

ANALYSIS OF CONCRETE CONSISTENCY USING STATISTICAL QUALITY CONTROL TOOL: A CASE STUDY ON LIKHU -2 HYDROPOWER

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ABSTRACT

Quality control of concrete works is essential for ensuring durability and safety in large infrastructure projects, especially hydropower projects in Nepal. Conventional quality control practices are mostly based on compliance with code limits and often do not adequately address process variability or early signs of quality deviation. This creates the need for a data-driven and process-oriented approach to quality control. The Likhu-2 Hydropower Project was selected as a case study to evaluate concrete quality control practices using statistical analysis of material test records collected during construction.

This study applied Statistical Quality Control (SQC) using Statistical Process Control (SPC) tools to assess the consistency of cement, fine aggregates, coarse aggregates, and concrete. Individual (I) charts, Moving Range (MR) charts, and Exponentially Weighted Moving Average (EWMA) charts were used to evaluate process stability, short-term variability, and gradual trends in material properties. The test results were assessed with reference to relevant Indian Standard (IS) codes to ensure technical compliance.

The analysis showed that most material properties and concrete performance parameters remained within statistical control limits, indicating that the overall quality control system at the project was stable and reliable. MR charts highlighted manageable day-to-day variations, while EWMA charts were effective in identifying small and gradual changes that may not be visible through conventional control charts. The consistent trends observed in cement strength, aggregate properties, and concrete workability and compressive strength confirm the positive influence of controlled material quality on concrete performance.

This study contributes practical insight into the application of SPC-based quality control in Nepal's construction industry. The findings emphasize the importance of integrating statistical monitoring tools into routine QA/QC practices to improve early detection of quality issues and enhance the overall reliability and durability of concrete structures.

Keywords: Statistical Quality Control, Statistical Process Control, Control Charts, EWMA, Concrete Quality

1. Introduction

The construction industry plays a pivotal role in Nepal's infrastructure development, with hydropower projects forming a major component of national economic and energy strategy. Concrete works constitute a significant portion of this construction, directly influencing structural performance, durability, and operational safety, making consistent concrete quality a critical concern for project stakeholders.

In practice, quality control in Nepalese hydropower projects is largely based on compliance with specification limits prescribed in Indian Standards (IS). While this approach verifies the acceptability of individual test results, it does not adequately assess process stability, variability, or long-term quality behavior. Concrete production is inherently variable due to fluctuations in material properties, batching accuracy, environmental conditions, and workmanship, which can lead to quality issues even when test results fall within specified limits.

Statistical Quality Control (SQC) provides a systematic framework for evaluating construction quality by distinguishing random variation from assignable causes. SPC tools such as control charts and capability indices are widely applied in manufacturing and are gaining relevance in construction quality management, yet their use in Nepalese hydropower projects remains limited. This gap prevents construction teams from implementing targeted improvements and can lead to unnecessary interventions that raise costs without improving quality. Traditional QC methods also have limited ability to distinguish random variation from systematic, assignable-cause variation requiring corrective action. According to Skrzypczak (2023), standard quality control procedures often fail to account for actual process defectiveness, as shown through analysis of concrete production data.

Haddad (2021) similarly found that Palestinian construction materials manufacturers could benefit from adopting SPC tools for process improvement, saving cost and materials, yet such tools remain underused in construction organizations despite their proven effectiveness in manufacturing. This gap between proven methodology and practical implementation highlights the need for research demonstrating the practical application and benefits of SQC in construction contexts. Real-time statistical monitoring has shown particular value in high-volume concrete production; research on ready-mix concrete operations found that automated SPC systems could monitor multiple quality parameters simultaneously and issue alerts as processes approached control limits, enabling proactive rather than reactive quality management (Gryna, 1999).

This study goes beyond the conventional practice of checking whether material test results meet codal requirements. By applying SQC tools to actual construction data from the Likhu-2 Hydropower Project, it provides deeper insight into the consistency and reliability of QA/QC practices throughout construction, showing how even acceptable test results can hide variations and trends that may affect long-term structural performance. The findings are expected to improve quality monitoring systems, support better decision-making, and contribute to more durable and efficient construction in future hydropower and infrastructure projects in Nepal.

ASTM standards provide comprehensive guidance for material testing and quality assessment in construction. ASTM C39, for instance, establishes standardized procedures for compressive strength testing, specifying specimen preparation, curing, testing, and result interpretation to enable consistent comparison of concrete quality across projects (Laguros, 1967). Integrating such material

testing with construction process control, within a comprehensive project-level quality management system, is essential for effective quality assurance—particularly in hydropower projects, where critical structural components and long-term performance demand rigorous quality management (Lu and Jin, 2023).

