

Influence of Mix Proportions on the Compressive Strength of Concrete: A Statistical Analysis of 1030 Concrete Mixtures

Ibrahim Siddique¹ and Sphurty Raman²

¹B. Tech. Student, Department of Civil Engineering, Sharda University, Greater Noida, Uttar Pradesh, INDIA

²Assistant Professor, Department of Civil Engineering, Sharda University, Greater Noida, Uttar Pradesh, INDIA



www.jrasb.com || June 2026

Date of Submission: 01-06-2026

Date of Publication: 12-06-2026

ABSTRACT

The compressive strength of concrete is governed by a complex interaction of its constituent proportions, the water-to-binder ratio, the use of supplementary cementitious materials, and the age of curing. This study presents a statistical investigation of these relationships using a consolidated dataset of 1030 concrete mixtures containing eight measured parameters: cement, ground granulated blast-furnace slag, fly ash, water, superplasticiser, coarse aggregate, fine aggregate, and curing age. Engineered parameters including the water-to-binder ratio, total binder content, and supplementary cementitious material replacement level were derived to interpret strength behaviour through established concrete technology principles. Descriptive statistics, Pearson and Spearman correlation analysis, banded grouping, and ordinary least-squares regression were employed. The results confirm the classical inverse relationship between the water-to-binder ratio and strength, with mean strength declining from 52.96 MPa at ratios below 0.35 to 17.67 MPa at ratios above 0.65. Cement content and curing age emerged as the strongest positive determinants of strength, while water content showed the strongest negative association. A logarithmic strength-age relationship was observed, and a multi-parameter empirical equation explained approximately 62 percent of the variance in compressive strength. The findings reaffirm fundamental mix-design principles on a large heterogeneous dataset and provide a transparent, practitioner-usable predictive equation for preliminary proportioning. By demonstrating that moderate replacement of cement with industrial by-products such as slag and fly ash can maintain compressive strength, the work supports the United Nations Sustainable Development Goals relating to resilient infrastructure (SDG 9), sustainable cities and communities (SDG 11), and responsible consumption and production (SDG 12).

Keywords- compressive strength, water-binder ratio, supplementary cementitious materials, curing age, statistical regression, concrete mix proportions, sustainable development goals.

I. INTRODUCTION

Concrete remains the most widely used construction material worldwide, and its compressive strength is the single most important property used in structural design and quality control. The strength developed by a hardened concrete is the outcome of the proportions of its constituents, the chemistry of the binder system, the degree of compaction, and the conditions and duration of curing [2]. Among these, the water-to-binder ratio has long been recognised as the dominant factor, a principle formalised by Abrams as early as 1918, which states that for a given set of materials the strength of concrete is inversely related to the ratio of water to cementitious material [1]. The mathematical form of this relationship and its underlying assumptions have since been examined in detail [7].

The increasing incorporation of supplementary cementitious materials (SCMs) such as ground granulated blast-furnace slag and fly ash has added further complexity to strength prediction [5]. These by-product materials partially replace ordinary Portland cement, reducing the embodied carbon of concrete and contributing to sustainability objectives, but they also alter the rate of strength development and the ultimate strength achieved. The pozzolanic and latent-hydraulic reactions associated with fly ash and slag typically proceed more slowly than the hydration of Portland cement, which influences both early-age and long-term strength; high-volume fly ash mixtures, for example, exhibit reduced early strength but continued

strength gain at later ages [9]. The judicious use of chemical and mineral admixtures allows low water-to-binder ratios to be achieved at workable consistencies, enabling economical high-performance mixtures [6].

While numerous experimental studies have examined individual mixtures, comparatively fewer have analysed the combined influence of all major mix parameters across a large and heterogeneous population of concretes using a consistent statistical framework. Recent work has shown that statistical and machine-learning approaches can estimate compressive strength from mixture proportions, although such studies are often limited to small laboratory datasets or focus on predictive accuracy rather than physical interpretation [12, 11]. The present study addresses this by analysing a consolidated dataset of 1030 concrete mixtures, originally compiled by Yeh [4]. The objectives are threefold: first, to characterise the statistical distribution and inter-relationships of the mix parameters; second, to quantify the influence of the water-to-binder ratio, SCM replacement level, and curing age on compressive strength through established concrete-technology reasoning; and third, to develop a transparent empirical regression equation suitable for preliminary mix proportioning. The intention is not to introduce a new predictive technique but to reaffirm and quantify fundamental principles on a large dataset in a manner that is directly interpretable by practising engineers.

II. MATERIALS AND METHODS

2.1 Description of the Dataset

The analysis was conducted on a publicly available consolidated dataset comprising 1030 concrete mixture records, originally compiled and published by Yeh [4]. Each record contains eight independent variables describing the mixture composition and curing condition, together with the measured compressive strength as the dependent variable. The eight independent variables are: cement content, blast-furnace slag content, fly ash content, water content, superplasticiser dosage, coarse aggregate content, fine aggregate content (all expressed in kilograms per cubic metre), and the age of testing in days. The compressive strength is expressed in megapascals (MPa). The dataset is secondary in nature; no laboratory testing was performed by the authors, and the analysis is presented as a statistical study of previously reported mixtures.

