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Cost and Quality Analysis of Prestressed Concrete Piles at PT Varia Usaha Beton Using Statistical Process Control

Nurul Kurniawan*, Budi Witjaksana, Hanie Teki Tjendani
Civil Engineering, Universitas 17 Agustus 1945 Surabaya, Surabaya, Indonesia

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Corresponding author*:
nxkurniawan@gmail.com

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Abstract: Prestressed concrete piles are crucial foundation elements in large-scale infrastructure projects, where consistency of concrete quality, particularly slump and compressive strength, is critical. Despite having implemented ISO 9001:2015, PT Varia Usaha Beton faces product nonconformities, with 95.24% of issues related to compressive strength. **Objective:** To apply Statistical Process Control (SPC) at PT Varia Usaha Beton to evaluate process capability, identify root causes of nonconformities, and assess the impact of corrective measures on quality and production costs. **Method:** A case study using descriptive quantitative analysis employed the seven quality control tools, including histograms, control charts, cause-and-effect diagrams, and scatter plots. **Results:** A strong negative relationship between slump and compressive strength led to an adjustment of the slump interval from 10–14 cm to 12–16 cm. Modifying the water–cement ratio from 0.36 to 0.38 increased the process capability index for the lower specification limit (Cpl) from 1.77 to 2.03, although some subgroups remained outside the control limits. Production costs increased by Rp 2,805/m (2.07%). **Implications:** Continued process monitoring is required to support control of the water–cement ratio and slump; the relatively minor cost increase provides an economic basis for quality improvement. **Originality:** The study integrates process capability analysis and production cost evaluation for prestressed concrete piles in a single industrial case study.

Keywords: Concrete Quality; Prestressed Concrete Piles; Slump; Statistical Process Control; Water–Cement Ratio.

INTRODUCTION

Prestressed concrete piles are widely used as foundation elements in large-scale infrastructure projects because they provide additional tensile resistance that enhances the strength of concrete piles. When loads act on the pile structure, the prestressing steel resists the resulting tensile forces, thereby preventing cracking in the concrete (Adma et al., 2020). In Indonesia, demand for piles continues to increase with rapid infrastructure development (Budiman et al., 2024). However, pile reliability depends heavily on consistent concrete quality, particularly slump and compressive strength, which are important indicators of compliance with design specifications (Okwori et al., 2015). Quality is a key asset for a company's development and growth because it is a primary consideration when customers select a product (Aprilia & Suryanto Hs, 2020). Products are never 100% identical because

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variation occurs during production. Such variation is normal, but it affects product quality and therefore needs to be controlled (Zagloel & Nurcahyo, 2022).

PT Varia Usaha Beton, a leading pile producer in Indonesia, has implemented a quality management system certified to ISO 9001:2015. This standard aims to provide quality assurance in contractual arrangements with external parties (Gandara & Hasibuan, 2020). Nevertheless, product nonconformities remain frequent. The data show that 95.24% of nonconformities involve concrete compressive strength, whereas 4.76% relate to slump test results. These conditions pose risks to structural safety and can cause economic losses through material waste, rework, and potential customer claims (Saiful Islam et al., 2021). PT Varia Usaha Beton continues to implement policies that support product quality improvement and cost efficiency to remain competitive globally. These improvements encompass human resources, materials, equipment, cost control, and working methods. These five aspects are interrelated, and appropriate measures are needed to maximize quality improvement and cost efficiency (Abdel-Motaleb, 2022). An analytical method is therefore needed to identify the dominant causes of nonconformities and provide a basis for continuous process improvement (Knop, 2022). *Statistical Process Control* (SPC) is an effective approach to controlling variation in production processes. SPC can characterize variation, identify its main causes, and support the design of corrective measures to consistently improve process capability and product quality (Yibing et al., 2007).

