Evaluating the Relationship between Curing Time and Compressive Strength in Concrete: A Statistical Analysis

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ORIGINAL RESEARCH

Abstract— limitations exist in relating curing time and strength through standardized testing methods. These limitations include difficulty replicating real-world variations in curing conditions. Accurately measuring the true curing history of concrete in the field remains challenging, making it difficult to precisely correlate curing time to achieve strength in real-world applications. This study investigated the statistical relationship between curing time and crushing resistance of concrete cubes cured by ponding. Minitab software was used to analyze the data. The compressive strength increased significantly with curing time, as the hydration process between cement and water continued for days after pouring. Data showed a strong positive correlation (r = 0.921) between curing days and strength. A polynomial regression model effectively captured this relationship (R-squared = 0.9803, adjusted R-squared = 0.9655). The model suggests that longer curing durations lead to stronger concrete. The fitted equation allows the estimation of compressive strength based on curing time. Analysis of Variance (ANOVA) confirmed that curing time significantly impacts compressive strength (p-value < 0.001). The cubic regression equation incorporates linear, curvature, and minor deviation terms to accurately model the strength gain pattern.

Keywords— compressive strength, correlation, concrete, Curing, R-squared.

1 Introduction

Concrete, the global workhorse of construction, underpins the foundation of our built environment. Its remarkable versatility stems from its ability to be tailored for specific purposes through adjustments in its composition and curing process Wang et al (2023). Numerous studies have established a positive correlation between curing time and compressive strength within concrete (Zou et al., 2018; Ding et al.,2016, & Wedatalla et al., 2019). To ensure proper concrete performance, curing involves ideal moisture and temperature conditions Upon initial placement. This allows a chemical reaction called hydration to occur throughout the concrete, leading to its full strength and durability. To achieve optimal properties, various curing methods can be employed, these methods include water curing (keeping the surface saturated with water), membrane curing (applying a liquid membrane to prevent moisture loss), formwork curing (leaving the formwork in place), and sheet curing (covering the surface with plastic sheeting). The most effective method can vary depending on project-specific factors, but proper curing is crucial for ensuring strong and durable concrete Gowsika et al (2017). Ponding emerged as the most effective curing method, demonstrably achieving the highest compressive strength and cube density James et al (2011). Compressive strength, a critical parameter for ensuring structural integrity, is heavily influenced by the duration and conditions of curing Ferraris et al. (2022).

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The link between curing time, compressive strength, and the long-term durability of concrete structures. Studies have shown that proper curing can enhance a concrete's resistance to cracking, weather damage, and chemical degradation Muthu et al (2022). Understanding the precise relationship between curing time and compressive strength is paramount for optimizing concrete production, ensuring safety in construction projects, and potentially even developing novel concrete formulations with superior properties Gesoglu et al (2021) and Li et al (2020). However, current methods for determining the relationship between curing time and compressive strength may have limitations. These limitations can include challenges in standardizing test methods to capture real-world variations, limited data for specific concrete mixes with admixtures, and difficulties in accurately measuring the true curing history in field applications. By acknowledging these weaknesses, researchers can emphasize the need for further development of methodologies to better understand this crucial relationship in concrete. Recent advancements in statistical analysis techniques, including powerful tools like regression analysis employed by researchers like Akanbi et al. (2022) to analyze how various factors impact the strength of sandcrete blocks, have opened new avenues for dissecting the complex interplay between curing time and compressive strength in concrete. Statistical methods allow researchers to move beyond qualitative observations and establish robust quantitative relationships. Prior research has employed linear regression models to model the strength gain of concrete with curing time, with promising results Mehta & Monteiro (2014). However, the inherent variability in concrete, arising from factors like mix design and environmental conditions, necessitates the exploration of more sophisticated statistical techniques Bremner et al (2016). Existing research highlights the complex interplay between curing methods, material types, and strength development. Studies by Benaicha et al. (2016) and

Hamada et al. (2022) explore the influence of curing methods on diverse concrete types, including Self-pacing and high-strength concretes, and ultra-high-performance concrete (UHPC). Additionally, Ahmed et al. (2021) investigate the impact of various parameters on the compressive strength of geopolymer concrete, a sustainable alternative gaining traction. This research builds upon these insights by employing statistical analysis to rigorously evaluate the correlation between curing time and compressive strength in concrete. We leverage a comprehensive dataset encompassing concrete specimens cured for various durations and subsequently tested for compressive strength. By employing a range of statistical tools, including correlation analysis, and regression modeling with techniques like analysis of variance (ANOVA).

