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Case study

Effect of quarry rock dust on the flexural strength of concrete

Bismark K. Meisuh*, Charles K. Kankam, Thomas K. Buabin

Civil Engineering Department, KNUST, Kumasi, Ghana

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ABSTRACT

The effect of quarry dust on the flexural strength of concrete has been experimentally studied and reported in this paper. Concrete used was prepared by replacing 25% and 100% of sand by weight with quarry dust. Also, conventional sand concrete was prepared as reference concrete for comparison. 100 mm cube and 100 × 100 × 500 mm plain beam specimens were prepared using concrete strengths ranging from 25 N/mm^2 to 47 N/mm^2 for the three replacement levels of 0%, 25% and 100% to obtain the compressive and flexural strengths respectively at 28 days. From the results, it was observed that the flexural strength of concrete with 25% and 100% quarry dust were respectively 2% and 4.3% higher compared with concrete with no quarry dust. By carrying out regression analysis, empirical formulas in the form $y = ax^b$ were obtained for concrete with quarry dust. The equations were compared with formulas proposed by ACI, BS, IS codes of practice for estimating the flexural strength using the compressive strength of concrete. It was found that incorporating quarry dust in concrete improves its flexural strength.

1. Introduction

Flexural strength of concrete also called modulus of rupture (MOR) is a measure of the tensile strength of concrete. It is an essential property in structural concrete design because it affects the flexural cracking, shear strength, deflection characteristics and brittleness ratio of concrete. Tensile strength has been conventionally defined as a function of compressive strength. The factors that affect this relationship between the two strengths include: level of strength of concrete, method of testing of concrete in tension, the concrete's moisture content, texture and shape of coarse aggregate and size of specimen [1]. A number of empirical equations have been posited to relate compressive (f_c) and tensile (f_t) strengths. The formulae are of the form $f_t = kf_C^n$ where n and k are constants. For flexural tensile strength the k varies from 0.33 to 0.94 and n from 0.5 to 0.67 [2]. Although, most codes of practice recommend a square root function (n = ½) to relate flexural strength with compressive strength, it has been reported that for a wide range of concrete strengths and for high performance concrete, the power function (n = ⅔) results in a more accurate prediction of the flexural strength of concrete [3,4]. Generally, the flexural strength is approximately taken as 10–15% of the compressive strength for medium strength concrete [5].

Some of the factors influencing the variability of flexural strength of concrete have been investigated and reported by a number of authors. Amudhavalli [6] and Mathew and Siddique [7] studied the effect of admixtures on the flexural strength of concrete. From their results, they observed that the flexural strength was improved at an optimum silica fume and fly ash content of 10–15% and about 15% respectively. Köksal et al. [8] reported greater flexural strength of concrete containing 1% of steel fibre compared with concrete with 0.5% steel fibre for various silica fume contents. Ahmed et al. [3] showed from an experimental study that the size of a concrete member has significant effect on the flexural strength and consequently proposed an equation incorporating the size effect, $f_t = \frac{0.827}{h^{0.1}} f_C^{2/3}$ (where fc is compressive strength in N/mm^2 and h depth of beam in mm), to predict the flexural strength of concrete.

* Corresponding author.
E-mail address: bisuh2004@yahoo.com (B.K. Meisuh).

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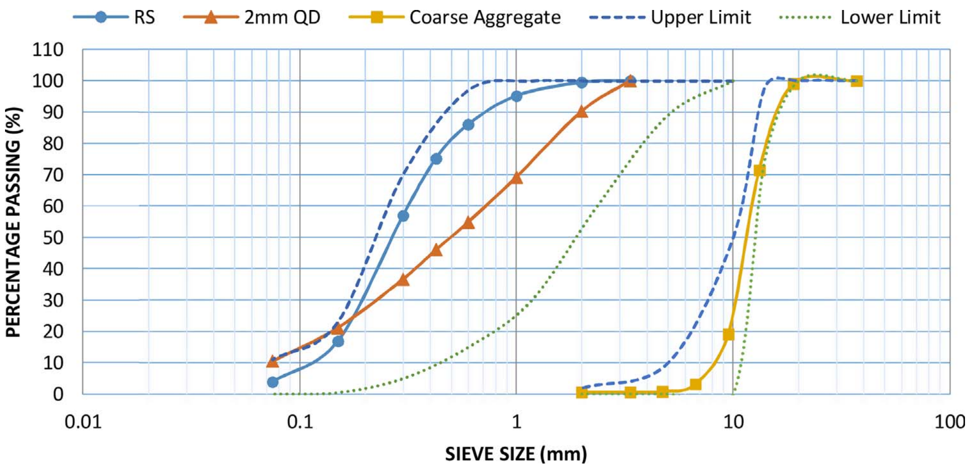