It was noted that 25 of the 1030 records were exact duplicates of other records. These were retained in the present analysis to remain consistent with the dataset as distributed, and their limited number is not expected to materially influence the aggregate statistical trends reported here.

2.2 Engineered Parameters

To interpret strength behaviour through established concrete-technology principles, four additional parameters were derived from the raw constituent quantities. The total binder content was computed as the sum of cement, slag, and fly ash. The water-to-binder ratio was computed as the water content divided by the total binder content, in line with the effective water-to-binder concept used in standard mix-design guidelines [13]. The SCM replacement level was computed as the combined slag and fly ash content expressed as a percentage of the total binder. The fine-to-coarse aggregate ratio was computed as the fine aggregate content divided by the coarse aggregate content. These engineered parameters allow the mixtures to be grouped and compared in terms that correspond directly to mix-design practice.

2.3 Statistical Methods

The statistical investigation comprised four stages. First, descriptive statistics (minimum, maximum, mean, standard deviation, and coefficient of variation) were computed for all parameters to characterise the range and variability of the dataset. Second, Pearson product-moment and Spearman rank correlation coefficients were calculated between each input parameter and compressive strength to quantify both linear and monotonic associations [10]. Third, the mixtures were grouped into bands according to water-to-binder ratio, SCM replacement level, and curing age, and the mean strength within each band was compared. Fourth, an ordinary least-squares (OLS) multiple regression was fitted using the eight original mix parameters as predictors to derive an interpretable empirical strength equation [10]. All computations were performed using standard scientific computing libraries.

III. RESULTS AND DISCUSSION

3.1 Descriptive Statistics of the Dataset

Table 1 summarises the descriptive statistics of the eight mix parameters and the compressive strength. The dataset spans a wide range of mixtures, with cement content ranging from 102 to 540 kg/m³ and compressive strength ranging from 2.33 to 82.6 MPa, with a mean of 35.82 MPa. The high coefficient of variation for slag (116.8%), fly ash (118.1%), and curing age (138.3%) reflects the deliberate inclusion of both plain Portland cement concretes and blended concretes tested across early and mature ages. In contrast, the coarse and fine aggregate contents show low variability, consistent with their role as bulk volume-filling constituents that are varied within narrower limits in practical mix design.

Table 1: Descriptive statistics of the mix parameters and compressive strength

Parameter	Min	Max	Mean	Std. Dev.	CV (%)
Cement	102	540	281.17	104.51	37.2
Blast-Furnace Slag	0	359.4	73.9	86.28	116.8
Fly Ash	0	200.1	54.19	64	118.1
Water	121.8	247	181.57	21.35	11.8
Superplasticiser	0	32.2	6.2	5.97	96.3
Coarse Aggregate	801	1145	972.92	77.75	8
Fine Aggregate	594	992.6	773.58	80.18	10.4
Age (days)	1	365	45.66	63.17	138.3
Strength	2.33	82.6	35.82	16.71	46.6

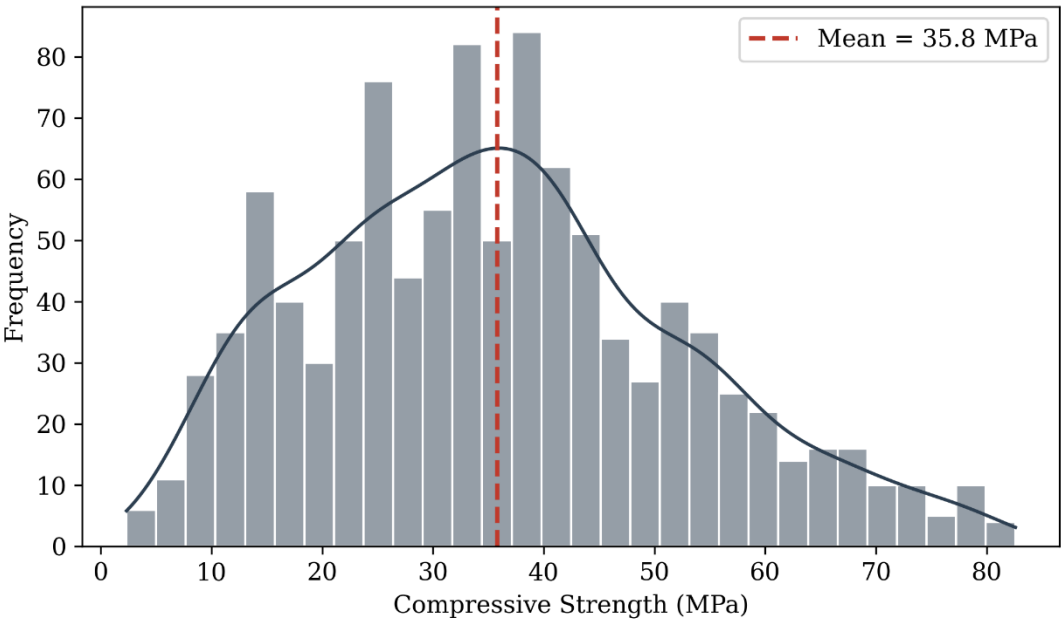


Figure 1: Distribution of compressive strength across the 1030 concrete mixtures

Figure 1 presents the distribution of compressive strength. The distribution is approximately unimodal with a mild positive skew, with the majority of mixtures falling between 20 and 50 MPa and a smaller population of high-strength mixtures exceeding 60 MPa. This spread provides a robust basis for examining how mix proportions drive strength across the normal, standard, and high-strength ranges encountered in practice.