2 MATERIALS AND METHODS

2.1 Materials

Forty 150 mm^3 concrete specimens were cast using a standard concrete mix design. The mix consisted of:

- Fine aggregates (Sand)
- Coarse aggregate (granite)
- Portland cement (binder)
- water

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2.2 Mix Design and Concreting

To achieve an M15 concrete mix design, cubes were cast with a 1:1:2 ratio of cement, sand, and aggregate. Forty (40) cubes were produced in total.

2.3 Experimental Investigation

2.3.1 Materials characterization

2.3.1.1 Sieve analysis: The particle size distribution of the aggregates was determined using dry sieve analysis, following the Sieve analysis method for determining particle size distribution (based on BS 812-103.1).

2.3.2 Determination of the Compressive Strength

The research involved a compressive strength test to evaluate the strength of the concrete cured, and the investigation was conducted following the BS EN 12390-3:2009 standard. To gain a comprehensive understanding of how curing time impacts compressive strength, concrete cubes were subjected to pond curing for various durations: 3, 7, 11, 14, 18, 21, 25, and 28 days. This wide range of curing periods allows for a detailed analysis of the strength development over time. To ensure data accuracy, five cubes were cast for each duration. The compressive strength of these five cubes was then averaged to provide a single, representative data point for each curing time. This approach helps account for minor variations within a single batch of concrete and strengthens the overall analysis of the relationship between curing time and compressive strength.

2.4 Model Formulation

To explore the relationships between concrete strength and the ponding curing period, a cubic regression model equation analysis was performed using Minitab software. Minitab employs multiple linear regression and utilizes a statistical approach to allow for the creation of mathematical models. It's a mathematical formula used to describe the correlation between (independent variable) and (dependent variable) (y).

$$y = a + bx + cx^2 + dx^3 \qquad (1)$$

Where:

y – (dependent variable), x – (independent variable)

a – (intercept), b – (coefficient of the linear term)

c – (coefficient of the quadratic term)

d – (coefficient of the cubic term)

3 RESULTS AND DISCUSSION

3.1 Materials characterization

3.1.1 Sieve Analysis (Sand)

Table 1, shows a gradation test to analyze the particle size range of the material. No material was retained on the largest sieve (5 mm), indicating all particles are smaller than 5 millimetres. The highest weight (137.1 g) was retained on the 0.425 mm sieve, suggesting a significant portion of the particles fall within this size range. As the sieve size decreases, the weight retained generally decreases, signifying a diminishing amount of larger particles. Figure 1, which is the Sieve Analysis graph for sand visually depicts the percentage of material passing through each sieve size. The relatively smooth curve suggests a continuous distribution of particle sizes across the range analyzed. Thus, the sand falls under the classification of medium, or fine sand according to the particle size limits outlined in Table 4 of BS 882-103.1.

Table 1. Sieve Analysis for fine aggregate (sand)

Sieve size (mm)	Weight retained (g)	Percentage retained (%)	Cumulative percentage retained (%)	Percentage passing (%)
5	0.00	0	0	100
3.35	4.40	0.88	0.88	99.12
2	17.40	3.48	4.36	95.64
1.18	34.30	6.86	11.22	88.78
0.85	40.30	8.06	19.28	80.72
0.6	96.20	19.24	38.52	61.48
0.425	137.10	27.42	65.94	34.06
0.3	98.10	19.62	85.56	14.44
0.15	64.50	12.9	98.46	1.54
0.075	5.60	1.12	99.58	0.42
Pan	2.10	0.42	100	0

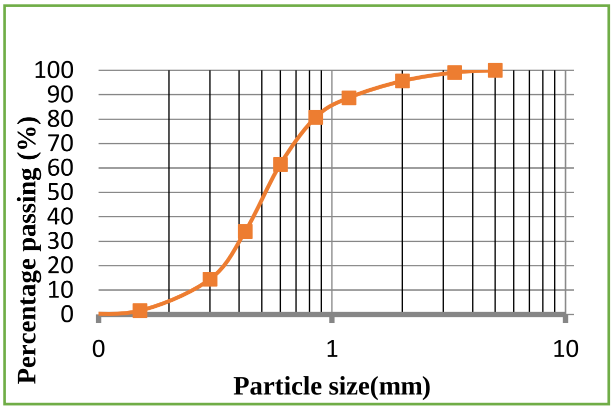

Figure 1: Sieve Analysis graph for sand

3.1.2 Sieve Analysis (granite)

Table 2, shows the Sieve analysis results for coarse aggregate, revealing that all particles were smaller than 28 mm, with no material retained on the largest sieve. The highest weight (476.4 g) was retained on the 14 mm sieve, indicating a significant portion of the material falls within the 14-20 mm size range. As the sieve size decreased, the weight retained generally decreased, signifying a diminishing amount of larger particles. This trend is particularly evident in the sharp drop between the 14 mm and 10 mm sieves. The corresponding graph visually confirms this, with a steep initial curve for percentage passing versus particle size, flattening out around 10 mm. This suggests a concentration of particles in the 14-10 mm range, with a smaller fraction of finer particles.