Fig. 1. Grading curves for fine and coarse aggregates.

Previous studies have shown that replacing sand with quarry rock dust produces concrete with about 8–20% increases in strength.

The use of quarry dust as replacement for sand in concrete has been extensively researched in recent years. This stems from the fact that there is growing concern in most parts of the world about the depletion of sand deposits, environmental and socio-economic threats associated with extraction of sand from river banks, coastal areas and farm lands. Quarry rock dust has been found to produce concrete with improved strength, mechanical and durability properties when used as fine aggregate [9–16]. Although quarry dust concrete is reported to have higher flexural strength compared with sand concrete, no studies have been carried out to investigate the correlation between the flexural strength and the compressive strength of concrete containing quarry dust. This paper is, therefore aimed at establishing an appropriate relationship between flexural strength and compressive strength for concrete containing quarry rock dust as fine aggregate.

2. Experimental program

2.1. Materials

Portland limestone cement, river sand and quarry rock dust both of 2 mm maximum size as fine aggregate, and 14 mm crushed rock coarse aggregate were used for the concrete The particle size distribution and the physical properties of the fine and coarse aggregates are shown in Fig. 1 and Table 1 respectively. The fine and coarse aggregates satisfied the BS EN 12620:2002 + A1:2008 [17] specifications.

2.2. Mix proportions and preparation of specimens

Three replacement levels of 0%, 25% and 100% quarry dust were used in the concrete mixes. The 25% is the optimum replacement percentage achieved by carrying out strength studies for 0%, 25%, 50%, 75% and 100% sand replacement levels. The respective 28-day compressive strengths were 24.49, 27.91, 24.64, 21.33 and 19.40 N/mm^2 [18]. The mixes were designed to achieve five different target strengths. The concrete mixes were designed to have a near constant slump in the range of 60–180 mm; and as such, the water-cement ratio varied. The procedure used for the mix design was in accordance with that outlined in "Design of Normal Concrete Mixes" [19]. Table 2 shows the detailed mix proportions.

The cement and aggregates were first mixed together in a concrete mixer. Two-thirds of the required water was first added to the cement-sand-coarse aggregate mixture and mixed thoroughly. The remaining water was added with further mixing to obtain a uniform and homogeneous mix. The mix for each sand replacement level of particular concrete grade was cast in 100 × 100 × 100 mm and 100 × 100 × 500 mm steel moulds and compacted with a tamping rod in three layers. The specimens were de-molded after 24 h and cured by immersion in water for 28 days at a room temperature of 27 °C. The plain beam specimens

Table 1
Physical Properties of Aggregates.

Aggregate	Bulk Density (kg/m^3)	Fines Content (%)	Fineness Modulus	Water Absorption (%)	Moisture Content (%)	Specific Gravity	Crushing Value
River sand	1600	3.89	2.66	6.8	3.56	2.66	–
Quarry dust	1650	10.45	3.54	10.6	0.54	2.64	–
Coarse Agg.	1625	–	–	0.54	0.09	2.71	18.3

Table 2
Mix Proportions of Concrete Mixes.