Previous studies have demonstrated the effectiveness of SPC in controlling the quality of concrete and precast products. (Helena & Suryanto Hs, 2020) showed that SPC could identify the dominant causes of defects in mortar production and reduce product rejection rates. (Aprilia & Suryanto Hs, 2020) demonstrated that applying SPC to precast floor panels improved the process capability index after production parameters were adjusted. (Widya Putri & Suryanto Hs, 2020) reported that SPC successfully reduced chipping defects in lightweight concrete blocks while improving compressive strength consistency. (Jannah & Dani, 2018) also showed that SPC effectively reduced quality variation in concrete roof tiles, while (Kumala & Suryanto Hs, 2018) found that SPC could reduce dimensional defects in concrete blocks. (Aini & Suryanto Hs, 2017) similarly reported improvements in process capability for precast products, and (Sinaga & Sriyanto, 2019) demonstrated that SPC reduced the number of defects and significantly improved quality. (Utomo, 2015) also found that SPC made precast concrete production more stable, although no significant variation was observed after the parameters were corrected. (Suwandi, 2012)

used a different approach, Design of Experiments (DOE), but likewise emphasized the influence of material properties and proportions on concrete quality. Overall, previous research indicates that SPC effectively reduces variation and improves quality across various concrete-based products. However, most of these studies focused on mortar, panels, lightweight blocks, roof tiles, concrete blocks, and other precast products. Comprehensive studies of SPC applied to prestressed square concrete piles remain limited, particularly those linking SPC to production cost implications.

This study aimed to apply SPC at PT Varia Usaha Beton to evaluate process capability, identify the root causes of nonconformities, and measure the effects of corrective measures on product quality and production costs. Analytical tools, including histograms, control charts, cause-and-effect diagrams, and scatter plots, were used to examine the relationship between slump and compressive strength, identify dominant factors, and validate corrective measures. By integrating technical analysis with cost evaluation, the study was intended to provide empirical evidence of SPC effectiveness in prestressed concrete pile production and support improvements in product quality while maintaining production cost efficiency.

RESEARCH METHOD

Research Design

The study used a case study design with descriptive quantitative analysis. It focused on the mass production of prestressed square concrete piles with a specified compressive strength of 35 MPa at the Gresik Plant of PT Varia Usaha Beton. The research began by collecting secondary data, including design drawings, cost estimates, quality control (QC) reports, and production reports. The data were then analyzed in several stages. First, quality problems were identified using check sheets, Pareto charts, control charts, and histograms. Second, influencing factors were examined through distribution and variable relationship analyses using Pareto charts and scatter plots. Third, the dominant causes of quality variation were identified using cause-and-effect diagrams (Oakland, 2007). Once the main causes had been identified, corrective measures and their cost implications were analyzed by comparing material requirements and concrete costs per cubic meter before and after SPC implementation.

Data Sources and Data Collection Techniques

The study used primary and secondary data. Primary data were obtained through direct field testing. Secondary data were collected from company documents, including pile design drawings, cost estimates, QC reports, and production reports recording production quantities, timing, and quality inspection results. Data collection involved accessing internal company reports, transferring the data to check sheets, and conducting direct tests.

Research Instruments

The analytical instruments comprised the seven quality control tools that underpin SPC implementation (Ishikawa, 1985). These included check sheets to record nonconformity frequencies, histograms to describe data distributions, Pareto charts to identify dominant problems, cause-and-effect diagrams to identify root causes, scatter plots to examine the relationship between slump and compressive strength, control charts to assess production process stability, and flowcharts to illustrate the stages of improvement (Wheeler & Chambers, 1992).

Research Procedures

The research was conducted in several stages. Initially, nonconformities were identified using check sheets and histograms, and Pareto analysis was used to determine the proportions of the dominant problems. Variable relationships were then examined using scatter plots and simple linear regression to model the relationship between slump and concrete compressive strength. Cause-and-effect analysis was subsequently used to identify the dominant factors contributing to quality variation. The corrective measures were then evaluated using histograms and control charts to assess process stability (Gaspersz, 2001). Finally, cost analysis was performed by calculating material requirements per cubic meter of concrete before and after SPC implementation and comparing them to determine the economic implications of the corrective measures.