Table 2. Sieve Analysis for coarse aggregate (granite)

Sieve size (mm)	Weight retained (g)	Percentage retained (%)	Cumulative percentage retained (%)	Percentage retained (%)
28	0	0	0	100
20	403.1	40.31	40.31	59.69
14	476.4	47.65	87.96	12.04
10	107.1	10.72	98.68	1.32
6.3	12.5	1.26	99.94	0.06
5	0	0	99.94	0.06
3.35	0	0	99.94	0.06
pan	0.4	0.06	99.99	0.00

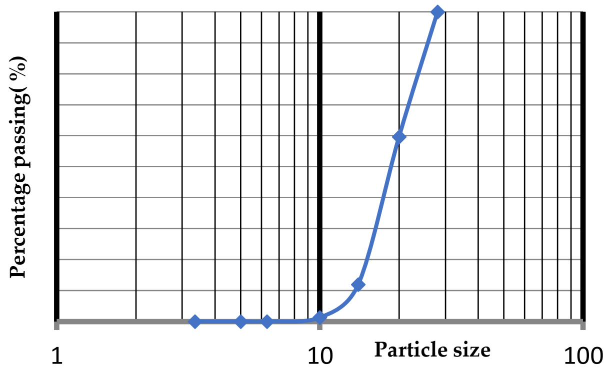

Figure 2: Sieve Analysis graph for granite

3.2 Compressive Strength

Table 3 – table 10, shows the compressive strength of concrete cubes cured for a period of 3, 7, 11, 14, 18, 21, 25, and 28 days respectively.

Table 3. Compressive strength for three (3) days curing period

S/N	CURING AGE (days)	CUBE AREA (mm²)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm²)	AVERAGE (N/mm²)
1			227	10.09	
2			218	9.69	
3	3	22500	243	10.80	10.12
4			255	11.33	
5			196	8.71	

Table 4. Compressive strength for seven (7) days curing period

S/N	CURING AGE (days)	CUBE AREA (mm²)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm²)	AVERAGE (N/mm²)
1			375	16.67	
2			389	17.29	
3	7	22500	401	17.82	17.04
4			358	15.91	
5			394	17.51	

Table 5. Compressive strength for eleven (11) days curing period

S/N	CURING AGE (days)	CUBE AREA (mm²)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm²)	AVERAGE (N/mm²)
1			427	18.98	
2			408	18.13	
3	11	22500	442	19.64	18.73
4			399	17.73	
5			431	19.16	

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Table 6. Compressive strength for fourteen (14) days curing period

S/N	CURING AGE (days)	CUBE AREA (mm^2)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm^2)	AVERAGE (N/mm^2)
1			469	20.84	
2			507	22.53	
3	14	22500	498	22.13	21.32
4			448	19.91	
5			476	21.16	

Table 7: Compressive strength for eighteen (18) days curing period

S/N	CURING AGE (days)	CUBE AREA (mm^2)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm^2)	AVERAGE (N/mm^2)
1			478	21.24	
2			485	21.56	
3	18	22500	502	22.31	21.52
4			493	21.91	
5			463	20.58	

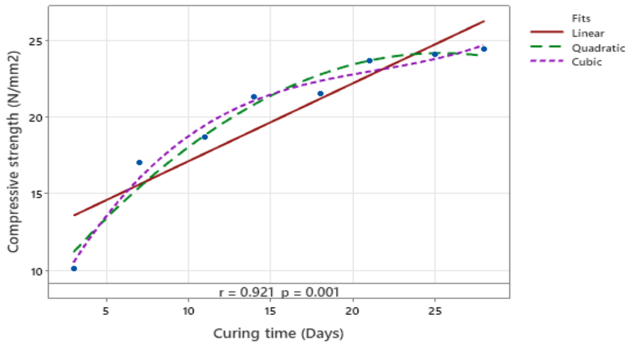
Table 8. Compressive strength for twenty-one (21) days curing period

