republic of Botswana a few studies have been carried out in which the popular BOTCHEM cement and Kgale quarry aggregates were used. Tshwenyego and Poulin [26] conducted an investigation into mineral aggregate production in Botswana and identified the source rock of aggregates around the greater Gaborone area as granite. Abadjeva and Sephiri [27] in their studies on performance of concrete mixes made with no-fines aggregate from Kgale quarries characterized the aggregates as having water absorbtion of 0.58 %. Ngwenya and Franklin [28] citing the Pretoria Portland Cement Company Limited or PPC, stated that BOTCHEM cement was a Type II cement containing between 21% – 35% of fly ash with a rate of hydration slower than average. Unfortunately there are no studies reported in the literature whose objectives were primarily to investigate the properties of concrete mixes made from both BOTCHEM and Kgale aggregates with respect to evaluating the tensile/compressive and the flexural/compressive strength relationships. Consequently the present study is devoted to investigating the compressive, tensile and flexural strength relations of concrete made with these local materials, and perhaps establish appropriate values and range of applicability relevant to Botswana, bearing in mind that there are several countries with existing national codes having their own derived ratios for the afore-mentioned relationships. For the current purpose, four different concrete mixes having 28-day ccompressive strengths ranging from 20 MPa to 60 MPa will be employed.

2 EXPERIMENTAL PROCEDURE

2.1 Materials, Mix Design, Casting and Test Methods

BOTCHEM Portland cement CEM II/B-W 32.5R containing a controlled amount of fly ash and possessing a 28-day compressive strength of 32.5 MPa was utilized for the present study. Crushed fine aggregates from Kgale quarries passing a 4.75 mm sieve and possessing a fineness modulus of 3.12 was employed. Crushed coarse aggregates passing through 13.2 mm sieve size but practically 100 % retained on a 6.7 mm sieve size were also utilized. The grading curves for both types of aggregates are shown in Fig. 1. Not unexpectedly, the fine aggregates were found to be well graded with well spread out percentage of mass retained. The coarse aggregate by comparison was found to be poorly graded with the major proportion lying between 13.2 mm and 9.5 mm sieve sizes.

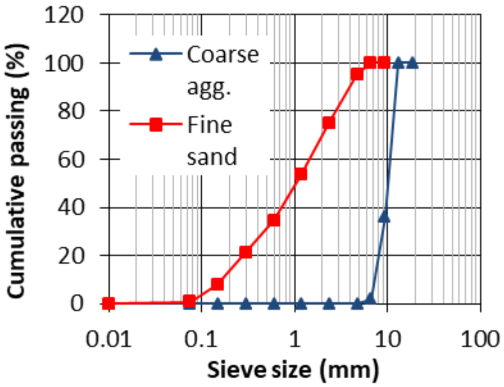

Fig. 1. Particle size distribution for coarse aggregate and fine sand

The Structures Laboratory of the Department of Civil Engineering at the University of Botswana was used for the preparation and the curing of all mixes. Mix design and proportions were in accordance with the Portland Cement Institute (PCI) method of concrete mix design derived primarily from ACI 211.1-89, as described by Addis and Goodman [29]. All mixing was carried out under laboratory conditions. The cement, fine and coarse aggregates were mixed together for two minutes prior to water being added and further mixing. Slump testing was done for each mix to determine the workability and consistency, and the results recorded. Details of the control mix proportions for a cubic metre of fresh concrete are shown in Table 2. It is ibvious that the water-cement ratio varies for each mix design.

TABLE 2
CONTROL MIX PROPORTIONS FOR 1M^3 OF FRESH CONCRETE

Designated strength (MPa)	Botchem cement (kg)	Coarse aggregate (kg)	Fine sand (kg)	Potable water (kg)
20	357	857	870	225
30	450	857	785	225
40	549	857	694	225
50	608	857	641	225

For each mix proportion, nine 100 mm cubes, six 150 mm by 300 mm cylinders, and six 100 mm x 100 mm x 400 mm beams were cast. Vibration was accomplished in a number of layers using steel or plastic moulds in conjunction with a vibrating table. Subsequently the cast specimens were covered in polythene sheets or hessian at ambient temperature for 24 hours. Afterwards the moulds were removed and the concrete specimens were cured in a regulated water bath until the time for testing.