Mix notation	TCS (N/mm^2)	SRL (%)	w/c ratio	Free water (kg/m^3)	Cement(kg/m^3)	River sand (kg/m^3)	Quarry dust (kg/m^3)	Coarse aggregate (kg/m^3)
RSC25	25	0	0.60	222	370	583	–	1210
RSC30	30	0	0.56	222	397	557	–	1210
RSC35	35	0	0.52	222	427	530	–	1210
RSC40	40	0	0.48	222	463	502	–	1200
RSC45	45	0	0.44	222	505	473	–	1185
SQC25	25	25*	0.60	233	388	517	173	1034
SQC30	30	25*	0.56	233	416	496	166	1035
SQC35	35	25*	0.52	233	448	474	158	1032
SQC40	40	25*	0.48	233	485	451	151	1025
SQC45	45	25*	0.44	233	530	427	143	1012
QDC25	25	100	0.60	240	400	–	789	926
QDC30	30	100	0.56	240	429	–	759	927
QDC35	35	100	0.52	240	462	–	727	926
QDC40	40	100	0.48	240	500	–	695	921
QDC45	45	100	0.44	240	546	–	659	910

TCS is Target characteristic strength; SRL is Sand replacement level; 25* is Optimum percentage level [18].

were used to obtain the flexural strength, and the cubes were used to obtain the compressive strength of the concrete.

2.3. Test setup and method

2.3.1. Compressive strength test

The compressive strength was determined by crushing 100 mm size cubes using a 1000 kn maximum capacity Universal Testing Machine. The rate of loading the specimens was maintained at 2 kn/s for the tests until failure. On each day of testing, the cube specimens were removed from the curing tanks and then left in the open air for about 2 h before crushing. The compressive strengths of the concrete were determined at age 28 days.

2.3.2. Flexural strength test

The plain beam specimens were tested under third-point loading. The flexural strength testing apparatus consisted of a loading frame fitted with a manually operated hydraulic actuator. The hydraulic actuator used for the loading had a load capacity of 230 kn. An average loading rate of 1 kn/s was maintained throughout the testing procedure. The loads were positioned within the middle third 150 mm of the specimen, thus maintaining a loading span of 450 mm during the test. The modulus of rupture of the beams was determined at age 28 days after the test depending on the place of occurrence of the failure fracture.

Under third-point loading, two scenarios are possible;

a For fracture occurring within the middle third, the MOR is calculated as;

$$f_r = \frac{Pl}{bd^2} \tag{1}$$

where f_r is maximum tensile strength; P is maximum load; l is span of beam; b is width of beam; d is depth of beam.

- For fracture outside the middle third, BS EN 12390-5 [20] suggests discarding of such results while ASTM C78 [21] allows the use of Eq. (2)

$$f_r = \frac{3Pa}{bd^2} \tag{2}$$

where a is average distance from the nearest support to the failure crack.

3. Results and discussion

3.1. Flexural and compressive strength test results

Table 3 presents the results of the experimental study of the compressive and flexural strength of concrete for concrete with 0%, 25% and 100% sand replacement levels at 28 days. The flexural strength of the concrete beams was calculated using Eq. (1) because the beam specimens were found to fracture within the middle third as per the third-point loading. It is observed from the test results that the flexural strength increases with increasing compressive strength of the concrete. Additionally, the increase in the flexural strength is observed to be lower than the corresponding increase in the compressive strength for each percentage sand replacement category as indicated by the values of f_t/f_{cu} ratio. It is also observed from the results that 100% SRL has, on the average, the highest

Table 3
Compressive Strength and Flexural Strength Test Results (N/mm^2).

Concrete Grade.	0% SRL			25% SRL			100% SRL		
	FTS, f_t	CS, f_{cu}	$\frac{f_t}{f_{cu}}$	FTS, ft	CS, f_{cu}	$\frac{f_t}{f_{cu}}$	FTS, f_t	CS, f_{cu}	$\frac{f_t}{f_{cu}}$
C25	3.53	26.70	0.13	3.65	26.10	0.14	3.84	26.90	0.14
C30	3.82	30.50	0.12	3.80	31.20	0.12	3.84	30.17	0.13
C35	4.56	36.17	0.12	4.68	38.00	0.12	4.14	35.53	0.12
C40	4.12	38.70	0.11	4.24	42.40	0.10	4.73	40.03	0.12
C45	4.57	44.43	0.10	4.98	46.40	0.11	4.93	47.27	0.10

SRL is sand replacement levels; FTS is flexural strength; CS is compressive strength.

flexural strength values (4.3% higher than 0% SRL) followed by 25% SRL while 0% SRL shows the least values. This is graphically represented in Fig. 2.