SQC methods also help optimize testing frequency and identify critical control points for quality management. Testing schedules must be coordinated with construction timelines and material delivery to allow proactive quality assessment without disrupting project progress (Agnihotri, 2020). This study applies SQC tools to evaluate concrete quality consistency in the Likhu-2 Hydropower Project using real construction data, contributing practical evidence for improving QA/QC practices in large infrastructure projects.

2. Materials and Methods

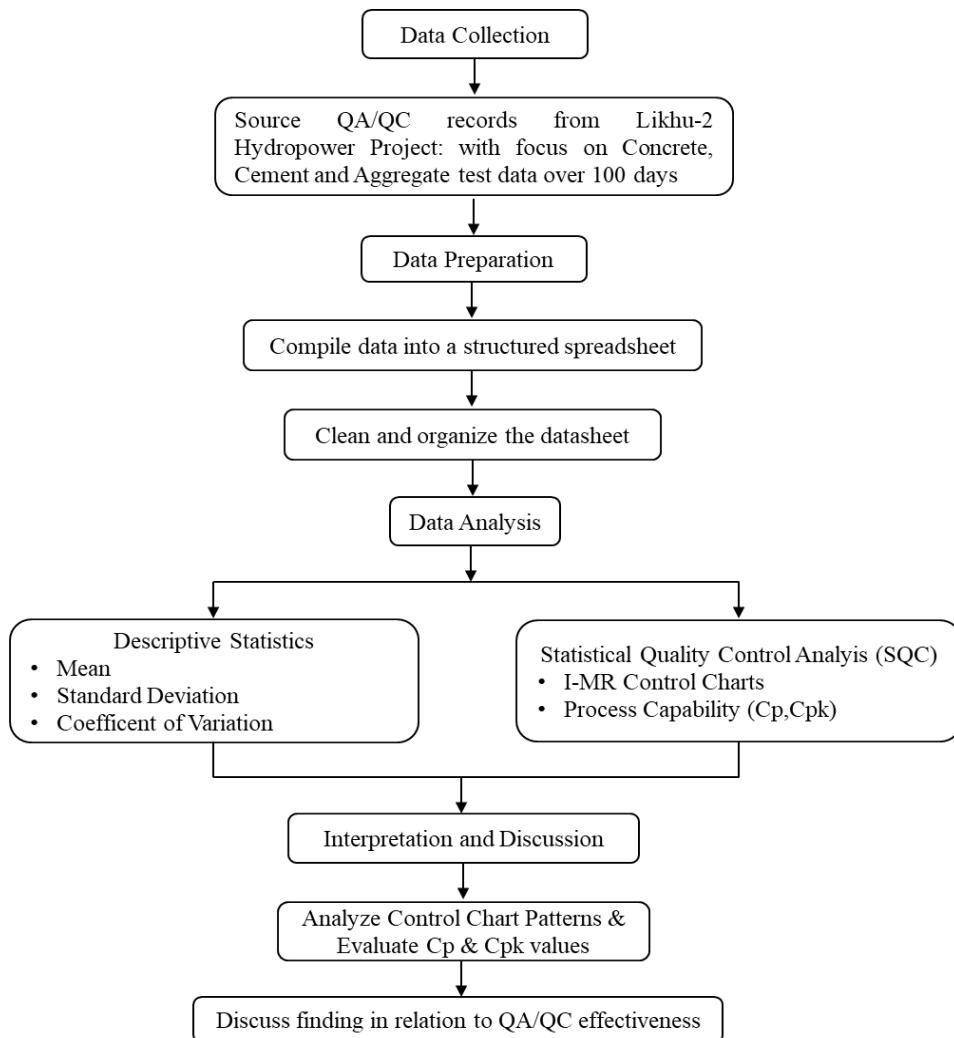


Figure 1: Flow chart of the study

2.1 Study Area

The Likhu-2 Hydropower Project is located in central Nepal and involves substantial concrete works for civil structures such as intake, headrace, powerhouse, and associated components. The project was selected due to the availability of systematic QA/QC laboratory records and the scale of concrete production.

2.2 Research Design and Data Collection

A quantitative, case-study-based research design was adopted. Secondary data were collected from the project's quality control laboratory, including test results for cement, fine aggregates, coarse aggregates, and concrete. A total of 100 consecutive working days of material test records were analyzed to ensure statistical reliability and meaningful trend identification. The flow chart of the study is as shown in the Figure 1.

