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# Compressive Strength Analysis of Solid Cylindrical Concrete K250 and K300: Effect of Curing Method on 28-Day Performance

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**Abstract**

**Purpose**: This study aims to determine and analyze the compressive strength of K250 and K300 concrete cylindrical specimens tested at 28 days, and to explain the mechanism by which differential curing methods applied to the two grades produced counterintuitive strength outcomes in the context of a nuclear technology education facility.

**Methodology**: Compressive testing was conducted on five K250 and five K300 concrete cylindrical specimens (diameter 150 mm x height 300 mm) at 28 days using a Cernusco Compression Testing Machine (Model 20063). K250 specimens underwent 28-day continuous water immersion, whereas K300 specimens received only ambient air curing from the date of casting. Compressive strength values were recorded, group means were computed, and results were compared against design strength targets per PBI 1971.

**Results**: K250 water-cured specimens produced a mean compressive strength of 346.28 kg/cm², exceeding the 250 kg/cm² design target by 38.5%. Air-cured K300 specimens attained only 287.87 kg/cm², falling below their 300 kg/cm² design target, resulting in K250 outperforming K300 by 58.41 kg/cm².

**Conclusions**: Curing method overrides nominal mix design grade as the controlling determinant of 28-day compressive strength.

**Limitations**: The small sample of five specimens per grade and the absence of controlled mix design parameters limit generalizability.

**Contributions**: This study provides an empirical case study of the compressive strength consequences of differential curing conditions on K250 and K300 concrete, offering practical evidence for construction quality control protocols in nuclear technology and general engineering facility contexts.

**Keywords:** *Cement Hydration, Compressive Strength, Concrete Curing, Cylindrical Specimens*

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## 1. Introduction

Concrete stands as the most extensively used construction material across the globe, underpinning infrastructure ranging from residential dwellings and high-rise commercial buildings to bridges, hydraulic structures, tunnels, and specialized nuclear technology facilities. Its widespread adoption is driven by the relative abundance of constituent raw materials, versatility in shape and form, and the capacity to be engineered to a broad range of compressive strength targets through careful mix design. According to SNI 03-2847-2013, concrete is defined as a composite mixture of Portland cement or other hydraulic cement, fine aggregate, coarse aggregate, and water, with or without supplementary admixtures (Badan, 2013). The mechanical behavior of hardened concrete in particular its compressive strength emerges from complex interactions among cement chemistry, aggregate characteristics, water-to-cement ratio, and the quality of the curing regime applied during the critical early hydration period (Mehta, & Monteiro, 2014; Alaskar, Albidah, Alqarni, & Alyousef, 2021; (Badan, 2013).

The global construction industry consumes roughly four billion metric tons of cement annually, producing concrete in volumes that dwarf any other manufactured material. Within Indonesia alone, rapid infrastructure expansion programs including the National Strategic Projects (Proyek Strategis Nasional) have elevated demand for reliable medium-grade concrete such as K250 and K300, both of which are specified in major reinforced concrete applications including bridge decks, retaining walls, precast elements, and industrial floor slabs (Mulyono, 2021). Ensuring that these grades consistently achieve their specified compressive strength at 28 days is not merely an academic exercise it is a structural safety requirement with direct implications for the serviceable life and integrity of engineered systems (Imran, & Zulfiar, 2021; Behera, & Bahoria, 2022).

Within the Indonesian K-grade concrete classification system established under PBI 1971, the designation K250 implies a characteristic compressive strength of 250 kg/cm² (equivalent to f'c = 21 MPa under SNI 2847:2013), while K300 denotes a characteristic compressive strength of 300 kg/cm² (f'c = 24 MPa). The higher cement content per unit volume in K300 relative to K250 is the primary mix design mechanism through which the higher strength target is pursued. Under ideal conditions when both grades are subjected to proper curing protocols the hierarchy is expected to hold: K300 should outperform K250 in compressive strength at 28 days. However, this hierarchy is contingent on a critical assumption: that curing conditions are equivalent and adequate for both grades (Husaini, Mahyiddin, & Alwi, 2022; Alogla, & Alotaibi, 2022).

Curing refers to the practice of maintaining adequate moisture and temperature conditions in freshly placed concrete to sustain the cement hydration reaction throughout the design period. Cement hydration the chemical reaction between Portland cement compounds and water is the fundamental process through which concrete gains strength. Calcium silicate hydrate (C-S-H) gel, the primary strength-forming reaction product, develops progressively over weeks, with the majority of 28-day strength achieved within the first 14 days of curing. Any interruption of this process caused by premature moisture loss through evaporation produces a permanent and irreversible reduction in compressive strength that cannot be remedied by subsequent rewetting (Mindess, Young, & Darwin, 2021; Bui, Satomi, & Takahashi, 2022; Choorackal, Schmid, Terzic, & Bhatt, 2022).

Despite the well-established scientific consensus on the critical importance of curing, field practice frequently diverges from recommended standards. In construction projects operating under time and resource constraints, curing is sometimes applied inconsistently across concrete elements with some members receiving systematic water immersion or wet curing while others are left to ambient exposure. The consequences of this inconsistency are compounded when two concrete grades of nominally different quality are prepared in the same project, because the grade with less intensive curing may underperform relative to the grade that received proper curing, regardless of mix design superiority (Salain, 2022).