The texture and shape of aggregate are reported to affect the flexural strength of concrete. Neville and Brooks [1] noted that the influence of aggregate shape is more apparent in modulus of rupture test than uniaxial compression or split cylindrical tensile tests. They attributed this behaviour to the presence of a stress gradient which delays the process of cracking leading to ultimate failure. Rough textured and angular shaped crushed particles produce concrete with greater flexural strength compared with rounded natural gravel by improving the physical and chemical bond between the cement paste and aggregate [1,5]. This may be the reason why at 100% SRL, the flexural strengths recorded were comparatively higher. Generally, quarry rock dust at optimum sand replacements is reported to cause increase in the strength properties of concrete [9–16,22–24]. However, the authors observed lower strength at 100% sand replacement. Bakri et al. [22], Bhikshma et al.[23], and Rao et al. [24] on the other hand reported increase in the flexural and compressive strengths of concrete with quarry rock dust as sand replacement and explained that the increase in strength could have been due to the inherent strength of aggregate particles and strong cement paste-fine aggregate interface bond. An increase of about 5.4% in flexural strength at 100% sand replacement with quarry rock dust was recorded by Bakri et al. [22].

Table 3 also shows the ratio of the flexural strength to the compressive strength (f_t/f_{cu}) for all five (5) grades of concrete used in the study. It is observed that the ratio f_t/f_{cu} decreases with increase in the strength of concrete. The largest f_t/f_{cu} ratio obtained is 14% and the smallest 10%. The range of the f_t/f_{cu} ratio estimated from the test results is consistent with the fact that the flexural strength of concrete is generally taken to be 10–15% of the compressive strength. The results show that the 10–15% rule of thumb could apply to the estimation of flexural strength from the compressive strength of quarry rock dust-sand concrete.

Table 4 shows the statistical comparison of flexural strength test results. Five statistical parameters were used to assess the reliability of experimental data and derived relationships. The parameters are the mean, standard deviation (SD), coefficient of variation (COV), standard error of estimate (SE), regression coefficient (R^2). From Table 4 it is seen that the results for 100% SRL shows very good correlation and has lower standard error of estimate.

The results of a *t*-test carried out to ascertain the statistical significance of variation in the observed flexural strength values when quarry rock dust was used in place of sand are presented in Table 5. From the table, given that t stat $<$ t critical two-tail, it can be concluded that the difference in the average or mean flexural strength values of the 100% or 25% SRLs and the 0% SRL values is not considered statistically significant.

3.2. Relationship between flexural strength and compressive strength

The results of the experimental study were also analyzed by using power regression analysis to derive empirical equations (Fig. 3)

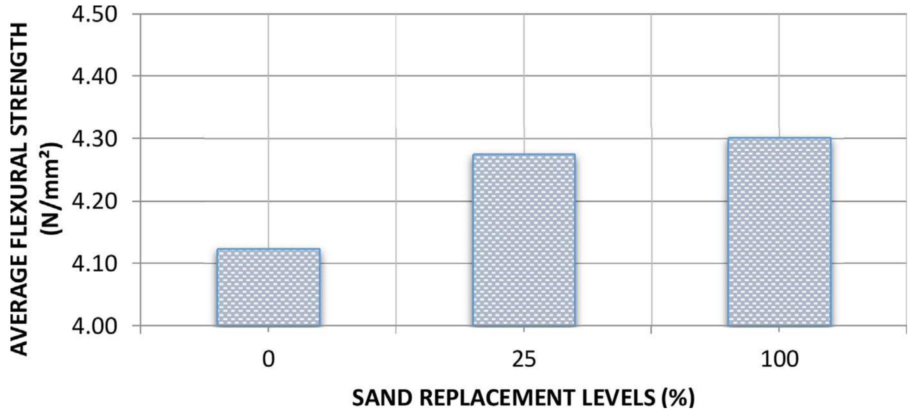

Fig. 2. Variation of flexural strength at 28-days with sand replacement levels.