All testing of hardened concrete specimens were carried out at 7, 14 and 28 days for each characteristic strength class, namely 20 MPa, 30 MPa, 40 Mpa and 50 MPa. For the compressive strength tests, three 100 mm cubes were crushed at any given time using an Amsler test machine. Loading was applied at a constant rate until specimen failure. The procedures were done in accordance with the South African standard SANS 5863: 2006 [30]. For the tensile strength tests, two 150 mm by 300 mm cylinders were used in conjunction with plywood packing strips and again the Amsler test machine was employed, the loading being applied at a constant rate until failure. With the flexural tensile strength or modulus of rupture tests, two 100 mm x 100 mm x 400 mm beams were each tested at any given time using a Dennison testing machine which applied a three-point load at a constant rate until failure occurred. In all the afore-mentioned cases, the failure load was taken as the average values of the loads recorded, whether of cubes, cylinders or beams.

3 RESULTS AND DISCUSSION

3.1 Slump Test Results

The slump test is used as a means of assessing the consistency of the fresh concrete, and essentially ascertains that the correct proportions of water have been added to the mix. It is much favoured in comparison to the Vebe test due to the simplicity of the apparatus and the procedure. For each mix, three slump tests were performed and the average slump was calculated. The results are presented in Fig. 2, and demonstrate that there is a gradual decrease in slump by approximately 20 mm, as the water-cement ratio is reduced. This trend is explained by the fact that the water-cement ratio directly affects the workability of the concrete mix.

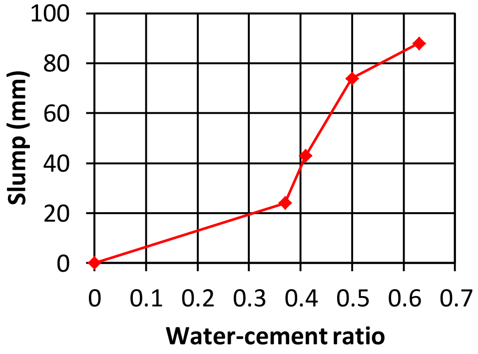

Fig. 2. Variation of slump with water-cement ratio

3.2 Compressive Strength Results

The compressive strength tests were conducted on cubes in accordance with SANS 5863: 2006 [30] at 7, 14 and 28 days respectively. The cube compressive strengths of concrete in the present study are relatively higher than the characteristic 28-day target strength, the disparity being as high as 20% in some cases. This can be attributed to the properties of BOTCHEM 32.5 R; this cement is Type II cement that gains strength rapidly, and according to Neville [1] rapid hardening Portland cement (RHPC) has a higher fineness than ordinary Portland cement (OPC). RHPC generally has a specific surface area of 450–600 m²/kg compared to 300–400 m²/kg for OPC. There is a significant increase in strength at 10–20 hours persisting up to 28 days, due to the higher fineness. The strength then equalizes after 2 to 3 months. In the present study, the mean concrete cube strengths have been converted to cylinder equivalents for comparison with the results of previous investigators by multiplying the cube strengths by a factor 0.83 as suggested by Mindess and Young [2]. The variation of the cylinder compressive strength with the characteristic 28-day target strength is shown in Fig. 3. Not surprisingly, there appears to be almost a linear trend, regardless of the age of testing.

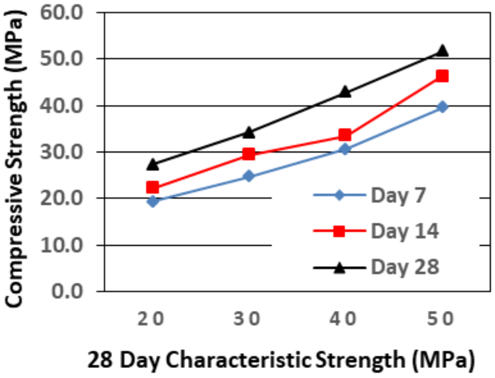

Fig. 3. Variation of compressive strength (cylinder equivalent) with characteristic strength

3.3 Tensile Strength Results

The tensile strengths were determined from split-cylinder tests conducted on concrete specimens in accordance with SANS 6253: 2006 [31] for 7, 14 and 28 days in that order. The variation of the split-cylinder strength and the 28-day characteristic strength is shown in Fig. 4. As expected, regardless of the age of testing, there is a rise in the tensile strength as the strength class increases. Malarics and Muller [32] suggest that both experimental and numerical investigations on fractured cylinders reveal a complex fracture mechanismduring such splitting tension tests. They opined that the cracking and location of the crack initiation are affected by the concrete strength, specimen geometry, and test set-up. They stated that their results were in conflict with the theory of elasticity which forms the basis for the split cylinder strength formula currently in use. The present investigators noted similar observations to those of Malarics and Muller [32] when examining crack propagation in the split cylinder specimens. While the cracks on the specimens appeared similar, there was no definite pattern as to the location of crack initiation in the cylinders.