2.3 Sampling Adequacy and Data Reliability

SQC literature suggests that 20–25 preliminary samples are sufficient for establishing control limits; however, larger datasets enhance robustness and reliability. Accordingly, the use of 100 days of test data provided adequate representation of process behavior. Data screening was performed to remove inconsistencies and verify alignment with laboratory records.

2.4 Statistical Analysis Techniques

The following SQC tools were applied:

- Descriptive statistics to summarize material properties
- Individuals (I) charts to evaluate overall process stability
- Moving Range (MR) charts to assess short-term variability
- EWMA charts to detect small and gradual process shifts
- Process capability indices (C_p and C_{pk}) to assess the ability of processes to meet specification limits

All analyses were conducted following standard SPC principles.

2.5 Data Analysis

Data analysis was conducted using SPSS. Reliability was assessed using Cronbach's alpha. PCA was applied to group related variables into principal components. RII was used to rank the identified factors based on perceived importance. Finally, Multiple Linear Regression was performed to develop and validate predictive models linking the extracted components to overall worker safety behavior.

3. Results and Discussion

The control chart analysis showed that the majority of cement (Figure 2), aggregate (Figure 4), and concrete parameters (Figure 3) remained within statistically defined control limits, indicating a stable quality control system throughout the study period. Cement properties such as consistency, setting time, and strength demonstrated controlled behavior, with EWMA charts revealing minor mid-period trends that did not indicate sustained deterioration.

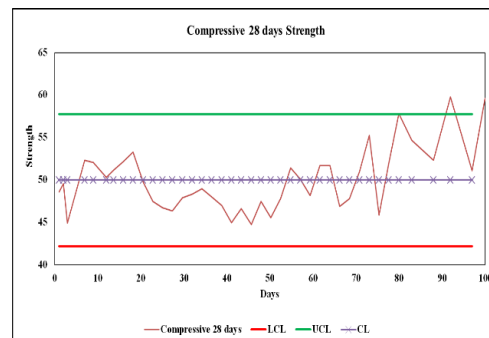
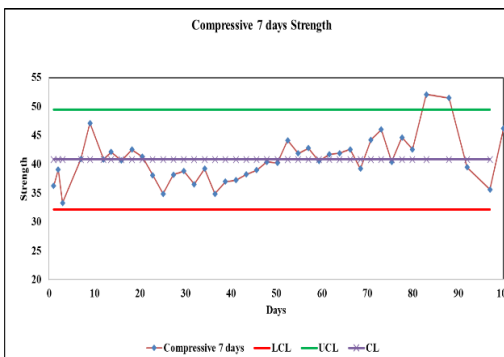
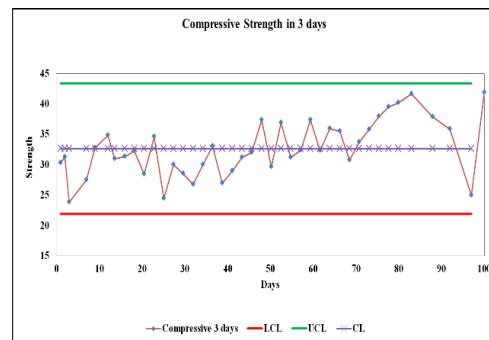
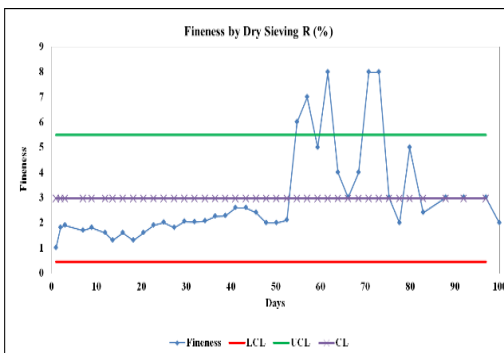
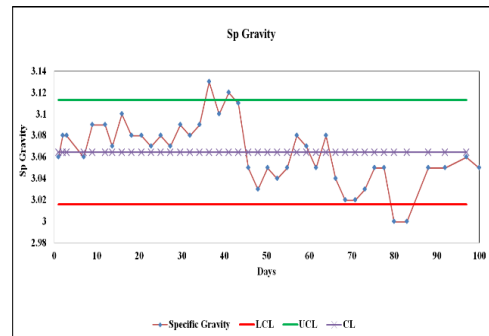
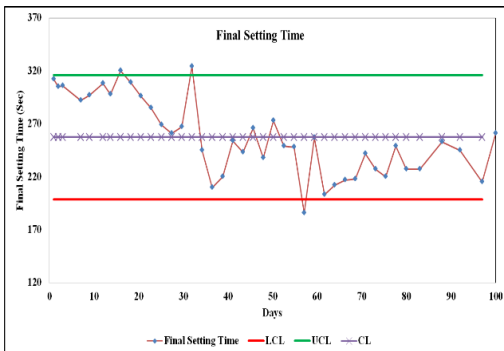
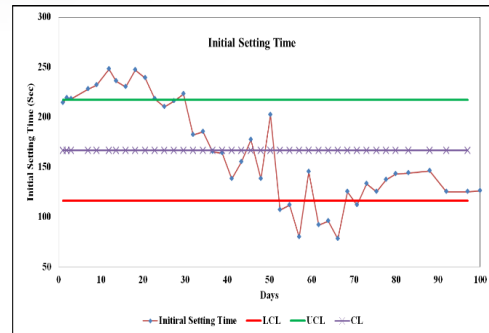
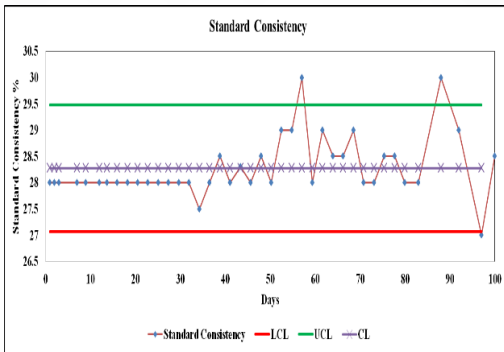