3.2 Correlation Between Mix Parameters and Strength

Table 2 reports the Pearson and Spearman correlation coefficients between each parameter and compressive strength. Cement content shows the strongest positive linear correlation ($r = 0.498$), confirming its primary role as the principal strength-generating constituent. Curing age, while showing a moderate Pearson coefficient ($r = 0.329$), exhibits a much stronger Spearman coefficient ($r = 0.596$), indicating a strong but non-linear monotonic relationship that is better captured by rank correlation. Water content shows the expected negative correlation ($r = -0.290$), consistent with the detrimental effect of excess water on the hardened paste structure. Superplasticiser dosage shows a positive correlation ($r = 0.366$), which is physically reasonable since superplasticisers permit a reduction in water content while maintaining workability.

Table 2: Pearson and Spearman correlation coefficients with compressive strength

Parameter	Pearson r	Pearson p-value	Spearman r
Cement	0.4978	1.32e-65	0.4776
Blast-Furnace Slag	0.1348	0.0000141	0.1641
Fly Ash	-0.1058	0.000675	-0.0778

Parameter	Pearson r	Pearson p-value	Spearman r
Water	-0.2896	2.35e-21	-0.3084
Superplasticiser	0.3661	5.1299999999999995e-34	0.3478
Coarse Aggregate	-0.1649	1.02e-7	-0.1835
Fine Aggregate	-0.1672	6.7e-8	-0.18
Age (days)	0.3289	2.11e-27	0.596

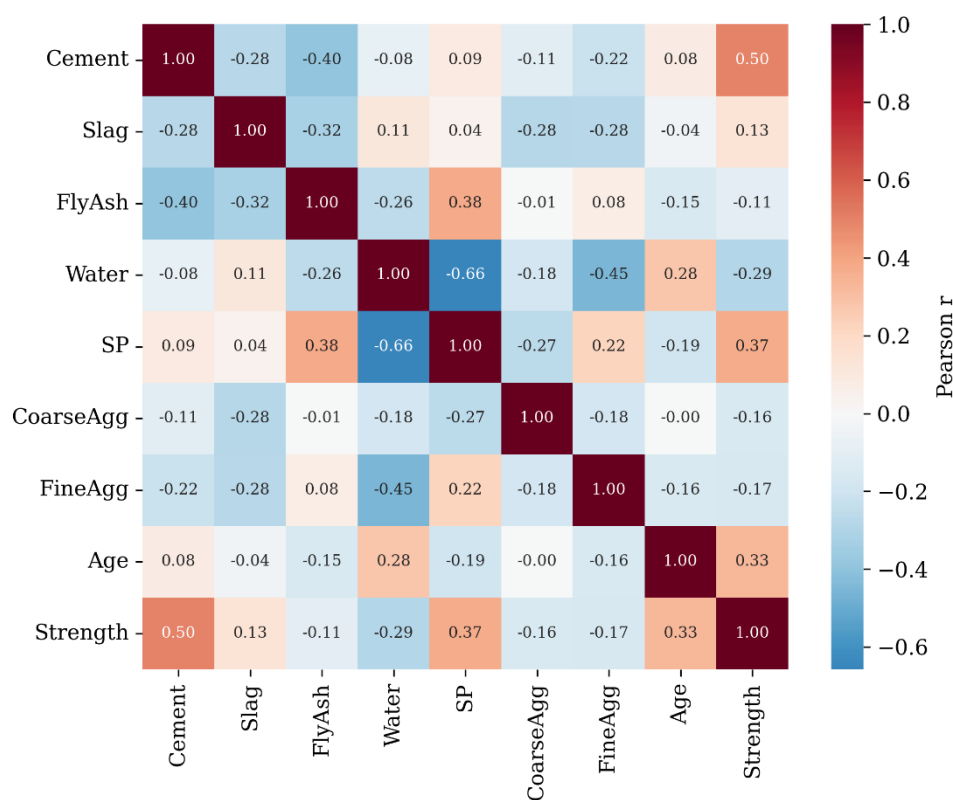


Figure 2: Correlation heatmap of mix parameters and compressive strength

The correlation heatmap in Figure 2 visualises the full matrix of inter-parameter relationships. A notable negative correlation exists between water and superplasticiser, reflecting the common practice of substituting chemical admixture for mixing water. The relatively weak correlation of individual aggregate contents with strength supports the established view that aggregates, while occupying the majority of the concrete volume, exert a secondary influence on strength compared with the binder and water phases [3].