This study documents and analyzes precisely such a scenario, observed at Politeknik Teknologi Nuklir Indonesia (PTNI) in Yogyakarta, Indonesia. Two groups of five cylindrical specimens each one group cast to K250 specification, the other to K300 specification were produced in the same testing program but subjected to fundamentally different curing conditions: continuous 28-day water immersion for K250 specimens and ambient air storage without water immersion for K300 specimens. The resulting compressive strengths were evaluated at 28 days using a Cernusco Compression Testing Machine (Model 20063), with capping performed using sulfur mortar per SNI 1974:2011. The results revealed a striking reversal of expected strength hierarchy that provides a vivid empirical illustration of the primacy of curing in governing real-world concrete compressive strength outcomes (Badan, 2011; Das, Singh, & Bhattacharyya, 2021; Divsholi, & Lim, 2022).

The significance of this finding extends beyond the immediate testing context. In nuclear technology facility construction, the primary operational setting of PTNI structural concrete elements is required to meet stringent performance criteria not only for conventional load-carrying capacity but also for radiation shielding density and long-term durability under radiation and thermal loading. In such environments, the assumption that a specified higher concrete grade will necessarily outperform a lower grade in the field is particularly dangerous if curing practices are inconsistent (Lacoste, Marrache, & Diong, 2021). The present study thus contributes both empirical data and analytical context to the ongoing conversation about concrete quality assurance in critical infrastructure construction.

## 2. Literature Review and Hypothesis/es Development

### *2.1 Compressive Strength and Design Grades in Indonesian Concrete Standards*

The Indonesian concrete grading system (K-system) was established under the Peraturan Beton Indonesia 1971 (PBI 1971 N.I.-2) and designates concrete by its characteristic compressive strength in kg/cm² at 28 days, determined through compression testing of either 15 cm × 15 cm cube specimens per PBI 1971 or 15 cm × 30 cm cylindrical specimens per SNI 1974:2011 (Badan, 2011). The characteristic strength is defined as the statistical value below which only 5% of test results are expected to fall, representing a quality assurance threshold rather than a simple average. The conversion relationship between the K-system and the MPa-based f'c system adopted in SNI 2847:2013 is approximately K250 = f'c 21 MPa and K300 = f'c 24 MPa, derived from the cylindrical-to-cube strength ratio and unit conversion factors (Mulyono, 2021).

Both K250 and K300 are classified as medium-quality structural concrete and are widely specified for reinforced concrete applications in Indonesia, including bridge decks, culvert structures, precast elements, and industrial buildings. The distinction between the two grades lies primarily in the Portland cement content per cubic meter of concrete: K300 incorporates a higher cement dose than K250, reflecting the fundamental principle that higher paste density and lower water-to-cement ratio yield greater compressive strength potential. Husaini et al. (2022) demonstrated that optimal cement dosage combined with appropriate water-to-cement ratios consistently achieves the nominal K-grade strength target when curing conditions are maintained, underscoring that mix design and curing are jointly necessary conditions for design strength achievement (Elahi, Shearer, Saha, Khan, Hossain, & Sarker, 2021).

Concrete compressive strength development follows a characteristic time-strength curve, progressing from approximately 40% of 28-day strength at 3 days, 70% at 7 days, and reaching near-full design strength at 28 days, with slow continued strength gain thereafter. This curve assumes adequate moisture and temperature conditions throughout. Deviations from design-level curing particularly moisture loss in the early hydration period shift the strength-time curve downward, resulting in a reduced asymptote and permanently compromised 28-day performance (Imran & Zulfiar, 2021). Understanding this time-dependent behavior is essential for interpreting test results obtained at any age other than 28 days and for evaluating the long-term structural implications of suboptimal early curing.

### *2.2 The Critical Role of Curing in Concrete Strength Development*

Water is the critical reactant in the cement hydration reaction not merely a processing aid for workability. The hydration of Portland cement clinker minerals (Tricalcium Silicate, Dicalcium Silicate, Tricalcium Aluminate, And Tetracalcium Aluminoferrite) produces calcium silicate hydrate (C-S-H) gel and calcium hydroxide ($Ca(OH)2$) as primary reaction products. C-S-H gel is the strength-forming phase, building a dense interlocked microstructure that physically resists compressive loading. This reaction requires continuous water availability at the capillary pore level throughout the hydration period (Mindess, Young, & Darwin, 2021). When the relative humidity within concrete drops below approximately 80%, hydration effectively ceases not because the reaction is complete, but because insufficient water remains to sustain it (Garg & Garg, 2022).

Curing methods that maintain external moisture supply including water immersion, ponding, wet curing blankets, and fogging prevent or minimize the internal humidity reduction caused by evaporation. Water immersion curing is the most effective method for maintaining saturated surface conditions because the concrete specimen is in continuous contact with free water, enabling osmotic and capillary replenishment of water consumed in the hydration reaction. Studies have consistently documented that water-cured concrete specimens achieve 20 to 30 percent higher compressive strength than identically mixed specimens subjected to air curing without water supply (Neville, 2011; Salain, 2022). The magnitude of this curing effect is amplified in hot and dry ambient conditions, where surface evaporation rates are elevated, and in thin-section elements where the surface-to-volume ratio is high.

Supriani and Islam (2017) investigated concrete curing practices in the Indonesian context, documenting that water-cured specimens follow the PBI 1971 strength-age curve closely, while air-cured specimens show systematically lower and more variable strength due to incomplete hydration. The variability itself not just the mean reduction is a practical concern, because higher variability in compressive strength results in a lower characteristic strength value (the 5th percentile statistical threshold) even when the mean is satisfactory. This means that inconsistent curing can cause concrete to fail the characteristic strength criterion even when average strength appears adequate (Mulyono, 2021).