Figure 2 Chart for Cement Test

Aggregate properties remained statistically stable, although moisture content exhibited higher variability due to environmental influences, which is typical in field conditions. Concrete workability and compressive strength results showed consistent performance, confirming effective material control and batching practices.

Process capability analysis revealed high C_p values, indicating low variability; however, lower C_{pk} values in certain parameters suggested centering issues. This finding emphasizes that compliance with codal limits does not necessarily guarantee optimal process performance and highlights the importance of continuous statistical monitoring.

Consistency of Concrete Quality:

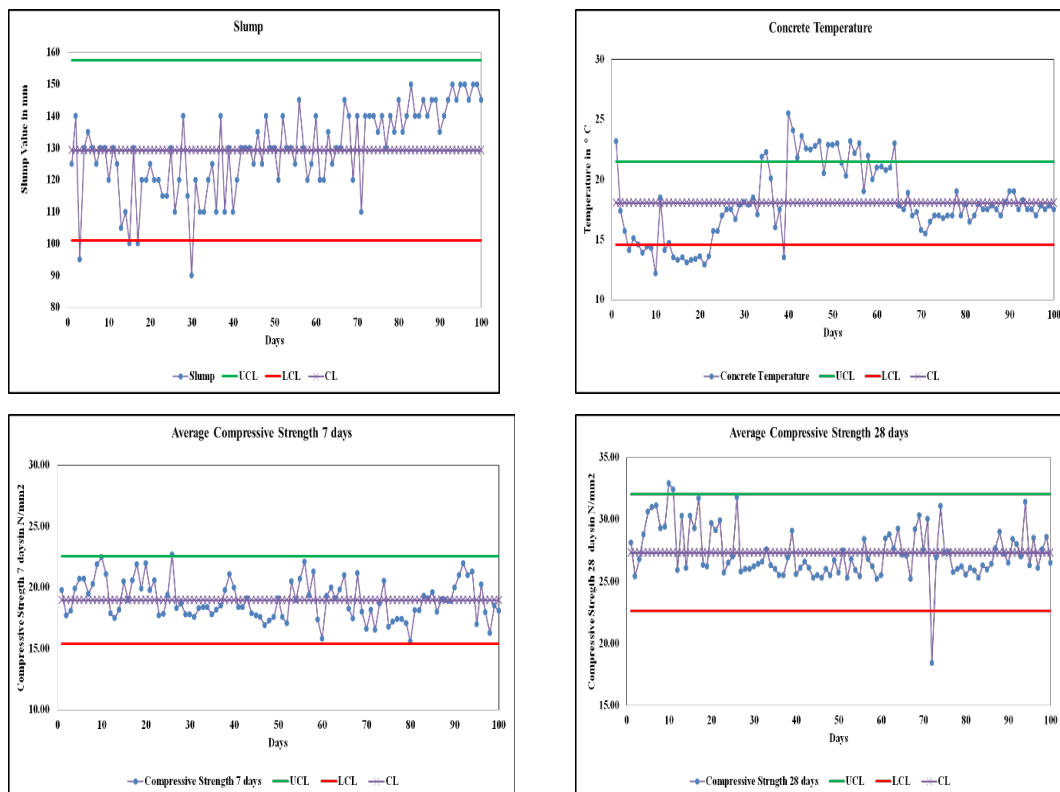


Figure 3 Chart for Concrete Test