3.3 Influence of the Water-to-Binder Ratio

The influence of the water-to-binder ratio on compressive strength is the most fundamental relationship in concrete technology [1, 7]. Table 3 presents the mean strength within five water-to-binder ratio bands. A clear and consistent decline in mean strength is observed as the ratio increases, falling from 52.96 MPa for mixtures with ratios below 0.35 to 17.67 MPa for mixtures with ratios above 0.65. This monotonic reduction across more than 1000 heterogeneous mixtures provides strong empirical confirmation of Abrams' law on a large independent dataset.

Table 3: Variation of compressive strength across water-to-binder ratio bands

W/B Band	N	Mean (MPa)	Std. Dev.	Min (MPa)	Max (MPa)
<0.35	215	52.96	16.31	7.75	82.6
0.35-0.45	258	39.48	12.88	9.56	78.8
0.45-0.55	267	30.23	11	6.27	53.9
0.55-0.65	210	27.78	12.94	4.83	56.14

W/B Band	N	Mean (MPa)	Std. Dev.	Min (MPa)	Max (MPa)
>0.65	80	17.67	8.42	2.33	33.7

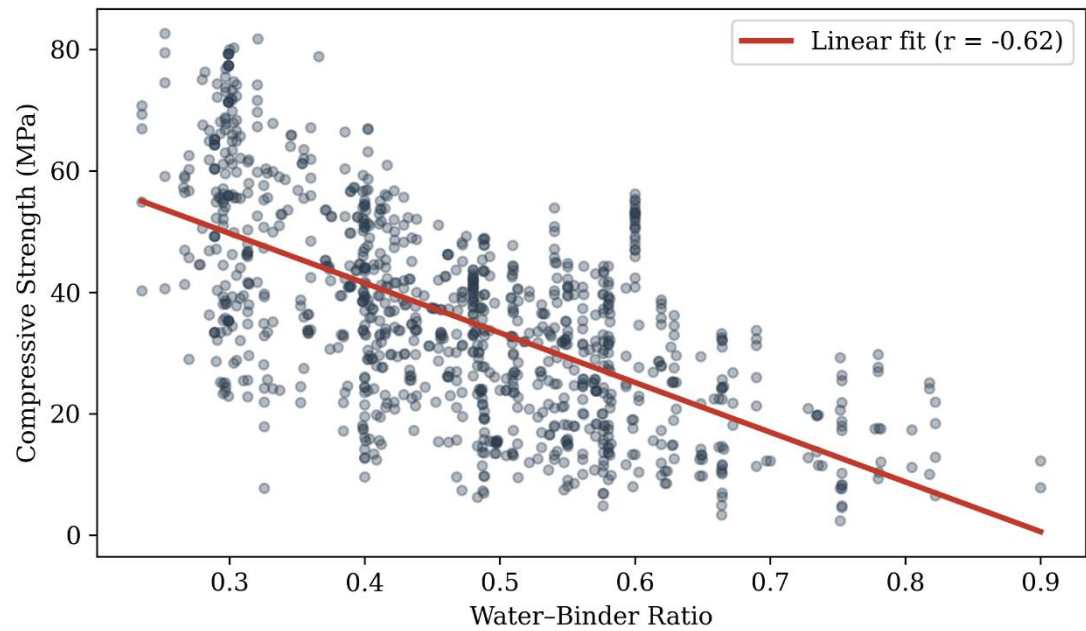


Figure 3: Compressive strength versus water-to-binder ratio

Figure 3 plots compressive strength against the water-to-binder ratio for all mixtures. Despite the scatter introduced by varying binder types, ages, and admixture dosages, the overall downward trend is unmistakable. The scatter at any given ratio reflects the additional influence of curing age and SCM content, which are examined separately below. The total binder content was also examined, as shown in Figure 4, which indicates a positive but weaker association with strength; this is consistent with the understanding that it is the proportion of water to binder, rather than the absolute binder quantity alone, that primarily governs strength. This observation aligns with studies questioning the value of prescriptive minimum cement content requirements, which have shown that at a given water-to-binder ratio, strength is largely a function of that ratio rather than of cement content per se [8].