The ACI Committee 308 Guide to External Curing of Concrete (ACI 308R-16) establishes that continuous moist curing during the first seven days is the minimum standard for achieving design compressive strength at 28 days in ordinary Portland cement concrete. Curing duration should be extended to fourteen days for blended cement concrete or concrete exposed to aggressive environments. The ACI 308R-16 standard further notes that interruption of curing during the early hydration period even temporarily causes irreversible strength loss that cannot be recovered by subsequent rewetting, because once the pore structure partially consolidates through early hydration, the pathway for water redistribution becomes restricted (ACI, 2016).

More recent research has extended the understanding of curing effects to specialized concrete types. Prasetya et al. (2023) examined the influence of wet and dry curing cycles on the compressive strength and porosity of high-performance concrete, finding that intermittent wetting-drying exposure consistently produced lower 28-day compressive strength and higher porosity than continuous wet curing, even when total water availability over the curing period was equivalent. This finding supports the ACI 308R-16 recommendation for uninterrupted curing rather than periodic rewetting. Similarly, Nugroho et al. (2022) reported that concrete specimens left to air cure in Indonesian ambient conditions (average temperature 28-32°C, relative humidity 60-75%) lost approximately 25% compressive strength relative to water-cured control specimens at 28 days, with the deficit attributable primarily to early moisture loss in the first seven days after casting.

### *2.3 Compression Testing of Concrete Specimens per SNI Standards*

Concrete compressive strength testing in Indonesia follows SNI 1974:2011 (Metode pengujian kuat tekan beton), which specifies the use of cylindrical specimens with standard dimensions of 150 mm diameter and 300 mm height (aspect ratio 2:1) for compressive testing. The cylindrical geometry produces a more uniform uniaxial stress state in the specimen during loading compared to cube specimens, reducing the influence of platen friction and end restraint effects on the measured strength. Prior to testing, specimen end surfaces must be capped with sulfur mortar, gypsum paste, or high-strength cement paste to ensure planeness and parallelism, eliminating stress concentrations from surface irregularities that would otherwise cause premature failure at reduced loads (Badan, 2011; Juenger, Snellings, & Bernal, 2019).

The compression testing machine applies a constant loading rate typically 2 to 4 kg/cm² per second until the specimen fails, recording the peak load at failure from which compressive strength is calculated as force divided by cross-sectional area. The failure mode of well-prepared specimens is typically a double cone or hourglass fracture pattern, indicating uniform stress distribution and satisfactory end capping. Premature or irregular failure modes splitting, corner spalling, or diagonal shear fracture may indicate poor capping, specimen eccentricity, or substandard concrete, and should prompt specimen rejection and retesting (Wibowo, Ridlo, & Pamungkas, 2021; Khan, Ahmed, Zafar, & Rasheed, 2022).

The accuracy of compressive strength testing is sensitive to testing machine calibration and loading rate consistency. Wibowo et al. (2021) evaluated the performance of compression testing machines in Indonesian laboratories, finding that machines with outdated calibration certificates and variable loading rate mechanisms produced compressive strength results with up to 8% systematic deviation from reference values obtained on calibrated equipment. This source of measurement uncertainty should be accounted for when interpreting results from any single testing program, including the present study. Machine calibration records for the Cernusco Compression Testing Machine (Model 20063) used in this study were not independently verified, which represents a limitation in the measurement validation chain (Lam, Wong, & Poon, 2022).

Specimen-to-specimen variability in compressive strength testing is inevitable even in nominally identical specimens cast from the same batch, due to microscale heterogeneity in aggregate distribution, minor variations in compaction, and statistical variability inherent in the fracture of quasi-brittle materials. Wirawan, Santoso, and Purnomo (2023) characterized the within-batch variability of K250 and K300 concrete test specimens, reporting coefficients of variation of 4 to 8 percent for well-controlled laboratory specimens, rising to 10 to 15 percent for site-cast specimens subject to greater mixing and placement variability. With only five specimens per grade in the present study, the statistical precision of the computed means is limited, a concern addressed in the limitations section.

### *2.4 Water-to-Cement Ratio and Mix Design Interactions*
The water-to-cement (w/c) ratio is the primary material-level determinant of concrete compressive strength potential, a relationship formalized by Duff Abrams in 1919 and confirmed by over a century of subsequent research. Lower w/c ratios produce a denser paste microstructure, smaller capillary porosity, and higher compressive strength, provided that sufficient water is available for workable placement and that curing sustains hydration to completion. The theoretical strength advantage of K300 over K250 concrete derives precisely from this principle: K300 is formulated with higher cement content and typically a lower w/c ratio than K250, giving it greater strength potential under equivalent curing conditions (Mehta & Monteiro, 2014).

However, the strength potential conferred by a favorable w/c ratio can only be realized if curing conditions support complete hydration of the cement paste. Handayani et al. (2023) demonstrated that a K300 concrete mix with w/c = 0.42 achieved 312 kg/cm² at 28 days under water immersion curing, but only 248 kg/cm² under air curing below even the K250 design target. This result is particularly instructive because it shows that the penalty from inadequate curing can more than offset the strength advantage conferred by a superior mix design. In practical terms, a K250 concrete with proper curing can outperform a K300 concrete without proper curing, as the present study demonstrates.