The Statistical Quality Control (SQC) methods applied in the Likhu-2 Hydropower Project show that most material properties (cement, coarse aggregates, fine aggregates, and concrete) were statistically within control limits throughout the study period.

I-Chart, MR-Chart, and EWMA Chart analyses confirmed that concrete production remained consistently within acceptable limits. Variations, where they occurred, were manageable and aligned with normal production process variability.

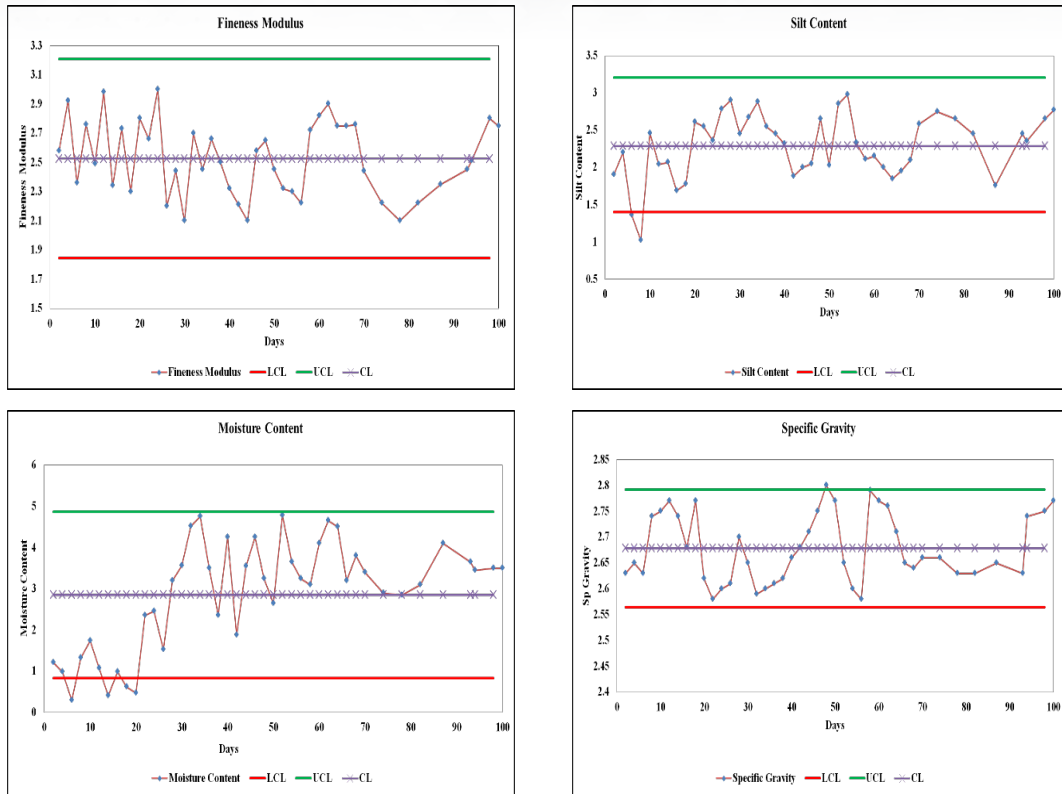


Figure 4 Chart for fine aggregate

Process Stability:

Individual and Moving Range (I/MR) charts indicated stable processes with most results remaining within control limits. The MR charts revealed manageable short-term variability in material properties, while EWMA charts were particularly sensitive to small shifts, providing early signals of gradual changes in quality.

