

The Correlation of Compressive and Flexural Strengths of Concrete Affected by Cement Type and Admixture

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Riwayat Artikel

Submitted : 8/09/2025
Published : 28/01/2026

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Abstrak: The compressive strength (f_c') and flexural strength (f_s) are common specifications used for concrete structures, and correlations between them have been proposed by several researchers; however, those models show reduced accuracy due to variations in cement type and admixture use. This study analyzes how cement type (Ordinary Portland Cement, OPC, and Portland Composite Cement, PCC), age, and chemical admixtures (superplasticizer and retarder) affect compressive and flexural strength, and develops an empirical f_c' - f_s correlation. Cylinders (150×300 mm) and beams (150×150×600 mm) were tested at 7 and 28 days. Admixture presence increased compressive strength by up to 49.6% (7 days) and 48.4% (28 days), and flexural strength by up to 30.8% (7 days) and 19.6% (28 days), relative to the no-admixture reference. Combining data from all four mixture types ($n = 64$), the f_c' - f_s relationship follows a power regression $f_s = 0.3209(f_c')^{0.8207}$ with $R^2 = 0.8572$, indicating higher goodness-of-fit than the ACI 318 square-root form over the tested range. These findings suggest the proposed model can represent the f_c' - f_s correlation across cement types and admixture conditions more closely than the standard design equation, though the applicability of a single equation across the full quality range examined here (18–63 MPa) warrants further validation.

Kata kunci: Admixture, Cement type, Compressive strength, Empirical equation, Flexural strength

1. Introduction

Concrete is a material widely used in various constructions such as buildings, dams, bridges, or roads considering its ease of implementation, cost efficiency, and mechanical properties such as compressive strength (f_c') and flexural strength (f_s). According to ASTM C39, concrete cylinders measuring 150 mm in diameter and 300 mm in height are tested to determine compressive strength. Flexural strength indicates the resistance of concrete to tensile stress due to flexural loads, obtained from testing concrete beams measuring 150×150×600 mm in accordance with ASTM C78 [1], [2].

In rigid pavement construction, flexural strength is very important because it determines resistance to cracking due to traffic loads and affects flexural cracking, shear strength, and deflection characteristics [3]. However, flexural strength testing tends to be more complex and

requires larger specimens [4]. In addition, the method used in evaluating rigid pavements in the field is by taking cylinder cores, so the empirical relationship between f_c' and f_s is important for estimating flexural strength without conducting a direct flexural test, since f_s is commonly reported as roughly 10–15% of f_c' in the literature [5].

Various studies show that compressive strength and flexural strength are influenced by many factors, such as mix proportions, cement type, water-cement ratio, temperature, mix homogeneity, use of admixtures, aggregate characteristics, specimen size, and fibers [6]–[8]. The presence of fibers increased initial cracking load and flexural strength [8].

Both compressive and flexural strength also are affected significantly by environmental changes and material modifications. The effect of exposure to seawater and brackish water could increase the permeability and reduce

compressive strength almost to 29% due to microstructural degradation [9]. The conditions of marine relating to submersion and tidal fluctuation also reduced compressive strength by up to 19% due to increasing of porosity and carbonation [10]. The use of chemical admixtures and curing implementations could change microstructure properties and produced strength variations which cannot predicted by standard empirical models [11]. These references state that the compressive–flexural correlation were affected by both external factors (seawater, carbonation) and internal factors (admixtures, porosity changes).

The empirical equations correlating between f_c' and f_s have been proposed by researchers and mentioned in several standards. ACI 318:2019 recommends to use an equation of $f_s = 0.62\sqrt{f_c'}$ [12]. In other hand, Raphael and other studies suggest an exponential form with exponent $2/3$ [7], [13]– [15]. The general form $f_s = k(f_c')^n$ yields with k as coefficients from 0.34 to 0.94 and n as exponents from 0.5 to 0.67 across studies [7], [16]. The summarizes of equations from standards and prior studies are presented in Table 1.