Table 4
Statistical comparison of flexural strength test results.

SRL (%)	R^2	Mean	SD	COV	SE
0	0.794	4.12	0.46	0.11	0.26
25	0.791	4.27	0.57	0.13	0.31
100	0.920	4.30	0.51	0.12	0.16

Table 5
Statistical *t*-test results of experimental data.

	SRL (%)		
	100	25	0
Mean	4.30	4.27	4.12
Variance	0.220825714	0.273942857	0.178757143
Observations	15	15	15
Pooled Variance	0.199791429	0.22635	
Hypothesized Mean Difference	0	0	
df	28	28	
t Stat	1.07833791	0.863438961	
P(T < = t) one-tail	0.145042742	0.197616165	
t Critical one-tail	1.701130934	1.701130934	
P(T < = t) two-tail	0.290085484	0.39523233	
t Critical two-tail	2.048407142	2.048407142	

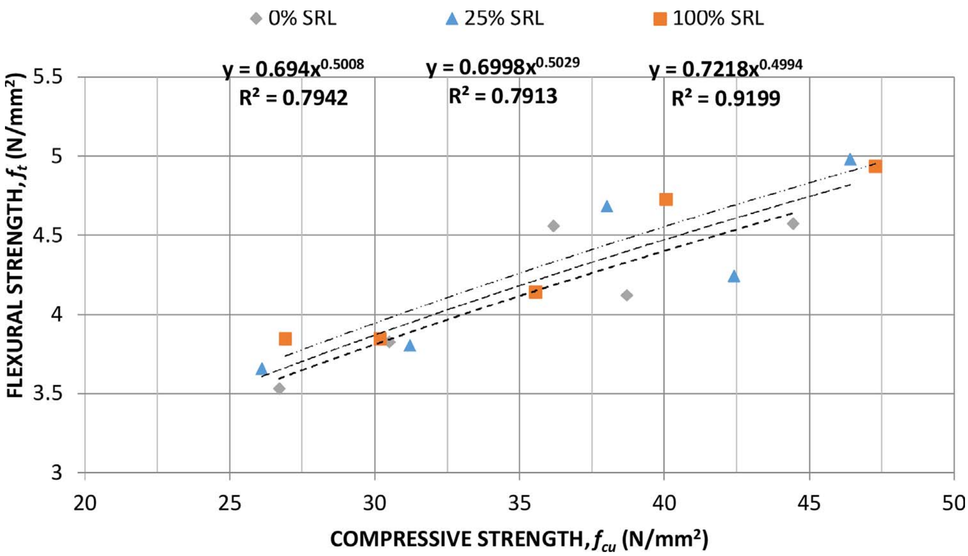

Fig. 3. Variation of Compressive strength with flexural strength.

to relate concrete flexural strength (f_t) to compressive strength (f_{cu}) in the standard form:

$$f_t = n_1(f_{cu})^{n_2} \tag{3}$$

where n_1 and n_2 are coefficients of the equation.

The empirical equations derived relating the flexural strength (f_t) to compressive strength (f_{cu}) for concrete with 0%, 25% and 100% sand replacement tested at 28 days are presented as Eqs. (4), (5) and (6) respectively, together with the regression coefficient, R^2.

$$f_t = 0.69(f_{cu})^{0.5} \quad R^2 = 0.794 \tag{4}$$

$$f_t = 0.70(f_{cu})^{0.5} \quad R^2 = 0.791 \tag{5}$$

$$f_t = 0.72(f_{cu})^{0.5} \quad R^2 = 0.920 \tag{6}$$

From the above relationships, it is seen that higher flexural strength is achieved for the same strength of concrete when quarry