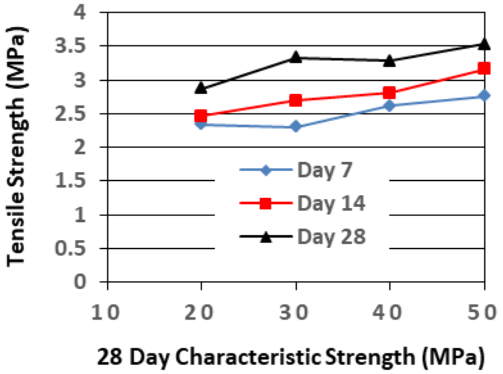

Fig. 4. Variation of tensile strength with characteristic strength

3.4 Flexural Tensile Strength Results

The flexural tensile strength or modulus of rupture was determined from prismatic beam specimen tests conducted in accordance with SANS 5864: 2006 [33]. The three-point loading flexural test results were recorded at 7, 14 and 28 days respectively. Comparisons of the flexural tensile with the 28 day characteristic strengths are shown in Fig. 5. It is apparent that the flexural tensile strength increases when the characteristic strength and age of the concrete increases.

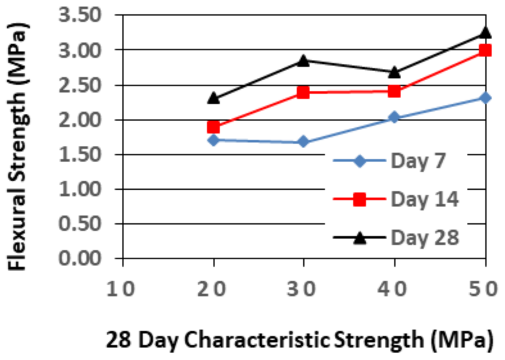

Fig. 5. Variation of flexural tensile strength with characteristic strength

3.5 Overall Summary of Strength Results

A summary of the mean values of the test results obtained together with their standard deviations reveals that the standard deviations of all the values obtained are considerably low, indicating that the data points are close to the mean of the set for all the strength categories. Hence the strengths acquired (or calculated) are generally precise; the tests were done reasonably precisely and there was very little variation between the individual tests.These observations are made largely because all the specimens of the same strength class were cast from the same batch, the concrete mix was very consistent, and all the tests were done under the same conditions. As an example for the 28 day characteristic strength of 40 MPa, the average cylinder compressive strength at 7, 14 and 28 days had standard deviations of 0.97, 0.75 and 0.90 respectively. The split cylinder tensile strength had standard deviations of 0.06, 0.10 and 0.05 at 7, 14 and 28 days respectively. The corresponding standard deviations in respect of flexural tensile strength were 0.06, 0.03 and 0.03.

3.6 Split Cylinder/Compressive Strength Relationship

In order to evaluate the ratio of the split cylinder tensile strength to the compressive strength for the present series of tests reported herein, i.e. the ratio f_t/f_c', regression analysis was carried out as illustrated in Fig. 6. The power regression of the scatter plot was found to be $f_t = 0.6936(f_c')^{0.4043}$. Using statistical procedures to assess the reliability of the proposed equation gave rise to Pearson's coefficient R =0.8602, the coefficient of determination R^2 = 0.749, and the relative error = 5.39%. Adjusting the given equation to fit the square root power series suggested by Ahmed et al. [6] resulted in the equation $f_t = 0.533(f_c')^{0.5}$.

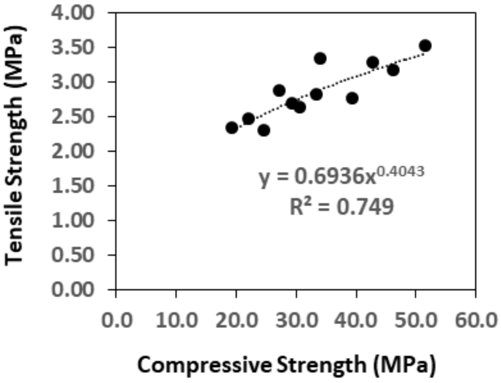

Fig. 6. Scatter graph of tensile against compressive strength, withpower regression