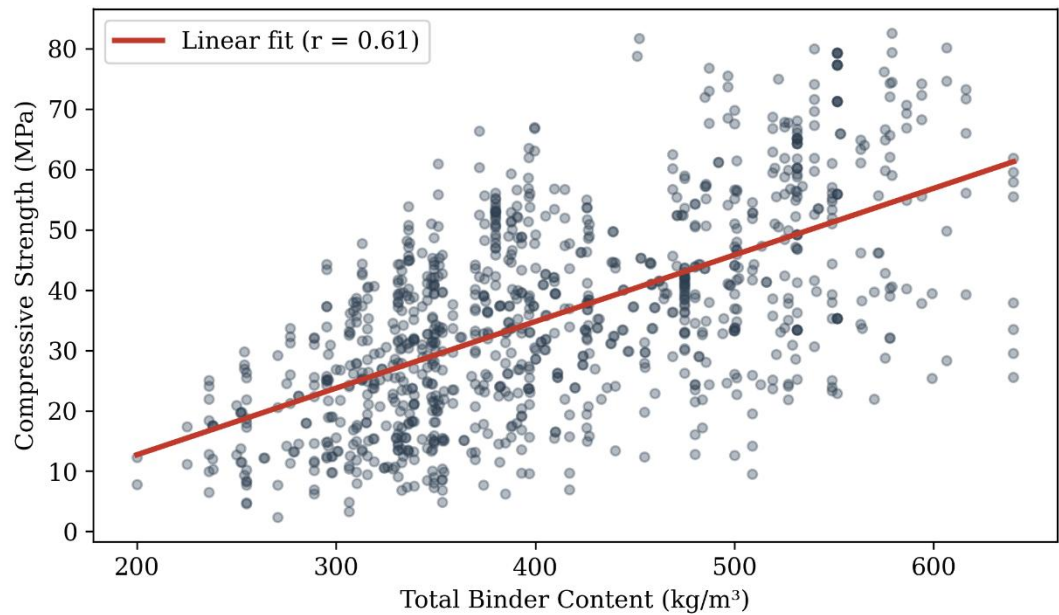


Figure 4: Compressive strength versus total binder content

3.4 Effect of Supplementary Cementitious Material Replacement

Table 4 summarises the mean compressive strength across SCM replacement bands. The mixtures containing moderate replacement levels of 15 to 30 percent achieved the highest mean strength of 44.17 MPa, exceeding the plain Portland cement mixtures, which had a mean of 31.99 MPa. At high replacement levels above 45 percent, the mean strength declined to 29.44 MPa. This pattern is consistent with the established behaviour of blended cements: moderate SCM replacement contributes to strength through pozzolanic and latent-hydraulic reactions and improved particle packing, whereas excessive replacement dilutes the reactive Portland cement phase and slows strength development, particularly at the testing ages represented in the dataset [5, 9].

It should be noted that replacement level alone does not fully isolate the SCM effect, since mixtures differ simultaneously in water-to-binder ratio and curing age. The banded comparison nevertheless captures the practically relevant trend that moderate replacement can maintain or enhance strength while reducing cement demand, supporting the use of SCMs for sustainable concrete production.

Table 4: Effect of supplementary cementitious material replacement level on mean strength

SCM Replacement (%)	N	Mean Strength (MPa)	Std. Dev.
0 (OPC)	232	31.99	16.03
>0-15	13	47.46	8.91
15-30	210	44.17	14.15
30-45	311	37.96	17.9
>45	264	29.44	14.29

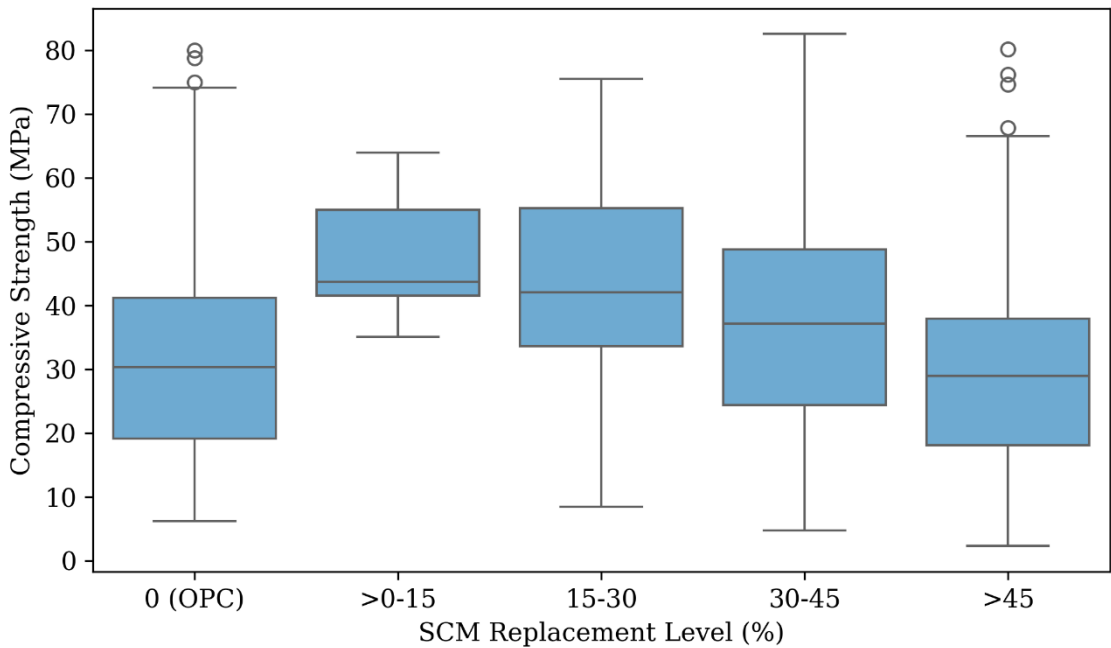


Figure 5: Distribution of compressive strength across SCM replacement levels

Figure 5 presents the strength distribution within each replacement band as box plots, illustrating both the central tendency and the spread. The figure reinforces that intermediate replacement levels deliver competitive strength performance, while the widest variability is associated with the 30 to 45 percent band, where the balance between dilution and pozzolanic contribution is most sensitive to other mix factors.