Table 1. Formula correlation of compressive-flexural strength by references

No	Source/Standard	Empirical Equation
1	ACI 318:2019 [12]	$f_s = 0.62\sqrt{f_c'}$
2	Bhanja and Sengupta [17]	$f_s = 0.275(f_c')^{0.81}$
3	Raphael [14]	$f_s = 0.32((f_c')^{2/3})$
4	Ahmed et al. [7]	$f_s = 0.45(f_c')^{2/3}$
5	Marín-Urbe [18]	$f_s = 0.6647(f_c')^{0.4417}$
6	Amudhavalli and Mathew [19]	$f_s = 0.039(f_c')^{1.35}$

Compressive and flexural strength both increase with age until reaching a relatively stable value [20], but the rate of increase in compressive strength tends to be faster than that of flexural strength [18]. ACI 363R-10 notes that this empirical relationship should be re-examined for high-strength or chemically admixed concrete, whose cracking and post-peak strain behavior differ from normal concrete [21].

Superplasticizers (SP) and retarders are commonly used in modern concrete mixtures. Superplasticizers permit reduced water-cement ratio while maintaining workability, producing a denser particle structure and lower porosity [22]– [24]. Retarders prolong setting time and workability retention, allowing reduced water content without loss of workability. Combined SP-retarder use has been reported to extend setting time by up to 331% and increase 28-day compressive strength by up to 45 MPa [25]; PCE-based SP with retarder has been shown to increase workability by up to 72% and extend setting time by more than 100% without significant strength loss [26]. These findings indicate that chemical admixtures can

meaningfully alter the f_c' – f_s relationship, yet few studies explicitly formulate this relationship for admixture-modified concrete.

The purpose of this study is to analyze how cement type and admixtures affect compressive and flexural strength, and to develop a new empirical model describing their relationship. Tests were performed at 7 and 28 days to capture both early-age and standard-age behavior for OPC and PCC concretes. The resulting empirical model is validated across normal concrete and admixture-modified concrete to assess the extent to which chemical admixtures alter the correlation pattern, with normal concrete serving as the design-standard reference.

The empirical model developed in this study is intended as a practical basis for estimating flexural strength without direct flexural testing, contributing to structural design accuracy and to the empirical basis for the use of modern admixture technology in concrete infrastructure.

2. METHODS

2.1. Concrete composition and samples

Materials comprised cement, water, coarse and fine aggregates, and SP and retarder admixtures in manufacturer-specified proportions. Cement types were Type I OPC and PCC. Fine aggregate was natural sand; coarse aggregate was crushed stone with a maximum size of 25 mm. Aggregate physical properties (specific gravity, absorption, bulk density, gradation, moisture, and silt content) are shown in Table 2.

Table 2. Physical properties of aggregates

Testing Type	Fine Aggregate	Coarse Aggregate	ASTM Standard
Moisture Content (%)	0.63	0.89	0 – 1
Specific Gravity	2.52	2.61	2.0 – 2.9
Absorption (%)	1.83	2.15	1 – 3 %
Fineness Modulus	2.68	7.31	2.3 – 3.1
Density (kg/m ³)	1515	1649	-
Mud Content (%)	1.8	1.3	< 5
Organic Content	No. 1	-	< No. 3

In this study, four types of concrete mixtures were made based on SNI 7656:2012 method for two targets of 3.8 and 4.5 MPa of flexural strength. The composition of material with Portland Composite Cement (PCC) and Ordinary Portland Cement (OPC) is shown in Table 3.

Table 3. Composition per 1m³ of concrete

Materials	Concrete no admixture			Concrete with admixture
	PCC	OPC	OPC	OPC
	F _s 3.8	F _s 3.8	F _s 4.5	F _s 4.5
Cement (Kg)	441	441	471	471
Water (kg)	193	193	193	193
Sand (kg)	684	684	684	684
Coarse agg. (kg)	1035	1035	1035	1035
Superplasticizer (%)	-	-	-	1
Retarder (%)	-	-	-	0.3

Sample codes and quantities are shown in Table 4. A total of 64 cylinders and 64 beams were cast, evaluated at 7 and 28 days.