The power expression obtained from the current tensile testshas been compared to the predictions of tensile strengths given by a number of researchers and code provisions. These predictions are elaborated as follows; $f_t = 0.56(f_c')^{0.5}$ by ACI 318–99 [9]; $f_t = 0.321(f_c')^{0.661}$ by Arioglu et al. [34]; $f_t = 0.59(f_c')^{0.5}$ by ACI 363R–1992 [20]; $f_t = 0.294(f_c')^{0.69}$ by Oluokun [18]; $f_t = 0.313(f_c')^{2/3}$ by Raphael [15]; $f_t = 0.3016(f_c')^{2/3}$ by CEB–FIP Model Code (1990) [10]; $f_t = 0.22(f_c')^{2/3}$ by Chen and Su [35]. The comparison is shown in Fig. 7, and it is obvious that at the lower levels of compressive strengths the f_t/f_c' ratios given by several of the predictions of other researchers and standards are close to those given by the present authors' formula. However there is considerable divergence as the compressive strength increases. In fact the test results presented in the current study which mirrors the authors' formula is consistent with the observations made by Mehta and Monteiro [36] who suggest that the tensile/compressive strength relationship is not proportional, but on the contrary reduces, as the compressive strength increases.

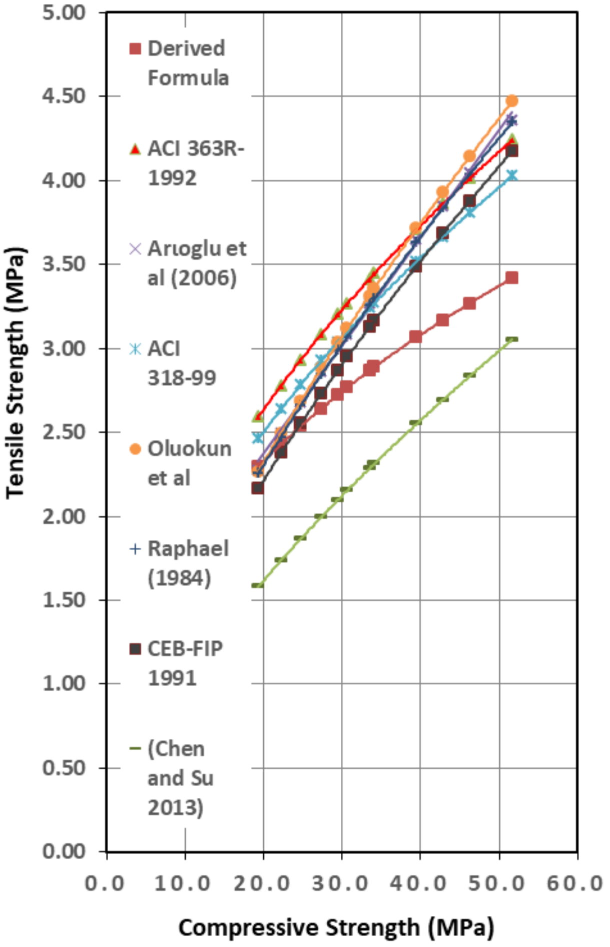

Fig. 7. Prediction of tensile strength based on formulas by various standards and investigators

3.7 FlexuralTensile/Compressive Strength Relationship

The tests carried out in the present study were analyzed using different regression formulae including linear, quadratic, cubic, power, logarithmic, exponential, etc. The details are not reported herein, however it can be stated that the different regressions have fairly similar coefficients of correlation and determination, i.e. R and R². Notwithstanding, the power series which has the second highest R value is best representative of the test results. This observation has also been made by other researchers based on empirical data reported in the literature.There are two standard forms of the power series equations that are widely accepted, namely the square-root and the two-thirds power models.For the tests of the present study, the power regression formula of the scatter plot was found to be given by $f_r = 0.2545(f_c')^{0.6371}$ as illustrated in Fig. 8. Adjusting this equation to the two-thirds format results in the formula $f_r = 0.234(f_c')^{2/3}$. From statistical procedures to assess the consistency of the proposed equation, it is found that R = 0.8965, R² = 0.8037 and the relative average error = 7.34%. The coefficient of correlation shows a very strong relationship between the two variables (i.e. 90%), while the coefficient of determination shows the good fit of the results.

