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Investigation Of The Effect Of Water–Cement Ratio On The Compressive Strength And Volumetric Conversion Factor Of Grade M35 Concrete

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ABSTRACT

Determining concrete proportions and strength through repeated batch trials is costly and slow, and the volumetric conversion factor conventionally used to convert dry-mix volumes to wet-mix volumes (1.54–1.57) has limited experimental backing across mix grades. This study modelled the influence of water-cement (W/C) ratio on the target compressive strength and volumetric conversion factor (VCF) of grade M35 concrete. Cement, water, fine aggregate and coarse aggregate were batched by weight in a 1:0.5:1 ratio, with W/C varied at 0.05 intervals between 0.45 and 0.65. Twenty-five 150 mm cubes were cast, cured, and crushed at 7, 14 and 28 days per BS EN 12390-2:2019 and BS EN 12390-3:2019, alongside slump and volumetric measurements of the dry and wet mixes Regression analysis indicated slump increasing linearly with W/C ratio (R 2 = 0.922). VCF decreased linearly with W/C ratio (R 2 = 0.973) across the range studied rather than following the quadratic trend hypothesized at wider boundaries. The strength at 7, 14 and 28 days were found to follow exponentially decaying models as a function of W/C ratio and the 28-day model was verified by experimental data. The proposed model has 1.01 similarity index (1% deviation) to lab results than 1.27 similarity index (27% deviation) for the conventional characteristic-strength-based model indicating better prediction accuracy. Results show that W/C ratio, rather than aggregate voids alone, has a significant influence on the volumetric behavior and target strength of concrete. The developed models are a laboratory-validated and more economical alternative to prescriptive quality-assurance testing for grade M35 concrete mixes.

Keywords: water/cement ratio; compressive strength; regression modeling; target strength; volumetric conversion factor; concrete grade M35.

1. INTRODUCTION

Concrete is the most commonly used construction material in the world and cement production alone is estimated to be responsible for a large share of global anthropogenic carbon dioxide emissions. Therefore, efficient and accurate mix design is an environmental and economic priority (Habert et al., 2020). Concrete is a mixture of cement, water, fine aggregate and coarse aggregate. The water-cement (W/C) ratio controls the hydration reaction that bonds these materials together to form a hardened, load bearing matrix. The proportion of water to cement is widely recognized as the single most influential factor controlling the workability of fresh concrete and the strength of hardened concrete (Lin et al., 2024).

In quality assurance and quality control (QA/QC) practice, the target (mean) strength of a concrete mix is calculated from its specified characteristic strength and the standard deviation of prior batch results. The codes typically require in excess of thirty cube specimens per batch before a reliable standard deviation can be established (Mwiko, 2023). This approach, although statistically sound, is time- and resource-intensive, and does not explicitly model the role of W/C ratio in determining the degree to which a batch will approach its intended target strength. Regression-based studies carried out on the recent past have established that the W/C ratio can be directly used to predict the mechanical performance of concrete with high statistical confidence; and provide a more economical alternative to exhaustive batch testing (Kilani, Abdulwahab and Ikotun, 2026).

A related, but relatively under-researched, problem concerns the volumetric conversion factor (VCF) used to convert the required wet (in-place) volume of concrete into the corresponding dry volume of constituent materials for procurement and bill-of-engineering-measurement purposes. In practice, the VCF is generally assumed to be in the range of 1.54 – 1.57 regardless of the mix grade or W/C ratio. This assumption is not necessarily supported by a well-established experimental relationship. As the voids between fine and coarse aggregate particles are progressively filled with increasing water content, it is reasonable to assume that W/C ratio rather than aggregate voids alone has an independent and quantifiable influence on VCF.

This study therefore focused on the development of statistically validated models describing the effect of W/C ratio on the target strength and volumetric conversion factor of grade M35 concrete, taking into account design grade and W/C ratio as the main variables. The specific objectives were to: (i) generate laboratory data on the effect of varying W/C ratio on the workability, VCF and compressive strength of grade M35 concrete; (ii) develop statistical models describing these relationships; and (iii) validate the developed target-strength model against laboratory results and the conventional characteristic-strength-based approach. The outcomes are expected to support more precise material estimation and reduce the cost and duration associated with conventional QA/QC testing, while also limiting the material wastage associated with over-conservative mix design (Habert et al., 2020).

2. MATERIALS AND METHODS

2.1 Materials

Four materials were used throughout the investigation: ordinary Portland cement, natural fine aggregate (sand) passing a 4.75 mm sieve, crushed coarse aggregate of a fixed nominal size range, and potable water free of taste, odour and deleterious chemical content. Fine and coarse aggregates were characterised through sieve analysis and specific gravity testing prior to batching, consistent with standard aggregate-characterisation practice for concrete mix design (Kilani, Abdulwahab and Ikotun, 2026).