Table 4. Code and number of samples.

Code	f _s (MPa)	Ages of test (days)				Total
		7		28		
		Cylinder	Beam	Cylinder	Beam	
CPNA	3.8	6	6	6	6	24
CONA		6	6	6	6	24
CONA	4.5	10	10	10	10	40
COWA		10	10	10	10	40
Total		32	32	32	32	128

Note:

CPNA = Containing PCC no Admixture

CONA = Containing OPC no Admixture

COWA = Containing OPC with Admixture

2.2 Compressive and flexural test

Compressive strength was tested on 150×300 mm cylinders using a 150-ton capacity compression testing machine at a loading rate of 0.15–0.35 MPa/s per ASTM C39 [27]. Specimen ends were cleaned and checked for flatness and perpendicularity before loading. Compressive strength was computed as:

$$f_c' = P / A \quad (1)$$

where f_c' is compressive strength (MPa), P is maximum load (N), and A is the cross-sectional area (mm²).

Flexural strength was tested on 150×150×600 mm beams using third-point (two-point) loading per SNI 4431:2011 [28], with load points at L/3 from each support, applied continuously to failure. Flexural strength was computed as:

$$f_s = P \cdot L / (b \cdot d^2) \quad (2)$$

where f_s is flexural strength (MPa), P is maximum load (N), L is span length (mm), b is beam width (mm), and d is beam depth (mm)

2.3 Empirical equation

The relationship between f_c' and f_s was analyzed via power-law regression, selected for its highest coefficient of determination (R^2) and stability across the dataset [29]. Regression was performed on the pooled dataset of all 64 specimens spanning all four mixture types (CPNA, CONA at the 3.8 MPa target, CONA and COWA at the 4.5 MPa target — see Table 4), so that the resulting model reflects the combined influence of cement type, age, and admixture rather than the admixture comparison alone. The resulting model was compared against the trends of prior standards and studies listed in Table 1.

3. RESULTS AND DISCUSSION

3.1. Effects of cement type

Table 5 displays the findings of tests on the compressive and flexural strengths of concrete at 7 and 28 days using two different types of cement (PCC and OPC).

Table 5. Compressive and flexural strength due to cement types at 7 and 28 days

Code	Prop.	1	2	3	4	5	6	Average
CPNA 7D	f_c'	16.91	17.91	19.00	19.27	20.03	20.06	18.86
CPNA 7D	f_s	3.05	3.06	3.55	3.60	3.66	3.74	3.44
CPNA 28D	f_c'	22.88	24.55	25.41	27.58	27.96	30.33	26.45
CPNA 28D	f_s	4.36	4.45	4.50	4.71	4.78	5.14	4.66
CONA 7D	f_c'	29.31	30.00	30.04*	21.66*	25.26	28.64	27.49
CONA 7D	f_s	4.17	4.37	6.65*	4.66*	4.83	5.23	4.99
CONA 28D	f_c'	30.73	31.90	34.82	36.35	36.80	37.50	34.68
CONA 28D	f_s	5.18	5.60	5.68	5.84	6.46	6.73	5.92

* *Flagged values: specimen 3 (f_c' =30.04 MPa, f_s =6.65 MPa) and specimen 4 (f_c' =21.66 MPa) in the CONA-7D set deviate substantially from sibling specimens — f_s =6.65 MPa corresponds to f_s/f_c' =22%, well above the 10–15% range cited in Section I and above every other individual data point in the study. These values should be re-verified against raw laboratory records before final submission; if confirmed as measurement/transcription errors, the row averages and any regression using these points should be recomputed.*