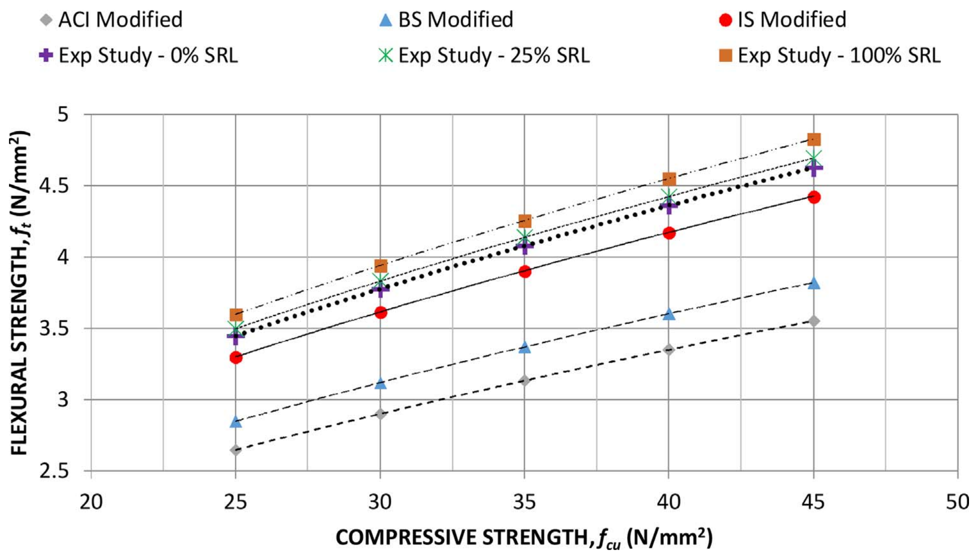

Fig. 4. Comparison of flexural strength estimation formulas.

dust is used as fine aggregate in place of natural sand. However, at 100% replacement the flexural strength is only about 4% higher than at no sand replacement. In other studies, Abdul Razak and Wong [4] observed that the power function $f_t = 0.078f_{Cu}^{1.06}$ was most suitable for determining the flexural strength of high-performance concrete with strengths over a wide range i.e. 45–110 N/mm^2. However, in this study the function of the form $f_t = kf_{Cu}^{0.5}$ was obtained for normal-weight medium strength concrete.

In Fig. 4, curves for predicting the flexural strength of concrete with 0%, 25% and 100% sand replacements are plotted. The American Concrete Institute (ACI) Code [25], British Standard (BS) [26] and Indian Standard (IS) [27] formulas proposed for estimating the flexural strength are also provided for comparison. These formulas have been modified to account for the difference between 100 mm cube compressive strength and 150 mm cube compressive strength for the IS and BS and cube compressive, and 150 mm by 300 mm cylindrical compressive strength for the ACI Code. Applying a compressive strength modification factor of 0.9 for the former and 0.72 for the latter [28], the modified formulas are given as;

$$\text{AC Imodified:}\boldsymbol{f_t} = 0.53\sqrt{\boldsymbol{f_{cu}}} \quad (7)$$

$$\text{BS modified:}\boldsymbol{f_t} = 0.57\sqrt{\boldsymbol{f_{cu}}} \quad (8)$$

$$\text{IS modified:}\boldsymbol{f_t} = 0.66\sqrt{\boldsymbol{f_{cu}}} \quad (9)$$

where f_{cu} is cube compressive strength (N/mm^2) for 100 mm concrete cube specimen.

Fig. 4 shows that the formulas proposed by the three codes of practice cannot reliably be used to estimate the flexural strength of concrete made using quarry dust as fine aggregate. It shows a comparison of the equations obtained in this study for estimating the flexural strength of concrete and those proposed by the ACI, BS and IS codes of practice. From the graphs it is observed that the IS modified values relate closely with 0% sand replacement level, though slightly lower. However, the 0% sand replacement level flexural strength values are much higher than those of the ACI and BS formulas. It is also observed that the flexural strength values for the 25% and 100% sand replacement levels are relatively higher than the flexural strengths from all three code formulas.