The interaction between w/c ratio and curing duration has also been explored in the context of Supplementary Cementitious Materials (SCMs). Prasetya et al. (2023) found that fly ash incorporation in K300-equivalent mixes reduced early strength development but improved long-term strength through continued pozzolanic reaction, provided that extended moist curing of at least 14 days was maintained. Under air curing, fly ash concrete showed even greater strength deficits than ordinary Portland cement concrete, because the slow pozzolanic reaction is more sensitive to moisture availability than the primary cement hydration reaction. While the specimens in the present study did not incorporate SCMs, this finding contextualizes the broader principle that mix design sophistication cannot substitute for curing discipline (Alaskar, Albidah, Alqarni, & Alyousef, 2021).

### *2.5 Curing Effects in Nuclear Technology Facility Concrete*

Nuclear technology facilities impose special requirements on structural concrete beyond the standard civil engineering performance criteria. Radiation shielding performance depends on concrete density and atomic composition; biological shielding concrete is specifically formulated with high-density aggregates to maximize gamma and neutron attenuation. Compressive strength, while not the primary shielding parameter, is relevant as an indicator of concrete density and microstructural quality denser, better-hydrated concrete with lower porosity provides superior radiation attenuation per unit thickness (Lacoste, Marrache, & Diong, 2021).

Falakhuddin (2021) conducted radiographic imaging studies of K250 and K300 concrete specimens at PTNI, demonstrating that radiographic density correlates with compressive strength: higher-density concrete (implying lower porosity and more complete hydration) produces both higher compressive strength and better radiation attenuation. This study established a non-destructive quality indicator for concrete at PTNI and provided a basis for comparing the internal quality of different concrete grades and curing conditions. The present study complements by Falakhuddin (2021) radiographic findings by providing direct compressive strength data for K250 and K300 specimens under differential curing conditions, allowing interpretation of the strength differences in terms of microstructural quality.

Lacoste et al. (2021) reviewed curing requirements for concrete in nuclear facility construction, emphasizing that the combination of proper mix design and systematic curing is non-negotiable in safety-critical applications. Structural concrete in nuclear facilities must achieve design compressive strength reliably and without exception, because structural failure in a nuclear facility context could compromise containment integrity or radiation shielding. The consequence of relying on nominal grade specification without verified curing compliance precisely the scenario documented in the present study is that concrete elements may be installed in safety-critical locations with strength well below the design requirement, without any visible indication of deficiency (Qasim & Hussain, 2023).

### *2.6 Summary of Prior Studies*

Table 1. Summary of prior studies on curing effects and concrete grade compressive strength

| Author(s) & Year | Concrete Grade / Focus | Curing Method | Key Finding |
|---|---|---|---|
| Supriani & Islam (2017) | K-grade (general) | Water immersion vs. air curing | Water-cured specimens follow PBI 1971 curve; air-cured show lower and more variable strength |
| Falakhuddin (2021) | K250 and K300 (radiographic) | Standard curing | Radiographic density correlates with compressive strength; density uniformity confirms homogeneous hydration |
| Nugroho et al. (2022) | K250–K300 equivalent | Air curing vs. water curing | Air-cured specimens in tropical ambient conditions lost ~25% compressive strength vs. water-cured controls |
| Handayani et al. (2023) | K300 (w/c = 0.42) | Water immersion vs. air | K300 water-cured achieved 312 kg/cm²; air-cured achieved only 248 kg/cm², below K250 design target |
| Prasetya et al. (2023) | High-performance concrete | Wet/dry cycles vs. continuous wet | Intermittent wetting produces lower strength and higher porosity than continuous moist curing |

Table 1 synthesizes the most directly relevant prior work. Collectively, these studies establish the foundational finding that this article extends: curing method is a primary determinant of concrete compressive strength, capable of overriding mix design grade differences in real-world testing conditions. The present study adds empirical evidence from a nuclear technology education facility context in Indonesia, where the curing method differential was not deliberately controlled but arose from actual laboratory practice, making the findings particularly relevant to quality control applications.

## 3. Research Methodology

### *3.1 Research Design and Setting*

This study employs a comparative laboratory research design, examining the compressive strength outcomes of two groups of concrete cylindrical specimens K250 and K300 that were produced and tested at Politeknik Teknologi Nuklir Indonesia (PTNI), Yogyakarta, Indonesia. The research design is observational rather than fully controlled experimental, in the sense that the differential curing conditions applied to the two groups reflect actual laboratory practice rather than a deliberately assigned treatment. The primary independent variable is the curing method (water immersion versus air curing), and the primary dependent variable is the 28-day compressive strength (kg/cm²). Results are compared against design strength targets per PBI 1971 and against each other to characterize the effect of differential curing on the expected strength hierarchy between the two grades (Wibowo, Ridlo, & Pamungkas, 2021).

### *3.2 Specimen Preparation*

Ten concrete cylindrical specimens were prepared at PTNI: five K250 specimens (Group A) and five K300 specimens (Group B). All specimens were cast with the standard cylindrical dimensions of diameter 150 mm and height 300 mm (aspect ratio 2:1) in accordance with SNI 1974:2011. The concrete mix compositions for K250 and K300 followed standard design mix proportioning per PBI 1971, with K300 incorporating a higher Portland cement content per unit volume to achieve its higher nominal design strength. Portland cement used in both groups met the requirements of SNI 2049:2015 (Ordinary Portland Cement, Type I). Fine and coarse aggregates were obtained from local suppliers and used without grading adjustment beyond standard sieving. Concrete was mixed in a drum mixer to ensure homogeneous distribution of constituents, placed into steel cylinder molds, and consolidated by rodding per SNI 1974:2011. Specimens were demolded at 24 hours after casting and immediately transferred to their respective curing environments.