3.5 Strength Development with Curing Age

Table 5 summarises the mean strength at standard testing ages, expressed also as a percentage of the 28-day mean strength. Strength develops rapidly at early ages, reaching approximately 52 percent of the 28-day value at 3 days and 71 percent at 7 days, before approaching and exceeding the 28-day value at later ages. The continued strength gain beyond 28 days is particularly associated with mixtures containing SCMs, whose slower pozzolanic reactions contribute to long-term strength [9]. The apparent variability at 90 days and beyond reflects the smaller number of records and the predominance of blended mixtures at these ages.

Age (days)	N	Mean Strength (MPa)	Std. Dev.	% of 28-day
3	134	18.98	9.86	51.6
7	126	26.05	14.58	70.9
14	62	28.75	8.64	78.2
28	425	36.75	14.71	100
56	91	51.89	14.31	141.2
90	54	40.48	9.82	110.1
180	26	41.73	10.93	113.6
365	14	43.56	9.62	118.5

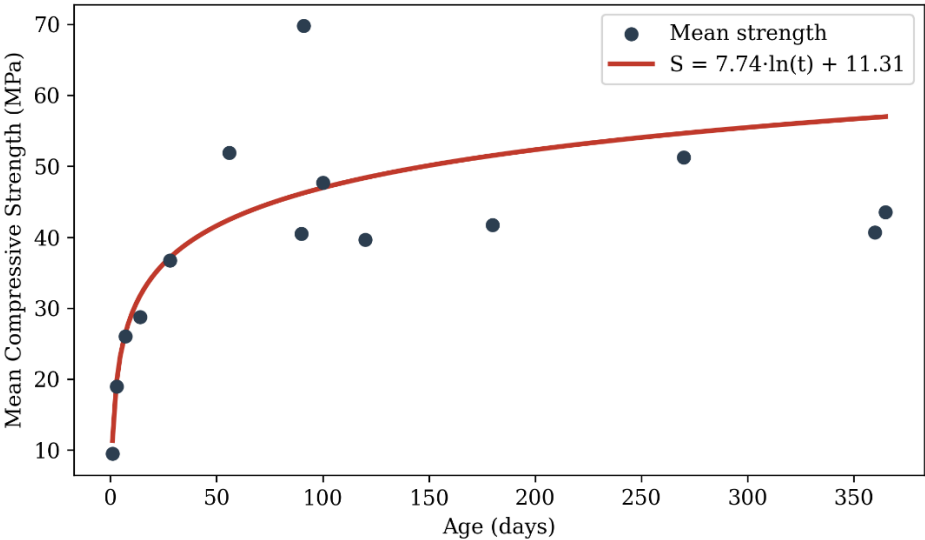


Figure 6: Compressive strength development with curing age and logarithmic fit

Figure 6 plots the mean strength against curing age together with a logarithmic regression of the form $S = 7.74 \ln(t) + 11.31$, where S is the compressive strength in MPa and t is the age in days. The logarithmic form captures the characteristic rapid early strength gain followed by a progressively slower rate of increase, in agreement with established maturity-based descriptions of strength development. The relationship explains the broad trend of strength gain with age, although a portion of the variability is attributable to differing binder compositions across the age groups.

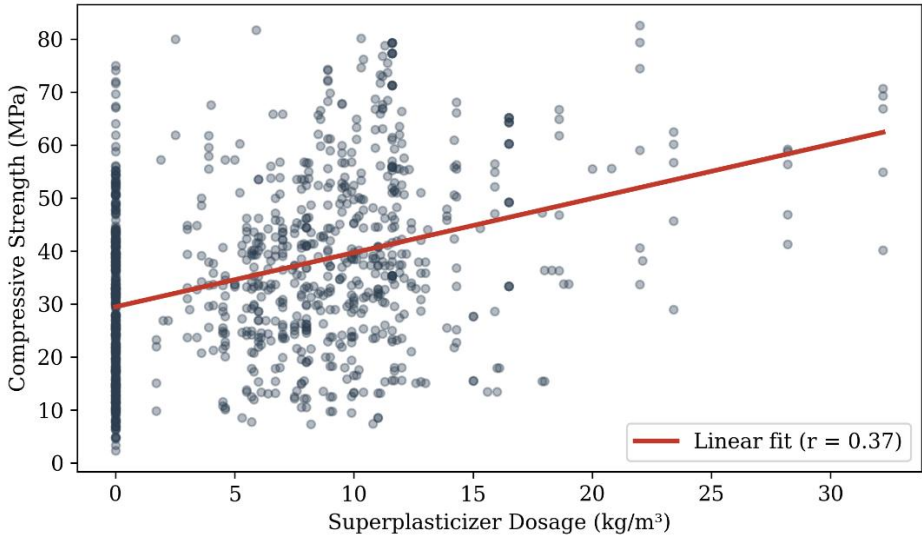


Figure 7: Compressive strength versus superplasticiser dosage

Figure 7 examines the relationship between superplasticiser dosage and strength. The positive association observed is interpreted as an indirect effect: higher admixture dosages enable lower water-to-binder ratios at workable consistencies, thereby supporting higher strengths. The admixture does not itself generate strength but facilitates the mixture proportions that do.