Table 1 Process Capability of Concrete

S. N	Concrete	Cp (Process Capability Index) $C_p = \frac{USL - LSL}{6\sigma}$	Cpk (Process Capability Performance Index) $C_{pk} = \min \left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma} \right)$
1.	Slump	1.44	2.01, 0.88
2	Concrete Temperature	2.44	-0.41, 0.33

S. N	Concrete	Cp (Process Capability Index) $Cp = \frac{USL - LSL}{6\sigma}$	Cpk (Process Capability Performance Index) $Cpk = \min \frac{(USL - \mu)}{3\sigma}, \frac{(\mu - LSL)}{3\sigma}$
3	Average Compressive Strength (N/mm2) – 7 Days	2.44	-0.41, 0.33
4	Average Compressive Strength (N/mm2) – 28 Days	3.1	0.56, 0.33

Process Capability:

Process Capability Indices (Cp and Cpk) were calculated for various materials (cement, aggregates, concrete), indicating good process control in most cases. However, the results showed mild centering issues, particularly in concrete temperature and early compressive strength (Table 1), suggesting that some adjustments were needed to better center processes within specification limits.

Table 2 Capability Analysis of Coarse Aggregate

S. N	Coarse Aggregate	Cp (Process Capability Index) $Cp = \frac{USL - LSL}{6\sigma}$	Cpk (Process Capability Performance Index) $Cpk = \min \frac{(USL - \mu)}{3\sigma}, \frac{(\mu - LSL)}{3\sigma}$
1.	Impact Value	1.59	0.57, 0.04
2.	Crushing Value	1.78	0.22, 0.041
3.	Flakiness Index	1.80	0.92, 0.041
4.	Elongation Index	1.70	1.12, 0.04
5.	Specific Gravity	1.41	1.41, -0.21
6.	Water Absorption	0.80	0.66, 0.11

Identification of Potential Areas for Improvement:

For cement (Table 3), slight deviations in setting time and fineness were noted, which could be attributed to environmental factors like temperature and moisture. These areas need close monitoring and potential corrective actions.

Table 3 Capability Analysis of Cement Test

S. N	Cement	Cp (Process Capability Index)	Cpk (Process Capability Performance Index)
		$Cp = \frac{USL - LSL}{6\sigma}$	$Cpk = \min \frac{(USL - \mu)}{3\sigma}, \frac{(\mu - LSL)}{3\sigma}$
1.	Standard Consistency	2.91	3.93, 0.03
2.	Initial Setting Time	2.08	1.45, 0.27
3.	Final Setting Time	5.12	5.85, 0.33
4.	Specific Gravity	1.67	3.00, 0.33
5.	Water Absorption	1.03	2.79, 0.00
6.	Fineness by Dry Sieving R	1.99	2.79, 0.33
7.	Average Compressive Strength (N/mm ²) – 3 Days	1.07	-3.04, 0.10
8.	Average Compressive Strength (N/mm ²) – 7 Days	1.91	-4.72, 0.06
9.	Average Compressive Strength (N/mm ²) – 28 Days	1.16	-3.22, 0.05

For fine aggregates (Table 4), moisture content exhibited higher variability, requiring better control during batching. Similarly, coarse aggregate properties like flakiness index and crushing value demonstrated some variability that needs improvement in material selection or processing methods.

Table 4 Capability Analysis of Fine Aggregate

S. N	Fine Aggregate	Cp (Process Capability Index)	Cpk (Process Capability Performance Index)
		$Cp = \frac{USL - LSL}{6\sigma}$	$Cpk = \min \frac{(USL - \mu)}{3\sigma}, \frac{(\mu - LSL)}{3\sigma}$
1.	Fine Modulus	0.66	0.80, 0.33
2.	Silt Content	1.69	0.80, 0.33
3.	Moisture Content	1.23	1.064, 0.33
4.	Specific Gravity	2.19	1.06, 0.33
5.	Water Absorption	0.80	0.65, 0.33

Summary of Results: Cement

The cement quality analysis in this study focused on several parameters, including consistency, setting times, specific gravity, fineness, and compressive strength. The Individual (I) charts for cement properties showed that most test results remained stable and within control limits,

indicating that the cement quality was consistently maintained over the 100-day monitoring period. Specifically, parameters such as standard consistency and specific gravity were mostly stable, with minimal fluctuations observed during the testing period.

However, some minor deviations were noticed, especially in setting times. The initial setting time displayed more variation, with a noticeable downward shift around day 40. Similarly, the final setting time showed some fluctuations, particularly between days 55–65, but these changes were still within the control limits. The cause for these fluctuations could be attributed to changes in environmental conditions such as temperature or variations in the gypsum content of the cement. These minor shifts did not represent significant quality issues, but they did indicate that cement properties were slightly affected by external factors.