Table 2. Test specimen specifications

| Group | Concrete Grade | Number of Specimens | Curing Method (28 days) |
|---|---|---|---|
| Group A | K250 (f'c = 21 MPa) | 5 cylinders | Water immersion in fresh water, continuous from demolding to test date |
| Group B | K300 (f'c = 24 MPa) | 5 cylinders | Outdoor air storage, no water immersion, ambient conditions from demolding to test date |
| Both groups | Cylinder dimensions | — | Diameter 150 mm x height 300 mm; sulfur mortar capping prior to testing per SNI 1974:2011 |

Table 2 presents the specimen specifications for both groups. The disparity in curing method between Group A and Group B is the defining characteristic of this study and the variable to which all observed strength differences are attributed. Group A specimens received continuous freshwater immersion a standard and well-established curing method that has been shown to promote complete cement hydration and maximize 28-day compressive strength development (Nugroho, Santosa, & Atmoko, 2022). Group B specimens, by contrast, were stored outdoors in ambient air conditions without any deliberate water supply, exposing them to surface evaporation and the progressive internal moisture reduction that compromises cement hydration in the K300 mix.

### *3.3 Curing Conditions*

K250 specimens were cured by continuous immersion in fresh water from demolding at 24 hours until the 28-day test date, in a dedicated water curing tank maintained at ambient temperature (approximately 27 to 30°C). This curing method is consistent with the standard water curing practice described in SNI 1974:2011 and ACI 308R-16 (2016). The immersion tank was checked daily to ensure that specimens remained fully submerged; evaporative water loss was replenished as needed. K300 specimens were stored outdoors on a wooden pallet in shade-partial conditions, exposed to ambient air at PTNI's Yogyakarta facility. No water was applied to the K300 specimens at any point during the 28-day period from demolding to testing. Ambient temperature during the curing period ranged from approximately 24 to 33°C, with average relative humidity of approximately 65 to 75%, conditions conducive to surface evaporation and internal moisture reduction (Prasetya, Herwono, & Sumardi, 2023).

The experimental design was not controlled for curing as a deliberate variable in the sense of a factorial experiment; rather, the differential curing reflects the actual conditions under which the two groups were prepared, which is the phenomenon this study documents. This distinction is important for interpreting the study's contribution: rather than providing controlled causal evidence in an experimental sense, the study provides an empirical record of the real-world consequences of curing method inconsistence a scenario that occurs routinely in construction practice and whose strength implications are often underappreciated by practitioners (Salain, 2022).

### *3.4 Compression Testing Procedure*

Prior to compression testing, all specimens underwent capping the application of a thin layer of sulfur mortar to the top and bottom bearing faces of each cylinder. The capping process involved melting sulfur mortar compound at approximately 130°C and pouring it into a capping plate, then pressing the cylinder end into the molten sulfur. After solidification, the capped face was inspected visually and by straightedge to confirm planeness within the 0.05 mm tolerance specified in SNI 1974:2011. Proper capping is critical because surface irregularities as small as 0.5 mm can produce stress concentrations that reduce measured compressive strength by 5 to 10 percent relative to a perfectly capped specimen (Wibowo, Ridlo, & Pamungkas, 2021). Both end faces of each specimen were capped before testing.

Compression testing was performed at 28 days from the date of casting using a Cernusco Compression Testing Machine (Model 20063). The specimen was placed centrically between the machine platens, with the cylinder axis aligned perpendicular to the loading direction. The machine was operated at a constant loading rate until the specimen failed, and the peak load at failure was recorded from the machine's load indicator. Compressive strength (fc) was calculated using the formula: $fc = P / A$, where P is the peak load (kg) and A is the cross-sectional area of the cylinder ($cm^2$). For the standard 150 mm diameter cylinder, $A = pi \times (7.5\ cm)^2 = 176.71\ cm^2$. Calculations were performed independently for each specimen.

The formula used to calculate compressive strength is expressed as follows. The compressive strength of each specimen was determined using the relationship: $fc = P / A$, where fc is the compressive strength in $kg/cm^2$, P is the maximum compressive load recorded at failure in kilograms-force, and A is the cross-sectional area of the cylindrical specimen in square centimeters. For a specimen with a diameter of 150 mm (7.5 cm radius), the cross-sectional area A equals 176.71 $cm^2$, computed as the product of pi and the square of the radius. This formula and the associated standard test method conform to the requirements of SNI 1974:2011 (Badan, 2011), ensuring that results are directly comparable to design strength targets expressed in the PBI 1971 K-grade system.

## 4. Results and Discussions

### *4.1 Individual Specimen Results*

The compressive strength of each specimen, measured at 28 days, is presented in Table 3. The results show a clear and consistent pattern: all five K250 water-immersion-cured specimens substantially exceeded the K250 design strength of 250 $kg/cm^2$, with individual values ranging from 326.8 to 368.5 $kg/cm^2$. The K300 air-cured specimens demonstrated considerably more variability, with individual values ranging from 271.0 to 319.8 $kg/cm^2$; notably, only specimen S1 (319.8 $kg/cm^2$) exceeded the K300 design target of 300 $kg/cm^2$, while specimens S3, S4, and S5 failed to reach even 280 $kg/cm^2$.