3.6 Empirical Regression Equation

An ordinary least-squares multiple regression was fitted using the eight original mix parameters as predictors of compressive strength. The resulting model explained approximately 62 percent of the variance in strength ($R^2 = 0.616$, adjusted $R^2 = 0.613$), with a root-mean-square error of 10.35 MPa and a mean absolute error of 8.21 MPa. The regression coefficients are reported in Table 6. Cement content, curing age, slag, and fly ash all contribute positively and significantly to strength, while water content contributes negatively, in full agreement with the correlation analysis and with concrete-technology theory. The coefficients for cement, slag, fly ash, water, superplasticiser, and age are all statistically significant at the one percent level.

Table 6: Coefficients of the empirical multiple-regression strength equation

Parameter	Coefficient	Std. Error	t-value	p-value
Intercept	-23.3312	26.5855	-0.88	0.38
Cement	0.1198	0.0085	14.11	1.9e-41
Blast-Furnace Slag	0.1039	0.0101	10.25	1.6e-23
Fly Ash	0.0879	0.0126	6.99	5.02e-12
Water	-0.1499	0.0402	-3.73	0.000201
Superplasticiser	0.2922	0.0934	3.13	0.00181
Coarse Aggregate	0.0181	0.0094	1.93	0.0544
Fine Aggregate	0.0202	0.0107	1.89	0.0595
Age (days)	0.1142	0.0054	21.05	5.78e-82

The empirical equation derived from the regression coefficients may be written as: $\text{Strength} = -23.33 + 0.120 \times \text{Cement} + 0.104 \times \text{Slag} + 0.088 \times \text{Fly Ash} - 0.150 \times \text{Water} + 0.292 \times \text{Superplasticiser} + 0.018 \times \text{Coarse Aggregate} + 0.020 \times \text{Fine Aggregate} + 0.114 \times \text{Age}$, where all constituent quantities are in kilograms per cubic metre and age is in days. While a linear model cannot fully capture the non-linear strength-age and strength-water relationships, the equation provides a transparent and readily computable first estimate of compressive strength for preliminary proportioning, with each coefficient carrying a clear physical interpretation. The moderate explained variance is consistent with prior statistical analyses, which have noted that linear models capture the broad trends in mixture-proportion data while more flexible methods are required to model the strongly non-linear behaviour at the extremes of the strength range [12, 11].

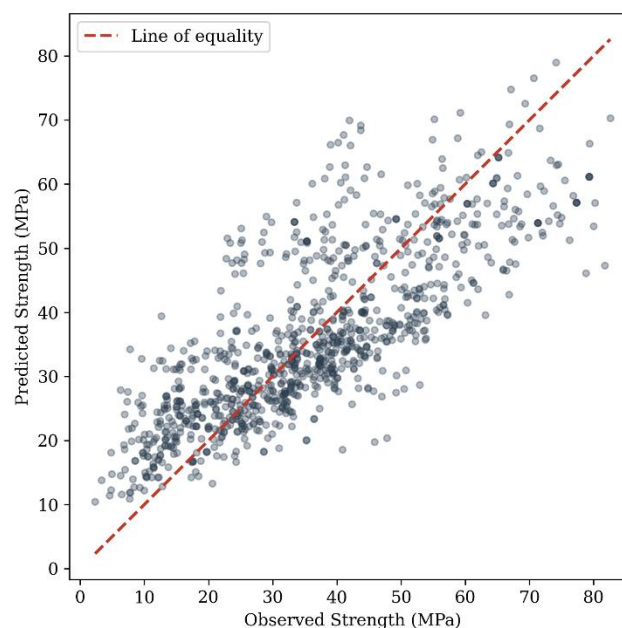


Figure 8: Observed versus predicted compressive strength from the empirical equation

Figure 8 compares the observed strengths with those predicted by the empirical equation. The points cluster around the line of equality, with the dispersion reflecting the unexplained variance inherent in a linear description of an intrinsically non-linear system. The systematic pattern of residuals at the extremes indicates that the linear form slightly underpredicts very high strengths and overpredicts very low strengths, a known limitation that more flexible models address at the cost of interpretability.