The average 7-day compressive and flexural strength of PCC concrete were 18.86 MPa and 3.44 MPa, respectively, compared to 27.49 MPa and 4.99 MPa for OPC. At 28 days, PCC reached 26.45 MPa (a 40.2% increase over 7 days) and 4.66 MPa (35.5% increase); OPC reached 34.68 MPa (26.1% increase) and 5.92 MPa (18.6% increase). PCC therefore shows a higher relative rate of strength development between 7 and 28

days, while OPC shows higher absolute strength at both ages — consistent with PCC's progressive pozzolanic hydration versus OPC's early alite-driven strength gain. These trends are shown in Fig. 1(a)–(b), where percentage labels denote the increase relative to the 7-day (baseline) value, consistent with the calculation used in the text. Figures 1 (a) and (b) illustrated these results.

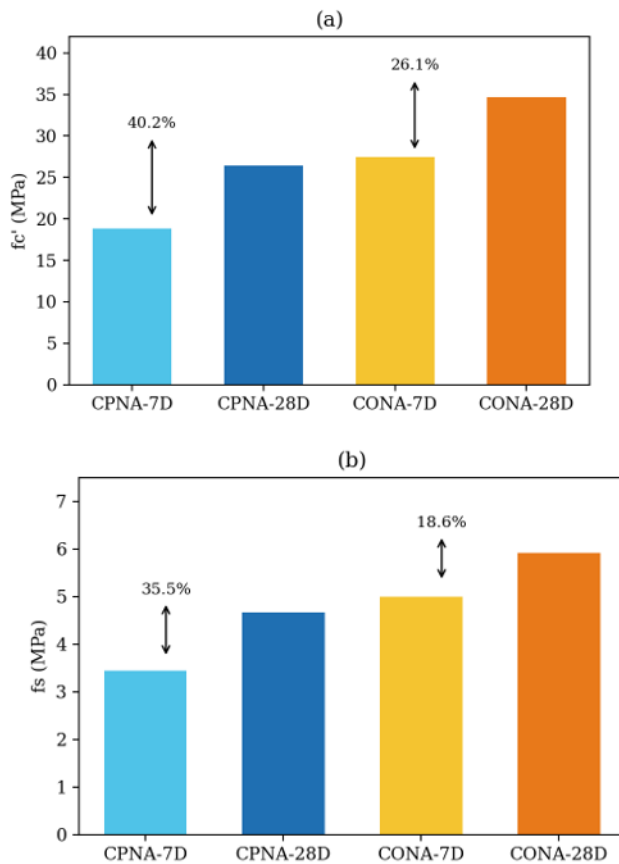


Figure 1. The compressive strength (a) and flexural strength (b) at 7 and 28 days for PCC and OPC type.

OPC demonstrated faster early-age strength development than PCC, having reached about 79% of its 28-day compressive strength and 84% of its 28-day flexural strength by day 7, compared to only about 71% and 74% respectively for PCC. This gap confirms OPC's faster early-age strength gain, which stems from its higher content of reactive clinker minerals (alite, C_3S) that drive rapid early formation of C–S–H. PCC, in contrast, develops strength more gradually through a progressive pozzolanic reaction that only proceeds once sufficient $Ca(OH)_2$ has accumulated [30]–[32]. Given this distinction, the choice between cement types should be guided by project requirements, with OPC favored when early strength is critical — as in fast-track construction — and PCC preferred when the priority is long-term durability alongside progressive strength gain.

3.2. Effects of admixture

The higher of flexural strength ($f_s = 4.5$ MPa) was used to evaluate the effect of admixtures. The results of testing for both condition is shown in **Table 6** and **Figure 2**.