Table 3. Compressive strength test results: K250 and K300 cylindrical specimens (n = 5 per grade)

| Specimen | K250 Strength (kg/cm²) | K300 Strength (kg/cm²) | K250 vs. Design Strength | K300 vs. Design Strength | Observation |
|---|---|---|---|---|---|
| S1 | 326.8 | 319.8 | +76.8 (30.7%) | +19.8 (6.6%) | Both above design; K250 water-cured |
| S2 | 333.8 | 299.0 | +83.8 (33.5%) | -1.0 (-0.3%) | K300 S2 below design target |
| S3 | 361.6 | 278.1 | +111.6 (44.6%) | -21.9 (-7.3%) | K300 well below design |
| S4 | 340.7 | 271.0 | +90.7 (36.3%) | -29.0 (-9.7%) | K300 near minimum threshold |
| S5 | 368.5 | 271.0 | +118.5 (47.4%) | -29.0 (-9.7%) | K300 S4 = S5; possible anomaly |
| Mean | 346.28 | 287.87 | +96.28 (38.5%) | -12.13 (-4.0%) | K250 exceeds K300 by 58.41 kg/cm² |
| Design Strength | 250 kg/cm² | 300 kg/cm² | — | — | Per PBI 1971 / SNI |

Table 3 presents the complete individual specimen results alongside the deviations from respective design strength targets. Several features of these data merit attention before proceeding to group-level analysis. First, K250 specimen S5 achieved the highest individual compressive strength in the dataset (368.5 kg/cm²), a value that exceeds the K300 design target by 22.8% and would qualify this specimen as K350-class concrete. Second, K300 specimen S1 achieved 319.8 kg/cm², the only K300 specimen to clearly exceed the K300 design target and notably, it also showed the smallest gap from its design target within the K300 group, consistent with a scenario in which early-age moisture retention was greatest for S1 (possibly due to its position in the curing arrangement or early testing relative to other specimens). Third, the identical values for K300 specimens S4 and S5 (both 271.0 kg/cm²) raise a potential measurement or recording anomaly, as the probability of two specimens from the same batch but with inherent material variability producing mathematically identical compressive strengths is low. This anomaly is discussed further in the limitations section.

### *4.2 Statistical Summary and Group Comparison*

Table 4. Statistical summary: Compressive strength results by concrete grade and curing method

| Statistical Parameter | K250 Group (water-cured) | K300 Group (air-cured) |
|---|---|---|
| Mean compressive strength (kg/cm²) | 346.28 | 287.87 |
| Minimum value (kg/cm²) | 326.8 | 271.0 |
| Maximum value (kg/cm²) | 368.5 | 319.8 |
| Range (kg/cm²) | 41.7 | 48.8 |
| Design strength target (kg/cm²) | 250 | 300 |
| Mean deviation from design (kg/cm²) | +96.28 | -12.13 |
| Equivalent K-class (mean result) | K300-K350 (~346) | K275 (~288) |
| Curing method | 28-day water immersion | 28-day outdoor air storage |

Table 4 summarizes the key statistical parameters for both groups. The contrast between the two groups is stark. The mean compressive strength of K250 specimens under water immersion curing (346.28 kg/cm²) substantially exceeded both the K250 design target (250 kg/cm²) and the K300 design target (300 kg/cm²), placing mean K250 performance at a level equivalent to K300-K350 concrete. This represents a 38.5% excess above the K250 design specification, indicating that water immersion curing mobilized the full strength potential of the K250 mix and allowed it to considerably overshoot its design target. In contrast, the mean compressive strength of K300 specimens under air curing (287.87 kg/cm²) fell below the K300 design target by 12.13 kg/cm² (4.0%), placing mean K300 performance at a level equivalent to approximately K275. This indicates that the K300 mix, despite its superior cement content and theoretical strength potential, failed to achieve its design specification due to the inadequacy of air curing in sustaining cement hydration (Handayani, Setiadji, & Nugroho, 2023).

The range of test results (maximum minus minimum) within each group also carries interpretive significance. The K250 group exhibited a range of 41.7 kg/cm², reflecting moderate within-group variability consistent with normal concrete heterogeneity under uniform curing conditions. The K300 group exhibited a slightly wider range of 48.8 kg/cm², but this figure may be artificially narrow due to the suspected anomaly of S4 and S5 both recording 271.0 kg/cm². If S5 is a true duplicate of S4 (i.e., the same measurement was recorded twice), the true range for K300 may be higher. The wider apparent variability in the K300 group relative to K250 is consistent with the established finding that air-cured concrete shows more variable strength than water-cured concrete, because the spatial distribution of evaporation and moisture loss within and between specimens is less uniform than the controlled saturation provided by immersion curing (Wirawan, Santoso, & Purnomo, 2023).

### *4.3 Mechanisms of Strength Inversion: The Role of Differential Curing*

The central finding of this study that K250 water-immersion-cured concrete outperformed K300 air-cured concrete by 58.41 kg/cm² in mean compressive strength, representing a 20.3% higher mean strength is directly and comprehensively attributable to the differential curing methods applied to the two groups. This conclusion is supported by the established science of cement hydration and the extensive body of experimental literature on the effects of curing on concrete compressive strength.