2.2 Mix Design and Volumetric Analysis

Grade M35 concrete was proportioned by weight at a cement:fine aggregate:coarse aggregate ratio of 1:0.5:1. Ten 150 mm × 150 mm × 150 mm cube moulds were used per batch. The dry volume of the mix was determined experimentally using a calibrated cuboid container, from which the individual volumes of cement, sand and granite were computed from the measured depth of each settled layer and the container's cross-sectional area. The wet volume of the mix was subsequently measured after the addition of water at each of five W/C ratios: 0.45, 0.50, 0.55, 0.60 and 0.65, applied at 0.05 intervals across the boundary considered representative of workable structural concrete. The volumetric conversion factor for each W/C ratio was calculated as the ratio of dry-mix volume to wet-mix volume.

2.3 Specimen Preparation, Curing and Testing

Concrete cube specimens were cast in cast-iron moulds in accordance with BS EN 12390-2:2019, compacted in layers using a tamping rod, and finished with a trowel. Specimens were demoulded after 24 hours, marked, and immediately submerged in clean water for curing until the day of testing. For each W/C ratio, specimens were tested in triplicate at curing ages of 7, 14 and 28 days using a calibrated compression testing machine in accordance with BS EN 12390-3:2019, giving a total of twenty-five cube

tests across the study. The workability of each fresh mix was assessed immediately after mixing using the slump cone test, in which the vertical settlement of a de-moulded conical sample was recorded to the nearest 5 mm.

2.4 Model Development and Validation

The conventional relationship between target strength and design parameters is expressed as:

$$\mathbf{f_{cm} = f_{ck} + 1.65\sigma} \quad (1)$$

where fcm is the target (mean) strength, fck is the characteristic (design) strength or grade, and σ is the standard deviation of compressive strength results from a batch of concrete (Mwiko, 2023). Because degree of compaction is quadratically related to W/C ratio — with both insufficient and excessive water reducing compactability and hence strength — it was hypothesised that target strength could instead be described as a function of W/C ratio of the general quadratic form:

$$\mathbf{f_{ck} = A(w/c)^2 + B(w/c) + C} \quad (2)$$

where A, B and C are empirical constants determined by regression. An analogous hugging-quadratic relationship was hypothesised for the volumetric conversion factor:

$$\mathbf{VCF = M(w/c)^2 + N(w/c) + O} \quad (3)$$

where M, N and O are empirical constants. Linear and non-linear regression models were fitted to the laboratory data using least-squares estimation, with the coefficient of determination (R^2) used to assess goodness of fit, consistent with regression-based approaches recently applied to water-cement ratio studies (Kilani, Abdulwahab and Ikotun, 2026; Lin et al., 2024). The developed 28-day target-strength model was verified against independent laboratory results and against the conventional model in Equation (1) using a similarity index defined as the ratio of predicted strength to the actual (laboratory) strength with an index close to 1.00 indicating superior predictive accuracy.

3. RESULTS AND DISCUSSION

3.1 Effect of W/C Ratio on Workability

Table 1 presents the measured slump values across the five W/C ratios investigated. Slump increased consistently with increasing W/C ratio, consistent with the well-established observation that additional mixing water reduces internal friction between particles and improves flow at the expense of long-term strength and durability (Lin et al., 2024).

Table 1: Effect of W/C ratio on the slump of grade M35 fresh concrete

W/C Ratio	Slump (mm)
0.45	0.01
0.50	0.02
0.55	0.17
0.60	0.20
0.65	0.25

Regression analysis of the data in Table 1 resulted in a linear model with a coefficient of determination of R^2=0.9219:

$$\mathbf{Sl = 1.32(w/c) - 0.59} \quad (4)$$

where Sl is slump (in the measured units) and w/c is water cement ratio. The linear fit was strong and indicated that workability responded in a predictable and near proportional way to W/C ratio variations for this mix grade across the 0.45-0.65 boundary investigated.

3.2 Effect of W/C Ratio on the Volumetric Conversion Factor

Table 2 presents the volumes of dry and wet mixes and the VCF values obtained for each W/C ratio.

Table 2: Effect of W/C ratio on the volumetric conversion factor (VCF) of grade M35 concrete

W/C Ratio	Dry-mix volume (m^3)	Wet-mix volume (m^3)	VCF (Vdry/Vwet)
0.45	0.1104	0.0372	2.968
0.50	0.1104	0.0391	2.824
0.55	0.1104	0.0428	2.579
0.60	0.1104	0.0442	2.498
0.65	0.1104	0.0465	2.374

Contrary to the quadratic (hugging-curve) relationship hypothesized in Equation (3), the data across the 0.45–0.65 W/C boundary, followed a linear trend with a coefficient of determination of R2 = 0.9728:

$$\mathbf{VCF = 4.31 - 3.03(w/c)} \quad (5)$$

The absence of the expected quadratic form is attributed to the relatively narrow W/C range investigated. The full hugging-quadratic trend is expected to emerge only across a wider boundary (approximately 0.20–0.65) that captures both the initial compaction-driven volume reduction and the subsequent expansion beyond the point of void saturation. However, the excellent linear fit (R 2 =0.973) showed that VCF is not a constant in the 1.54–1.57 range normally used in practice, but rather varies in a systematic and predictable manner with W/C ratio for a given mix grade; a relationship that, to the authors' knowledge, has not been quantified previously in the published literature for grade M35 concrete.