The fineness of the cement, which influences its reactivity, also showed some peaks during certain periods, particularly between days 55–75. These peaks suggested occasional variations in the particle size distribution, possibly due to adjustments in the cement grinding process. However, these fluctuations remained within acceptable limits, indicating that the fineness was generally well-controlled.

Compressive strength values at 3, 7, and 28 days showed moderate variability but remained within the required limits. The early compressive strength values (3 days) showed slightly more scatter, which is expected given the natural variation in hydration rates and curing conditions. The 28-day compressive strength results were more consistent, with most values clustered around the target strength, confirming that the cement met the expected strength requirements for concrete production.

In conclusion, the cement quality during the 100-day period remained stable and within acceptable limits for most parameters. Minor fluctuations in setting time and fineness were observed, but they did not indicate any special cause for concern. The findings suggest that the cement quality was reliable for use in the Likhu-2 Hydropower Project, with no significant quality deviations that would affect the overall concrete performance.

Summary of Results: Fine Aggregate

The fine aggregate quality was assessed based on parameters like fineness modulus, silt content, moisture content, specific gravity, and water absorption. The I-charts for fine aggregates indicated that most parameters remained within control limits, confirming that the quality of the fine aggregates used in the project was consistent over the study period.

The fineness modulus of the fine aggregates, which indicates the coarseness or fineness of the sand, showed stable results, remaining within the typical range specified by the Indian Standard (IS 383:2016). There were some fluctuations, particularly between days 10–25 and again near day 90, but these variations did not exceed the control limits, suggesting that the grading of the fine aggregates was consistent throughout the monitoring period.

The silt content remained within the acceptable range of 3% as per the IS code, with only minor fluctuations observed during the early stages of testing (days 5–15) and some peaks between days 40–55. These variations are typical for natural sand and were attributed to moisture or handling conditions. Since the values remained within control limits, no special-cause variations were detected, confirming that the cleanliness of the fine aggregates met the required standards.

The moisture content showed higher variability compared to other parameters, ranging from 0.5% to 4.5%. This is expected due to environmental conditions, such as changes in weather and storage of sand. Despite these fluctuations, the moisture content remained within control limits, suggesting that the batching process accounted for the variability through appropriate adjustments to the water-cement ratio.

The specific gravity of the fine aggregates remained stable throughout the monitoring period, falling within the standard range of 2.5–2.9. Similarly, water absorption values stayed below the acceptable limit of 2%, indicating that the aggregates had low porosity, which is ideal for concrete mix design.

Overall, the fine aggregate quality remained stable and within the acceptable limits prescribed by the IS codes. The observed variations, particularly in moisture content, were attributed to natural environmental factors and did not indicate any major issues with the material's suitability for concrete production. The results suggest that the fine aggregates used in the project were of good quality and contributed positively to the overall concrete mix.

Summary of Results: Coarse Aggregate

The coarse aggregate quality was assessed by analyzing properties such as impact value, crushing value, Los Angeles abrasion value, flakiness index, elongation index, specific gravity, and water absorption. The I-charts for coarse aggregates showed that all parameters remained within the specified limits according to IS 2386 (Part I–IV), indicating stable and consistent material quality throughout the project.

The impact value, which measures the toughness of the aggregates, showed moderate variability but remained consistently below the IS limit of 30%, which is acceptable for concrete production. Some fluctuations were observed between days 10–25 and around day 60, but these variations did not exceed the upper control limit, suggesting that the toughness of the aggregates remained stable.

The crushing value also remained well within the prescribed limit (30–35%), with a slightly narrower range of variation compared to the impact value. This indicates that the aggregates had good compressive strength, which is essential for ensuring the durability of the concrete. The Los Angeles abrasion value, which measures resistance to wear, showed some higher peaks between days 20–35 but remained within the control limits, confirming that the aggregates had good durability and were suitable for use in concrete subjected to abrasion.

The flakiness index and elongation index, which assess the shape characteristics of the aggregates, showed some fluctuations but remained within the IS 2386 limit of $\leq 35\%$ for combined flakiness and elongation. These minor variations are typical for aggregate material and did not indicate any issues with the aggregates' ability to pack well and contribute to the concrete's strength.

The specific gravity and water absorption charts showed consistent values, with specific gravity ranging between 2.6–2.8 and water absorption staying below 2%, both of which are within the acceptable limits. These results suggest that the coarse aggregates used were dense and had low porosity, which is ideal for ensuring the durability and strength of the concrete.

In conclusion, the coarse aggregate quality was stable and consistently met the required standards. The minor fluctuations observed in certain properties, such as the impact value and abrasion resistance, were within acceptable limits and did not indicate any significant quality issues. The findings suggest that the coarse aggregates contributed positively to the concrete mix and met the

necessary requirements for the project.