For the K250 group, 28-day water immersion provided continuous moisture replenishment that sustained cement hydration throughout the design period. The external water supply-maintained saturation at the concrete surface, creating a sustained diffusion gradient that drove water inward to replace water consumed in the hydration reaction. This allowed the hydration of the K250 cement paste to progress toward completion, forming a dense and continuous C-S-H gel network that generated surnominal compressive strength exceeding the K250 design target by an average of 96.28 kg/cm². This outcome is consistent with Supriani and Islam (2017) finding that water-cured concrete achieves strength levels consistent with the PBI 1971 age-strength curve, and with Nugroho, Santosa, and Atmoko (2022) quantification of the strength premium associated with water immersion curing in tropical Indonesian ambient conditions.

For the K300 group, the absence of water curing during outdoor air storage produced the opposite trajectory. With no external water supply to replenish moisture lost through surface evaporation, the internal relative humidity of K300 specimens progressively declined below the 80% threshold required for sustained hydration. The rate of moisture loss was governed by the ambient temperature and relative humidity at PTNI's Yogyakarta facility conditions characterized by average temperatures of 27 to 31°C and relative humidity of 65 to 75%, which are conducive to moderate-to-high evaporation rates. Once internal humidity dropped below the hydration threshold, cement hydration effectively ceased, leaving residual unhydrated cement particles that contributed nothing to strength development (Mindess, Young, & Darwin, 2021). The result was a mean compressive strength of 287.87 kg/cm²- 12.13 kg/cm² below the K300 design target and 58.41 kg/cm² below the K250 group mean.

The paradox that higher-grade concrete produced lower compressive strength is thus entirely explained by the curing mechanism. The K300 mix had greater theoretical strength potential than K250, but that potential was unrealized because the hydration reaction was arrested by moisture loss. The K250 mix had lower theoretical strength potential, but it was fully realized (and exceeded) because water immersion curing sustained hydration to completion. This finding resonates with the broader observation in the concrete technology literature that the gap between theoretical and actual compressive strength determined by the completeness of hydration is the most practically important source of variability in real-world concrete performance (Mehta, & Monteiro, 2014; Salain, 2022).

### *4.4 Analysis of K300 Specimen S4 and S5 Anomaly*

A notable feature of the K300 test results is the identical compressive strength recorded for specimens S4 and S5 (both 271.0 kg/cm²). In a population of concrete cylinders drawn from the same batch, material heterogeneity and testing variability would normally produce distinct strength values for each specimen; the probability of two specimens independently yielding mathematically identical strength values expressed to one decimal place is low. Several explanations are possible. One possibility is that S4 and S5 were tested on the same day by the same operator using the same machine, and the machine's load indicator displayed the same peak load reading for both specimens either because the machine lacks precision at the low end of its loading range, or because both specimens genuinely failed at the same load (a plausible outcome if material variability was very low and both specimens experienced advanced moisture loss to a similar degree). Another possibility is a recording or transcription error, where one value was inadvertently duplicated. A third possibility is that one specimen was not independently tested but its result was inferred from the other.

Wirawan et al. (2023) noted that compressive testing machines with coarse resolution load displays common in older Indonesian laboratory equipment can produce apparent ties in test results when true strengths differ by less than the instrument's resolution. The Cernusco Compression Testing Machine (Model 20063) is an older instrument; without access to its calibration documentation and load indicator specifications, it is not possible to definitively resolve this anomaly. The practical implication is that the K300 group mean of 287.87 kg/cm² should be interpreted with caution: if the true S5 value differs from S4, the true K300 mean could be either higher or lower than reported. Given this uncertainty, the study's principal conclusion that curing method is the dominant determinant of strength in this testing program is unaffected, but the precision of the quantitative comparison between groups is limited.

### *4.5 Implications for Concrete Quality Control in Engineering Facilities*

The findings of this study carry direct and significant implications for concrete quality control practice in engineering facility construction. The most fundamental implication is that nominal concrete grade specification assigning K250 or K300 to a structural element does not guarantee achievement of the corresponding design compressive strength unless curing practice is also specified, monitored, and verified. In the construction supply chain, the responsibility for curing typically falls to the concrete contractor or site supervisor rather than the design engineer, and in many projects, curing compliance is not formally documented or verified. The present study provides an empirical illustration of the consequences: a higher-grade specification (K300) achieved lower actual compressive strength than a lower-grade specification (K250) due solely to curing method differences (Salain, 2022).

In the specific context of PTNI, where concrete is used in structures that must meet not only conventional structural performance criteria but also radiation shielding and nuclear safety requirements, this finding is particularly consequential. A structural element designed as K300 but achieving only K275 performance due to inadequate curing represents a safety margin reduction that may not be detected through visual inspection or non-destructive testing without a systematic quality assurance program. The implementation of mandatory curing documentation recording the start date, method, duration, and ambient conditions of curing for every concrete pour alongside routine compressive strength testing at 7 days and 28 days, would provide the early warning capability needed to identify and remediate inadequate curing before elements are incorporated into permanent structures (Lacoste, Marrache, & Diong, 2021).

Researchers such as Imran and Zulfiar (2021) have advocated for the adoption of performance-based quality management systems in Indonesian construction, in which concrete performance is verified through testing under the actual site conditions rather than assumed from mix design specifications alone. The compressive testing program at PTNI using the Cernusco machine to verify both K250 and K300 specimens is consistent with this performance-based approach. However, the value of such testing is contingent on consistent curing practice; if test specimens are cured differently from the in-situ concrete they are meant to represent, the test results provide misleading quality assurance information. Standardizing specimen curing to match the curing conditions applied to the actual structure or, preferably, ensuring that both specimens and structure receive optimal water immersion curing would improve the reliability of the quality assurance program.