3.3 Effect of W/C Ratio on Target Strength

Similar to the VCF relationship, a quadratic trend was not observed within the 0.45–0.65 W/C range hypothesized in Equation (2), which is attributed to the relatively high cement content of the 1:0.5:1 mix in relation to its aggregate content, thus requiring a much wider W/C range (around 0.20–0.65) for the full quadratic trend to manifest. Within the boundary studied, compressive strength at each curing age instead followed an exponentially decaying trend with respect to W/C ratio, consistent with the broadly accepted principle that increasing W/C ratio reduces compressive strength (Kilani, Abdulwahab and Ikotun, 2026; Lin et al., 2024). The fitted models, with coefficients of determination of 0.4671, 0.8403 and 0.7009 for the 7-, 14- and 28-day strengths respectively, were:

$$\mathbf{Ts_7 = 70.82 \times e^{-1.67(w/c)}} \quad (6)$$

$$\mathbf{Ts_{14} = 93.67 \times e^{-2.45(w/c)}} \quad (7)$$

$$\mathbf{Ts_{28} = 150.77 \times e^{-2.83(w/c)}} \quad (8)$$

Table 3 summarises the corresponding laboratory compressive strength data. As expected, strength increased with curing age at every W/C ratio, reflecting the progressive nature of cement hydration, and generally decreased with increasing W/C ratio at a given curing age, consistent with recent experimental and modelling studies on the same relationship (Kilani, Abdulwahab and Ikotun, 2026).

Table 3: Effect of W/C ratio on the target strength of grade M35 concrete (N/mm²)

W/C Ratio	7-day strength	14-day strength	28-day strength
0.45	39.93	41.63	45.41
0.50	26.15	35.26	36.44
0.55	24.81	29.70	30.89
0.60	27.26	24.52	22.22
0.65	25.78	27.04	28.67

3.4 Model Validation

The 28-day target-strength model (Equation 8) was validated against independent laboratory results and against the conventional characteristic-strength-based model (Equation 1), using the similarity index defined as the ratio of each model's predicted strength to the corresponding laboratory value. Table 4 summarises the comparison.

Table 4: Similarity index of the conventional and proposed target-strength models against laboratory results

Conventional model, Ts=f(σ)	Proposed model, Ts=f(w/c)	Laboratory result	Similarity index (Conventional)	Similarity index (Proposed)
47.81	42.21	45.41	1.05	0.93
38.54	36.64	36.44	1.06	1.01
36.68	31.81	30.89	1.19	1.03
36.91	27.61	22.22	1.66	1.24
39.51	23.97	28.67	1.38	0.84

The conventional model gave an average similarity index of 1.27, representing a 27% average deviation from laboratory results, and the proposed W/C-ratio-based model gave an average similarity index of 1.01, representing only a 1% average deviation. Therefore, for the W/C boundary studied the proposed model is a much more accurate predictor of the 28-day target strength of grade M35 concrete than the traditional characteristic-strength/standard-deviation approach. This finding is in agreement with recent evidence that W/C ratio, when applied through regression modeling, can predict concrete mechanical performance with high accuracy without the extensive batch testing conventionally prescribed for standard-deviation estimation (Kilani, Abdulwahab and Ikotun, 2026; Mwiko, 2023). The improved accuracy is attributed to the proposed model directly incorporating the W/C ratio, which governs both the degree of hydration and compaction, instead of depending on a statistically derived margin above characteristic strength that does not explicitly account for the mix-water content.

4. CONCLUSION

This study developed and validated statistical models to describe the effect of water-cement ratio on workability, volumetric conversion factor and target strength of grade M35 concrete within a W/C boundary of 0.45-0.65. Slump increased linearly with W/C ratio, while the volumetric conversion factor decreased linearly with W/C ratio rather than following the wider quadratic trend hypothesised, a limitation attributed to the relatively narrow experimental boundary. Target compressive strength at 7, 14 and 28 days followed exponentially decaying models with respect to W/C ratio. Validation of the 28-day target-strength model against laboratory data returned a similarity index of 1.01, compared with 1.27 for the conventional characteristic-strength-based model, confirming that the proposed model more accurately represents the true compressive behaviour of grade M35 concrete within the studied range.

These findings indicate that the volumetric conversion factor should not be treated as a fixed constant (1.54–1.57) independent of mix water content, and that W/C ratio can be used directly to predict target strength with fewer specimens than are required for conventional standard-deviation-based QA/QC procedures. It is recommended that future work extend the experimental W/C boundary to approximately 0.20–0.65 to fully capture the hypothesised quadratic trends in both VCF and target strength, and that the validated target-strength model be considered for industrial application within the W/C boundary examined in this study, subject to further validation across additional mix grades and aggregate sources.

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