Summary of Results: Concrete

The concrete quality was evaluated by analyzing properties such as slump, temperature, and compressive strength at 7 and 28 days. The I-charts for concrete properties indicated that the concrete production process remained statistically stable and within control limits for all parameters, confirming that the concrete produced during the monitoring period met the required quality standards.

The slump test, which measures the workability and consistency of fresh concrete, showed moderate variation during the early days but remained within the acceptable range (75–150 mm) throughout the monitoring period. A slight upward drift in slump was observed toward the later days, possibly due to increased ambient temperature or higher fine content in the aggregates. However, the values remained within the control limits, suggesting that the workability was consistent and manageable throughout the study period.

The concrete temperature remained well within the acceptable limits, with only minor fluctuations observed. Concrete temperature is critical for hydration, and maintaining it within the recommended range ensures optimal curing and strength development. The temperature variations were likely due to environmental factors, such as changes in ambient temperature, but did not affect the quality of the concrete.

The compressive strength at 7 days showed moderate variability, which is typical for early-age concrete due to differences in curing conditions. However, the strength results remained within the control limits, indicating that the concrete had adequate early strength development. The 28-day compressive strength values exhibited tighter clustering, confirming that the concrete met the expected long-term strength requirements.

Contribution to Knowledge:

The thesis underscores the value of integrating SPC tools into construction QA/QC practices, particularly for hydropower projects, which is a novel contribution in Nepalese construction practices. The study emphasizes that data-driven quality control methods, such as statistical process control, are critical for improving material consistency and long-term structural performance.

Comparison to Existing Literature:

The results were compared to similar studies in the literature. For instance, findings align with those from Haddad (2021), who showed that SPC tools can help achieve consistency in concrete production. The thesis demonstrates how statistical charts, particularly EWMA charts, can identify gradual process shifts those traditional methods might miss.

In contrast to Jha (2019), who found higher variability in cement properties in Nepal, this study showed more stable results due to controlled curing conditions and batch processes. This highlights the effectiveness of better mixing and curing management in improving cement quality consistency.

Improvement in Nepal's Hydropower Construction:

While Nepalese hydropower projects like the Likhu-2 project generally maintain compliance with basic material quality standards, the thesis suggests that adopting SPC-based tools would allow for early intervention and more precise control over material variability, improving both short-term and long-term project outcomes.

Contribution to Existing Knowledge:

Enhancing Quality Control with SPC:

This research builds on previous work by demonstrating the applicability of SPC tools in a real-world hydropower project setting. It provides an empirical basis for further incorporating these tools into QA/QC protocols for large-scale infrastructure projects, particularly in Nepal's hydropower sector. The thesis not only confirms the value of existing quality control standards but expands upon them by incorporating real-time statistical analysis, which can guide improvements in processes and materials handling for consistent and reliable concrete performance.

Unexplored Areas:

The study opens doors for future research in exploring how SPC tools could be applied across different construction phases and in other materials such as steel reinforcement and admixtures. This research contributes to the existing body of knowledge by demonstrating how SPC-based quality control practices can be implemented in Nepalese hydropower projects and offers a roadmap for future applications of these techniques in similar infrastructure projects. It also emphasizes the need for ongoing monitoring and process adjustments to maintain optimal material quality, which can lead to cost savings and better structural reliability.

4. Conclusion

This study evaluated the quality control practices of the Likhu-2 Hydropower Project using Statistical Quality Control (SQC) methods. The analysis showed that most material properties (cement, aggregates, concrete) remained within statistical control limits, indicating stable and reliable quality control. However, minor variations in cement setting time, aggregate moisture content, and early compressive strength were observed, suggesting areas for improvement in process centering.

Limitations:

One limitation of this study was the reliance on secondary data, which could have been influenced by data entry errors or incomplete records. Additionally, the study focused only on cement, aggregates, and concrete, leaving other materials and construction processes unexamined. The limited timeframe also restricted the ability to assess long-term trends in quality control.

Suggestions for Future Research:

Future studies could explore the application of SPC tools across different construction phases and materials, such as steel reinforcement and admixtures. Additionally, research could address the integration of real-time SPC systems in construction projects to detect and address issues promptly. Future work should also examine how environmental factors and material sourcing influence process variability, providing a deeper understanding of factors impacting quality control.

Conflict of Interest

The authors declare no conflict of interest.

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