Table 6. Compressive and flexural strength due to admixture (MPa)

No	CONA f_c' 7D	CONA f_s 7D	CONA f_c' 28D	CONA f_s 28D	COWA f_c' 7D	COWA f_s 7D	COWA f_c' 28D	COWA f_s 28D
1	23.08	4.35	30.34	5.71	36.29	5.28	42.07	6.01
2	23.94	4.60	30.56	5.75	40.05	5.59	47.63	6.47
3	25.47	4.67	32.02	5.84	40.49	5.65	48.76	6.60
4	26.40	5.00	33.56	5.86	40.49	5.96	49.17	7.12
5	26.83	5.04	33.67	5.88	41.11	7.36	49.67	7.80
6	27.09	5.09	35.86	6.13	41.52	7.45	53.93	7.97
7	30.29	5.10	37.21	6.25	43.51	7.68	55.83	8.24
8	32.05	5.23	37.39	6.37	44.44	8.16	57.78	8.69
9	33.62	6.77	41.11	8.21	45.93	8.34	61.91	9.36
10	34.25	7.70	45.09	9.08	49.62	8.50	62.95	9.66
Avg	28.30	5.35	35.68	6.51	42.35	7.00	52.97	7.79

Note: f_c' and f_s within each row are treated as a paired cylinder/beam specimen cast from the same batch. Both columns happen to be monotonically increasing within each group; authors should confirm in the final manuscript that this reflects true specimen pairing (e.g., sequential batch order) rather than independent sorting of each property, since the latter would inflate the apparent f_c' – f_s correlation used in Eq. (3).

At 7 days, average CONA and COWA strength were 28.30/5.35 MPa and 42.35/7.00 MPa (f_c'/f_s), a 49.6% increase in compressive strength and a 30.8% increase in flexural strength with admixture. At 28 days, CONA and COWA averaged 35.68/6.51 MPa and 52.97/7.79 MPa, a 48.4% increase in compressive strength and 19.6% increase in flexural strength. COWA therefore outperforms CONA at both ages across both properties, shown in Fig. 2, where percentage labels denote the increase of COWA relative to CONA at the same age.

CONA reached 76% of its 28-day compressive strength at 7 days, versus 79% for COWA, indicating that admixtures both raise absolute strength and accelerate early strength gain. For flexural strength, CONA reached about 85% of its 28-day value at 7 days versus 88% for COWA. These trends are consistent with the admixture's role in lowering effective water-cement ratio, densifying the cement paste–aggregate bond, and reducing capillary porosity [33]–[38], which improves both compressive and flexural performance and durability relative to conventional concrete.

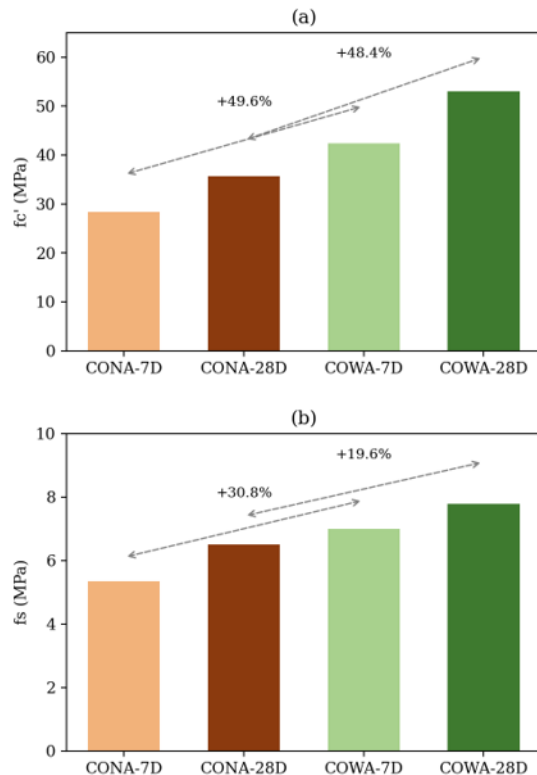


Figure 2. The mean compressive strength (a) and flexural strength (b) of samples at 7 and 28 days.

3.3. Correlation of compressive and flexural strength

Fig. 3 shows the empirical relationship between fc' and fs for all 64 specimens spanning all four mixture types (CPNA, CONA at both design targets, and COWA), fitted with a single power-law model and compared against the standard/prior-study equations of Table 1.