The experimental and predicted flexural strength obtained using Eqs. (2)–(9) are presented in Table 6. It can be observed from the average predicted/experimental flexural strength ratios in the table that for 0% sand replacement level, the ACI code and BS underestimate the flexural strength by a difference of about 24% and 18% respectively while the IS predicts values that compare closely (about 5% difference) with the flexural strength values from the experiment. For 25% sand replacement level, average differences of 25%, 19%, 6% with respect to experimental values are observed for ACI code, BS and IS respectively. Also average differences of 26%, 21%, 8% with respect to experimental values are observed for ACI code, BS and IS respectively at 100% sand replacement level. Whereas the IS appears to predict flexural strength values close to those from the experiment with the incorporation of quarry rock dust, the ACI code and BS greatly underestimate the flexural strength of concrete with quarry dust.

4. Conclusions

Based on the results obtained and the analysis presented, the following conclusions are drawn:

1. The flexural strength of concrete made with quarry dust as fine aggregate is higher (about 4.3%) than conventional river sand concrete.
2. The 10–15% rule of thumb was found to be applicable in the estimation of flexural strength of quarry-sand concrete based on its

Table 6
Comparison of Empirical Flexural Strength Estimation Formulas.

SRL (%)	Experimental Values (N/mm^2)		Predicted Flexural Strength Values (N/mm^2)							
			Derived Eq.		ACI Modified Eq.		BS Modified Eq.		IS modified Eq.	
	f_{cu}	$f_{t,exp}$	$f_{t,pre}$	$f_{t,pre}/f_{t,exp}$	$f_{t,pre}$	$f_{t,pre}/f_{t,exp}$	$f_{t,pre}$	$f_{t,pre}/f_{t,exp}$	$f_{t,pre}$	$f_{t,pre}/f_{t,exp}$
0	26.70	3.53	3.57	1.01	2.74	0.78	2.95	0.83	3.41	0.97
	30.50	3.82	3.81	1.00	2.93	0.77	3.15	0.82	3.64	0.95
	36.17	4.56	4.15	0.91	3.19	0.70	3.43	0.75	3.97	0.87
	38.70	4.12	4.29	1.04	3.30	0.80	3.55	0.86	4.11	1.00
	44.43	4.57	4.60	1.01	3.53	0.77	3.80	0.83	4.40	0.96
Avg.				**0.99**		**0.76**		**0.82**		**0.95**
25	26.10	3.65	3.58	0.98	2.71	0.74	2.91	0.80	3.37	0.92
	31.20	3.80	3.91	1.03	2.96	0.78	3.18	0.84	3.69	0.97
	38.00	4.68	4.32	0.92	3.27	0.70	3.51	0.75	4.07	0.87
	42.40	4.24	4.56	1.08	3.45	0.81	3.71	0.88	4.30	1.01
	46.40	4.98	4.77	0.96	3.61	0.72	3.88	0.78	4.50	0.90
Avg.				**0.99**		**0.75**		**0.81**		**0.94**
100	26.90	3.84	3.73	0.97	2.75	0.72	2.96	0.77	3.42	0.89
	30.17	3.84	3.95	1.03	2.91	0.76	3.13	0.82	3.63	0.94
	35.53	4.14	4.29	1.04	3.16	0.76	3.40	0.82	3.93	0.95
	40.03	4.73	4.56	0.96	3.35	0.71	3.61	0.76	4.18	0.88
	47.27	4.93	4.95	1.00	3.64	0.74	3.92	0.79	4.54	0.92
Avg.				**1.00**		**0.74**		**0.79**		**0.92**

SRL is sand replacement level; f_{cu} is cube compressive strength for 100 mm cube.

compressive strength.

3. A relationship between the flexural strength and the compressive strength in the form $f_t = 0.72(f_{cu})^{0.5}$ was derived to predict the flexural strength of medium strength concrete with quarry dust as fine aggregate at age 28 days.

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