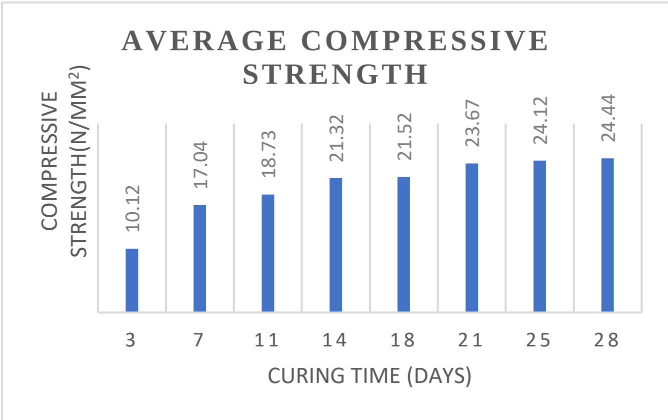
S/N	CURING AGE (days)	CUBE AREA (mm^2)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm^2)	AVERAGE (N/mm^2)
1			558	24.80	
2			539	23.96	
3	21	22500	524	23.29	23.67
4			556	24.71	
5			486	21.60	

Table 9. Compressive strength for twenty-five (25) days curing period

S/N	CURING AGE (days)	CUBE AREA (mm^2)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm^2)	AVERAGE (N/mm^2)
1			542	24.09	
2			534	23.73	
3	25	22500	559	24.84	24.12
4			532	23.64	
5			546	24.27	

Table 10: Compressive strength for twenty-eight (28) days curing period





S/N	CURING AGE (days)	CUBE AREA (mm^2)	LOAD AT FAILURE (KN)	COMPRESSIVE STRENGTH (N/mm^2)	AVERAGE (N/mm^2)
1			548	24.36	
2			553	24.58	
3	28	22500	559	24.84	24.44
4			556	24.71	
5			533	23.69	

From the tables, curing time directly impacts concrete strength, with longer durations leading to higher strength this is because of the hydration process, Concrete's hardening is due to hydration, a chemical reaction between cement and water continues for several days after the concrete is poured, supporting previous findings by Kumar et al. (2012)

Figure 3: Average compressive strength

The histogram in Figure 3, shows the average compressive strength of concrete over a 28-day curing period. The data reveals a positive association between curing time and concrete strength. From Figure 1, it can also be seen that the average compressive strength for ages 3, 7, 11, 14, 18, 21,

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25 and 28 days are 10.12, 17.04, 18.73, 21.32, 21.52, 23.67,24.12, 24.44 KN/m² respectively.

3.2 Correlations between average compressive strength, and curing days.

Figure 4 and Table 11, show a matrix plot showing the relationship between curing days and average compressive strength. It also includes a 95% confidence interval (CI) for the Pearson correlation coefficient. Data in the figure reveals a strong positive correlation between curing days and average compressive strength. The Pearson correlation coefficient (r) is 0.921, which is very close to 1. A perfect positive correlation would be indicated by a value of 1. The analysis yielded a 95% confidence interval for the Pearson correlation coefficient between 0.616 and 0.986. This means that we are 95% confident that the true correlation coefficient between curing days and corn strength falls within this range. Overall, the graph shows a strong positive correlation between curing days and average compressive strength. This means that as the number of curing days increases, the average compressive strength also tends to increase.

Table 11: Pairwise Pearson Correlations

Sample 1	Sample 2	N	Correlation	95% CI for ρ	P-Value
Compressive strength (N/mm2)	Curing time (Days)	8	0.921	(0.616, 0.986)	0.001

3.3 Regression Analysis Results

Table 12, evaluates how well the model fits the data. The standard error of the estimate (S) indicates the average difference between the model's predictions and the actual measurements. A lower standard error of the estimate (S) signifies a better model fit. This indicates that the model's predicted values are closer to the actual observed values of the compressive strength. R-squared (R^2) is a score that shows how well the model explains the data. A value closer to 1 means the model explains the data almost perfectly, while 0 means it has no explanatory power. Here, the R-squared value is 0.9803 (or 98.03%), which suggests a very strong positive relationship between curing days and the dependent variable. While R-squared tells us how well a model fits the data, adjusted R-squared takes into account the model's complexity. It does this by penalizing models with more terms, helping us avoid overfitting. Overfitting happens when a model memorizes the training data too closely and may not perform well on new, unseen data. Here, the adjusted R-squared value (0.9655 or 96.55%) is still very high, indicating that the model explains a large portion of the variance while considering the model complexity. Table 10, suggests that the model has a very strong fit (based on R-squared). The adjusted R-squared value is also high, indicating that the model complexity is likely not a major concern.