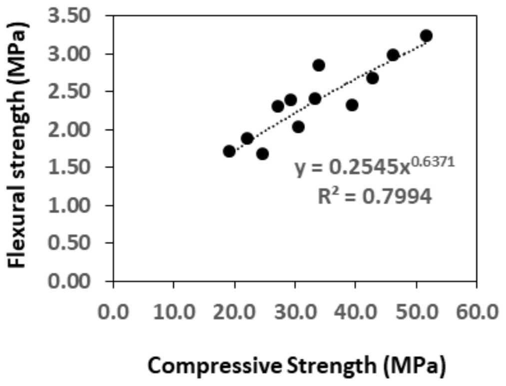

Fig. 8. Scatter graph of flexural tensile against compressive strength, with power regression

The power expression obtained from the modulus of rupture tests has been compared to the prediction of the flexural strengths by other researchers and standrds. These predictions are listed as follows: $f_r = 0.517(f_c')^{0.5}$ by ACI 318–2005 [37]; $f_r = 0.81(f_c')^{0.5}$ by CEB–FIP Model Code (1990) [10]; $f_r = 0.342(f_c')^{2/3}$ by the European Committee for Standardization, CEN (2002) [38]; $f_r = 0.626(f_c')^{0.5}$ by the Indian Standard IS 456–2000 [11].The comparisons are shown in Fig. 9. It is obvious that the power expression derived by the present authors gives a relatively lower value of flexural tensile strength compared to the predictions based on other researchers and standards. This implies that the flexural tensile strengths of concrete made from BOTCHEM and crushed rock from Kgale quarries is relatively different (and lower) than those made from the cements and crushed aggregates as used by other researchers and several national and recommended standards.

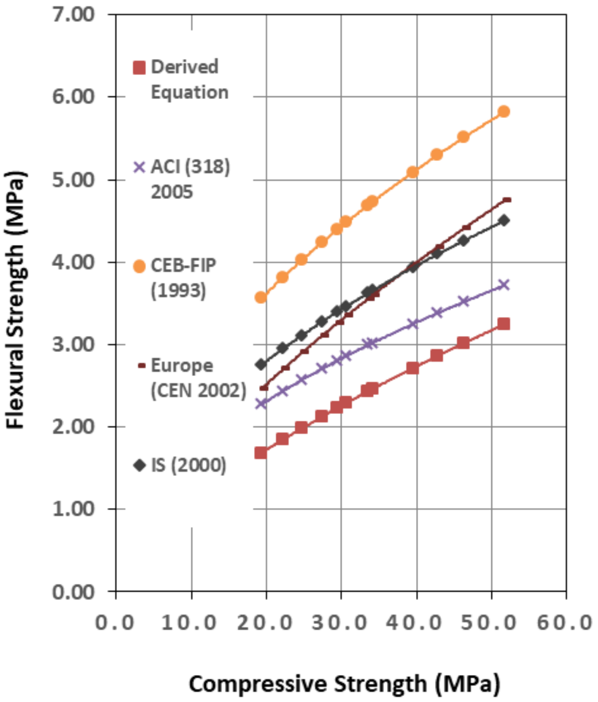

Fig. 9. Prediction of flexural tensile strength based on formulas by various standards and investigators

4 CONCLUSIONS AND RECOMMENDATIONS

The compressive, tensile and flexural strengths of concrete are important parameters for the design of structural concrete elements such as beams and slabs. The present study primarily through experimental testing utilizing local materials like BOTCHEM and crushed Kgale aggregates has sought to evaluate the relationships between these parameters.

Empirical relationships between the flexural and compressive strengths as well as between the split tensile and compressive strengths have been proposed in power series format with the aid of regression analysis. The association between the flexural tensile and compressive strengths is expressed as $f_r = 0.234(f_c')^{2/3}$, while the connection between the the split tensile and compressive strengths is best represented by $f_t = 0.533(f_c')^{0.5}$. The proposed equations are generally satisfactory for BOTCHEM and local aggregates based concrete in the range 20 MPa – 50 MPa, but might not be completely satisfactory in respect of the overall range of concrete strengths used in engineering practice.

Furthermore there are some disparities between the results obtained in the present study and those available in the literature. With reference to the flexural tensile strength, the disparity appears to be at all levels of characteristic compressive strengths covered in the current study, i.e. the range 20 MPa – 50 MPa. However in respect of the split tensile strength, the disparity is also mirrored particularly in the range 35 MPa – 50 MPa characteristic compressive strengths.

Summarizing it can be stated that the proposed equations have been derived from the limited experimental results presented in the current study. Additional tests are required for a more accurate evaluation of the relationships between the flexural tensile, split cylinder and compressive strengths. In particular, extensive studies utilizing local materials are necessary to ascertain the influence of other parameters that were practically kept constant during the present work, such as the effect of aggregate sizes and curing methods, to mention a few. These additinal studies may well lead to constants being factored into the proposed equations to account for differing compressive strengths, aggregate types and sizes, as well as methods of curing.

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