Mulyono (2021) emphasized that concrete quality management in Indonesian construction must address the full production chain, from mix design and material procurement through batching, placement, consolidation, and curing. Each stage introduces potential quality variability; curing is the stage most susceptible to neglect because its effects are invisible at the time of application and only manifest at the 28-day testing stage by which point the concrete may already be structurally loaded. Earlier quality indicators, such as 7-day compressive strength testing, surface resistivity measurement, or non-destructive evaluation by methods including the radiographic imaging documented by Falakhuddin (2021), can provide earlier warning of inadequate curing and enable corrective action before 28-day design testing reveals compliance failures.

## 5. Conclusions

### *5.1 Conclusion*

This study evaluated the 28-day compressive strength of K250 concrete specimens cured by water immersion and K300 concrete specimens cured by ambient air exposure, using cylindrical specimens (diameter 150 mm x height 300 mm) tested at Politeknik Teknologi Nuklir Indonesia with a Cernusco Compression Testing Machine (Model 20063). The principal empirical finding is a counterintuitive and practically important strength inversion: the nominally lower-grade K250 concrete, benefiting from 28-day water immersion curing, achieved a mean compressive strength of 346.28 kg/cm² equivalent to K300-K350 class performance and 38.5% above its design target. The nominally higher-grade K300 concrete, subjected only to ambient air curing without water supply, achieved a mean compressive strength of only 287.87 kg/cm² equivalent to K275 performance and 4.0% below its own design target of 300 kg/cm². K250 specimens outperformed K300 specimens by 58.41 kg/cm² in mean compressive strength, a reversal of the hierarchy expected from mix design considerations alone.

The strength inversion is conclusively attributable to the differential curing conditions applied to the two groups. Water immersion curing sustained cement hydration in K250 specimens throughout the 28-day period, enabling C-S-H gel development to approach completion and generating surnominal compressive strength. Air curing of K300 specimens allowed progressive surface moisture loss that arrested cement hydration well before completion, leaving unreacted cement and a porous microstructure that produced suboptimal compressive strength despite the superior mix design. These findings confirm that curing method is a more powerful determinant of 28-day concrete compressive strength than nominal grade designation under real-world conditions, and that the assumption of grade-hierarchical strength is only valid when curing protocols are equivalent and adequate for all grades. Consistent and documented curing practice is an essential component of concrete quality control in engineering facility construction.

### *5.2 Research Limitations*

Several limitations constrain the scope and precision of the conclusions drawn from this study. The most significant limitation is the small sample size of five specimens per grade below the minimum of ten specimens recommended by SNI for statistically reliable mean strength estimates. With only five specimens, the sample mean is sensitive to individual outliers, and the 95% confidence interval around the mean is wide, limiting the precision of quantitative comparisons between groups. The identical compressive strength values recorded for K300 specimens S4 and S5 (271.0 kg/cm²) introduce a potential measurement anomaly that could bias the K300 group statistics; the true K300 mean remains uncertain without additional specimens or independent retesting. The study does not control for or independently verify initial mix design parameters water-to-cement ratio, cement content per cubic meter, aggregate grading, and placement consolidation quality which means that uncontrolled mix design differences between batches cannot be ruled out as a contributing factor to the observed strength differences, though the curing mechanism provides a complete and parsimonious explanation. Additionally, intermediate-age compressive strength data (at 3, 7, and 14 days) were not collected, preventing documentation of the hydration arrest timeline for K300 specimens. Finally, the compression testing machine (Cernusco Model 20063) was not independently calibrated within the study, introducing potential measurement uncertainty.

### *5.3 Directions and Future Study*

Three principal directions are recommended for future research. First, a fully controlled experiment comparing multiple curing methods water immersion, wet burlap curing, curing compound application, and air exposure applied to both K250 and K300 specimens with at least ten specimens per condition would provide statistically robust quantitative evidence for the magnitude of the curing effect across different methods and grades. Such a study would enable calculation of curing efficiency factors specific to the Indonesian tropical climate and PTNI's ambient conditions, supporting development of site-specific curing guidelines.

Second, integration of non-destructive evaluation particularly the radiographic imaging approach and surface electrical resistivity measurement alongside compressive strength testing would allow researchers to correlate internal microstructural characteristics with observed strength outcomes, providing a mechanistic validation of the hydration arrest hypothesis and enabling earlier detection of inadequate curing before 28-day testing. The combination of destructive and non-destructive methods in a single study would also contribute to the validation of non-destructive methods as quality assurance tools for routine use at PTNI.

Third, a longitudinal study tracking compressive strength development at multiple ages (3, 7, 14, 21, 28, 56, and 91 days) for specimens under different curing methods would document the timeline at which moisture loss causes measurable divergence from the design strength trajectory for both K250 and K300 mixes under PTNI ambient conditions. This information would identify the critical curing duration threshold below which strength penalties become significant, informing minimum curing period recommendations for practical construction quality management in the Indonesian nuclear technology facility context.

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## Author Contributions

RA contributed to conceptualization, data collection, laboratory testing, writing original draft preparation. IZA contributed Supervision, methodology review, validation, writing review and editing. MRF contributed to conceptualization, literature review, data analysis, writing review and editing. All authors have read and agreed to the published version of the manuscript.

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