Table 12: Model summary

S	R-sq	R-sq(adj)
0.894215	98.03%	96.55%

Figure 5, shows a fitted line plot showing the relationship between compressive strength and curing time for concrete cubes. The red line represents the average compression strength, the green line is the confidence interval (CI) and the purple line indicates the prediction interval (PI). The red line shows that the compressive strength of the concrete cubes increases as the curing time increases. This is a typical relationship for concrete as it cures. The R-squared value (98.0%) and adjusted R-squared value (96.5%) are shown in the graph. These values indicate a very strong correlation between the curing time and the compressive strength. Overall, the graph suggests that curing concrete cubes for longer durations results in stronger concrete. The data reveals a clear relationship between curing time and predicted compressive strength.

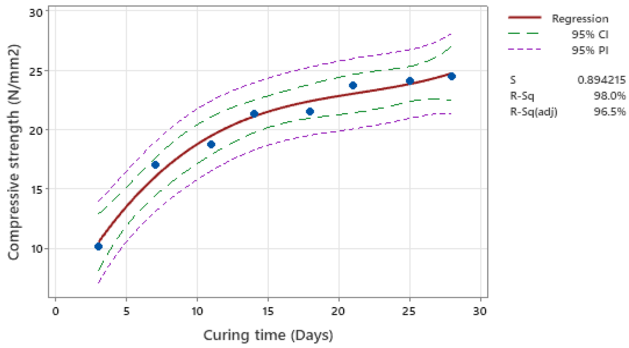

Figure 5: Fitted Line Plot

Table 13, provides the results of the (ANOVA) test, based on this ANOVA table, the fitted model explains a significant portion of the variation in compressive strength (p-value < 0.001). There's very little unexplained variation (Error MS). The high F-statistic (66.23) further supports this conclusion. The curing time has a statistically significant impact on the compressive strength of the concrete cubes, as predicted by the fitted model.

Table 13: Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	158.885	52.9616	66.23	0.001
Error	4	3.198	0.7996		
Total	7	162.083			

3.4 Regression Equation

The equation is a mathematical model that captures how the curing time influences the compressive strength of

concrete cubes. It considers not only a linear increase but also a diminishing rate of gain and slight deviations from a perfect quadratic relationship.
The regression equation generated for the linear model is as follows:

$$C_S = 4.723 + 2.196C - 0.09377C^2 + 0.001459C^3 \quad (2)$$

Where:
C_S =Compressive strength (N/mm^2)
C = Curing time (days)

Equation 2, is a cubic regression equation that predicts the compressive strength of concrete cubes based on their curing time. The value 4.723 is the intercept it represents the predicted compressive strength when the curing time is 0 days. In reality, concrete cannot achieve strength without curing time, so this value is more theoretical than practical. The term "2.196 C" represents the linear effect of curing time on compressive strength. With a positive coefficient, it indicates that as the curing time increases, the compressive strength also increases. "-0.09377 C^2" This term accounts for the curvature in the relationship between curing time and compressive strength. The negative coefficient suggests that the rate of strength gain slows down over time (diminishing returns). This term captures the fact that concrete won't gain strength infinitely as curing time increases. "0.001459C^3" is a cubic term and it's much smaller than the other terms. It captures any minor deviations from a purely quadratic relationship. It may account for slight variations in the strength gain pattern that the quadratic term doesn't fully capture.

4.0 CONCLUSION

This statistical analysis has conclusively demonstrated a strong positive correlation between curing time and the compressive strength of concrete. The data revealed a progressive increase in compressive strength as the curing duration extended. This aligns with established principles of concrete science, where hydration reactions continue for days after casting, fostering a denser and more robust microstructure.

The employed statistical techniques, including correlation analysis and regression modeling, provided valuable insights. The Pearson correlation coefficient of 0.921 indicated a very strong positive relationship between curing time and compressive strength. The high R-squared values (0.9803 and 0.9655) obtained from the regression analysis further reinforced this association. The fitted regression equation provided a mathematical model to estimate compressive strength based on curing time, allowing for informed predictions.

These findings offer significant benefits for the construction industry. By understanding the impact of curing time on concrete strength, practitioners can optimize curing practices to achieve desired strength levels within specific timeframes. This translates to efficient project schedules, cost savings, and ultimately, the construction of durable and safe concrete structures.

Furthermore, the statistical analysis methodology employed in this study paves the way for future investigations. By incorporating additional variables like concrete mix design and environmental conditions, a more comprehensive understanding of factors influencing concrete strength can be achieved. This will lead to further advancements in concrete technology and construction practices.

4.1 Recommendations

- Multiple curing methods: The research should be expanded to investigate the relationship between curing time and compressive strength for various curing methods used in practice.
- Real-world conditions: Studies should incorporate real-world curing environments to account for the variability in temperature, humidity, and wind exposure that can impact concrete curing.

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