The pooled data show a high, positive, non-linear correlation, best modeled by power regression:

$$fs = 0.3209 (fc')^{0.8207} \quad (3)$$

with $R^2 = 0.8572$, indicating that 85.7% of the variation in flexural strength is explained by compressive strength across the pooled dataset spanning all cement types, ages, and admixture conditions tested. This is consistent with the general expectation that concrete mechanical parameters follow a power-law relationship reflecting the contribution of microstructure to tensile/flexural load transfer.

Visual inspection of Fig. 3 suggests the data may follow the normal-strength model trend of Ahmed et al. [7] over roughly 20–40 MPa, and trend closer to the high-strength model of Amudhavalli and Mathew [19] above approximately 40 MPa. This apparent regime change has not been tested with a formal breakpoint or segmented-regression procedure

in this study and should be treated as a qualitative observation motivating further, statistically confirmed investigation rather than an established finding.

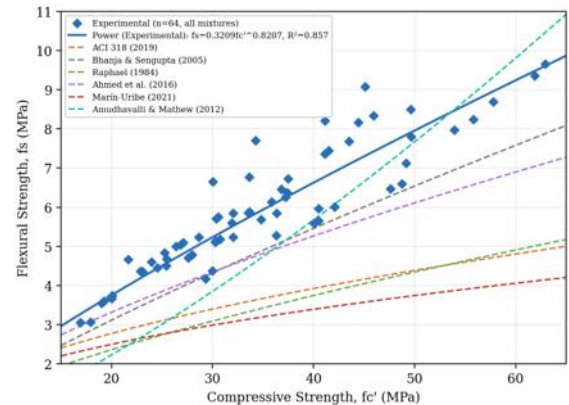


Figure 3. Comparison of the pooled experimental fc' – fs data ($n=64$, all mixtures) and fitted power model against reference equations from Table 1.

ACI 318's square-root form tends to under-predict flexural strength across the tested range, since it does not capture the more rapid fs growth with fc' observed in admixture-modified concrete with denser, more homogeneous microstructure. This suggests that a single general equation may not adequately represent the full spectrum of concrete quality and composition, and that normal- and high-quality concrete — governed respectively by capillary porosity/ITZ heterogeneity and by C–S–H densification/microstructural continuity — may warrant separate calibration ranges in future work [35]. Conventional design equations, largely developed from admixture-free databases, may also require re-calibration for concretes using modern superplasticizer/retarder technology [39].

Overall, the study indicates that chemical admixtures meaningfully affect the fc' – fs relationship, plausibly through reduced capillary porosity, improved paste homogeneity, improved ITZ quality, and a more continuous C–S–H network. Future empirical models should consider microstructural and mixture characteristics alongside compressive strength as predictors.

4. CONCLUSION

This study investigated how cement type and chemical admixtures affect the compressive and flexural strength of concrete, culminating in an empirical fc' – fs relationship. Early-age results favored OPC concrete, which developed strength more quickly than PCC; however, PCC caught up over time, showing a proportionally larger strength gain at later ages. Regardless of cement type, adding admixtures consistently boosted both compressive and flexural strength across

the two testing ages. When data from all four mixture types were pooled, the resulting relationship — $f_s = 0.3209(f_c')^{0.8207}$, $R^2 = 0.8572$ — fit the observed dataset more closely than the square-root form specified in ACI 318, across the 18–63 MPa range examined. This range covers both normal- and high-strength concrete, and a possible shift in trend emerged around 40 MPa, though it was not statistically confirmed. Before extending the model beyond the specific mixtures and materials tested here, future studies should apply segmented or breakpoint regression to a larger, independently replicated dataset to validate this observation.

5. ACKNOWLEDGMENT

The authors thank the Laboratory of Material and Construction, University of Lampung, for supporting this research.

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