IV. CONCLUSIONS

This study presented a statistical analysis of 1030 concrete mixtures to quantify the influence of mix proportions on compressive strength using established concrete-technology principles. The principal conclusions are as follows:

- (1) The water-to-binder ratio is the dominant factor governing compressive strength. Mean strength declined consistently from 52.96 MPa at ratios below 0.35 to 17.67 MPa at ratios above 0.65, providing large-scale empirical confirmation of Abrams' law.
- (2) Cement content and curing age are the strongest positive determinants of strength, while water content shows the strongest negative association. Curing age exhibits a markedly non-linear monotonic relationship, best described by a logarithmic strength-age function.
- (3) Moderate supplementary cementitious material replacement of 15 to 30 percent produced the highest mean strength, exceeding plain Portland cement mixtures, whereas replacement above 45 percent reduced strength. This supports the use of slag and fly ash for sustainable concrete without compromising, and potentially enhancing, strength at moderate replacement levels.
- (4) A transparent empirical regression equation explained approximately 62 percent of the strength variance, with all major coefficients statistically significant and physically interpretable, offering a practitioner-usable tool for preliminary mix proportioning.

The analysis reaffirms fundamental mix-design relationships on a large, heterogeneous dataset and demonstrates that classical concrete-technology principles remain robust descriptors of strength behaviour. Future work could extend the analysis by incorporating durability and workability parameters, which were not available in the present dataset, and by isolating the SCM effect through controlled grouping of water-to-binder ratio and age.

The outcomes of this study carry direct relevance to the United Nations Sustainable Development Goals. The finding that moderate replacement of cement with industrial by-products such as ground granulated blast-furnace slag and fly ash can sustain, and in some bands enhance, compressive strength supports responsible consumption and production through the beneficial reuse of waste streams that would otherwise require disposal (SDG 12). The provision of a transparent equation for preliminary strength estimation contributes to efficient and innovative infrastructure practice by reducing reliance on trial mixtures (SDG 9). More broadly, the promotion of resource-efficient concrete that lowers clinker demand while maintaining structural performance advances the development of durable and sustainable construction for cities and communities (SDG 11).

LIST OF SYMBOLS AND ABBREVIATIONS

S — Compressive strength (MPa)
t — Curing age (days)
W/B — Water-to-binder ratio
SCM — Supplementary cementitious material
OPC — Ordinary Portland cement
OLS — Ordinary least squares
R² — Coefficient of determination
RMSE — Root-mean-square error
MAE — Mean absolute error
CV — Coefficient of variation
r — Correlation coefficient

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Department of Civil Engineering, Sharda University, Greater Noida, for providing the academic environment and computational support that enabled this study. The authors also acknowledge the original compilers of the publicly available concrete strength dataset used in this analysis.

REFERENCES

- [1] Abrams, D.A. (1918). Design of concrete mixtures. Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago, pp. 1-20.
- [2] Neville, A.M. (2011). Properties of concrete. (5th ed.). Harlow: Pearson Education Limited.
- [3] Mehta, P.K., & Monteiro, P.J.M. (2014). Concrete: Microstructure, properties, and materials. (4th ed.). New York: McGraw-Hill Education.
- [4] Yeh, I.C. (1998). Modeling of strength of high-performance concrete using artificial neural networks. *Cement and Concrete Research*, 28(12), 1797-1808. DOI: 10.1016/S0008-8846(98)00165-3.
- [5] Lothenbach, B., Scrivener, K., & Hooton, R.D. (2011). Supplementary cementitious materials. *Cement and Concrete Research*, 41(12), 1244-1256. DOI: 10.1016/j.cemconres.2010.12.001.
- [6] Bharatkumar, B.H., Narayanan, R., Raghuprasad, B.K., & Ramachandramurthy, D.S. (2001). Mix proportioning of high performance concrete. *Cement and Concrete Composites*, 23(1), 71-80. DOI: 10.1016/S0958-9465(00)00071-8.
- [7] Popovics, S. (1990). Analysis of the concrete strength versus water-cement ratio relationship. *ACI Materials Journal*, 87(5), 517-529.
- [8] Wassermann, R., Katz, A., & Bentur, A. (2009). Minimum cement content requirements: a must or a myth? *Materials and Structures*, 42(7), 973-982. DOI: 10.1617/s11527-008-9436-0.
- [9] Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. *Cement and Concrete Research*, 34(3), 487-493. DOI: 10.1016/j.cemconres.2003.09.002.
- [10] Snedecor, G.W., & Cochran, W.G. (1989). Statistical methods. (8th ed.). Ames: Iowa State University Press.
- [11] Chou, J.S., & Pham, A.D. (2013). Enhanced artificial intelligence for ensemble approach to predicting high performance concrete compressive strength. *Construction and Building Materials*, 49, 554-563. DOI: 10.1016/j.conbuildmat.2013.08.078.
- [12] Young, B.A., Hall, A., Pilon, L., Gupta, P., & Sant, G. (2019). Can the compressive strength of concrete be estimated from knowledge of the mixture proportions? New insights from statistical analysis and machine learning methods. *Cement and Concrete Research*, 115, 379-388. DOI: 10.1016/j.cemconres.2018.09.006.
- [13] Bureau of Indian Standards. (2019). IS 10262: Concrete mix proportioning - guidelines. (2nd revision). New Delhi: BIS.