Data Analysis Techniques

Data analysis referred to the concrete standard SNI 2847:2019 (Badan Standardisasi, 2019) to assess compliance with the required specifications. Process capability was calculated using the Cpl index to evaluate production capability relative to the lower specification limit of 35 MPa. Cpl values before and after SPC implementation were compared to assess the improvement in process capability (Ryan, 2000). Linear regression

was used to explain the relationship between slump and concrete compressive strength. Cost analysis compared material costs per cubic meter of concrete before and after the corrective measures. These techniques were selected to show the links between quality variation, process improvement efforts, and production cost implications. Concrete compressive strength is reported in MPa, and slump is expressed in cm.

RESULT

Identification of Quality Problems

The initial analysis of quality control data showed that nonconformities in prestressed concrete piles primarily involved compressive strength. As shown in Figure 1, samples that did not meet the compressive strength specification accounted for approximately 95.24% of all nonconformities, while the remaining 4.76% involved slump test results.

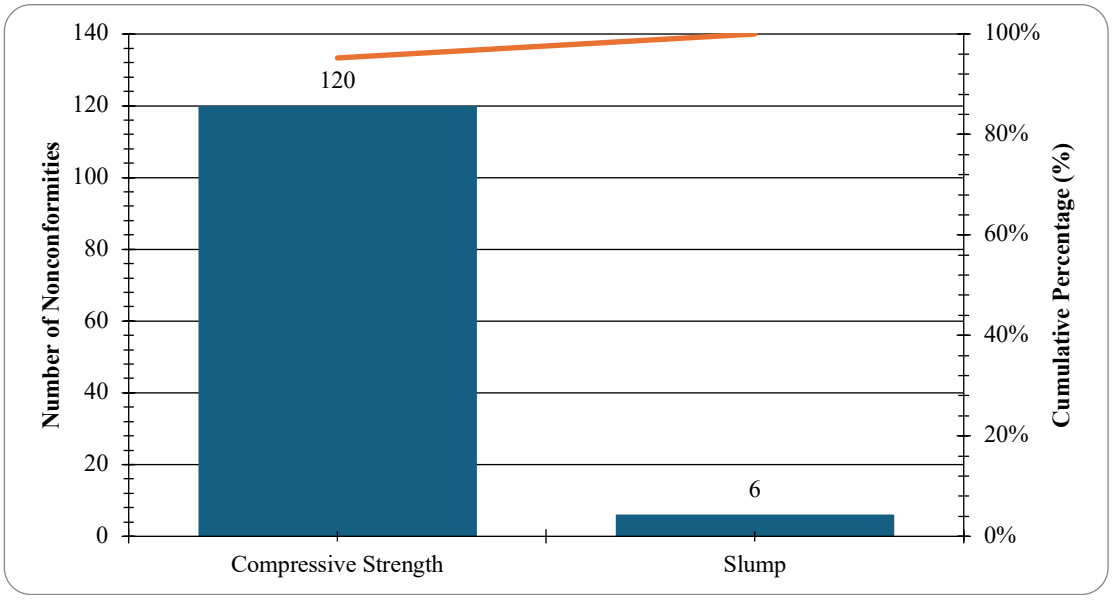

Figure 1. Quality Nonconformity Data

Initial Analysis Before Improvement

The initial quality control results are presented in Figures 2 and 3. The mean control chart (Figure 2) shows the variation in the mean of each production subgroup. The center line (CL) was 47.494 MPa, with an upper control limit (UCL) of 50.371 MPa and a lower control limit (LCL) of 44.618 MPa. Subgroup 11 was above the UCL, indicating that the initial process was not fully under statistical control. The range control chart (Figure 3) shows variation within the subgroups. The average range (CL) was 5.955 MPa, with a UCL of 11.934 MPa and an LCL of 0 MPa; all subgroup ranges were within the control limits.

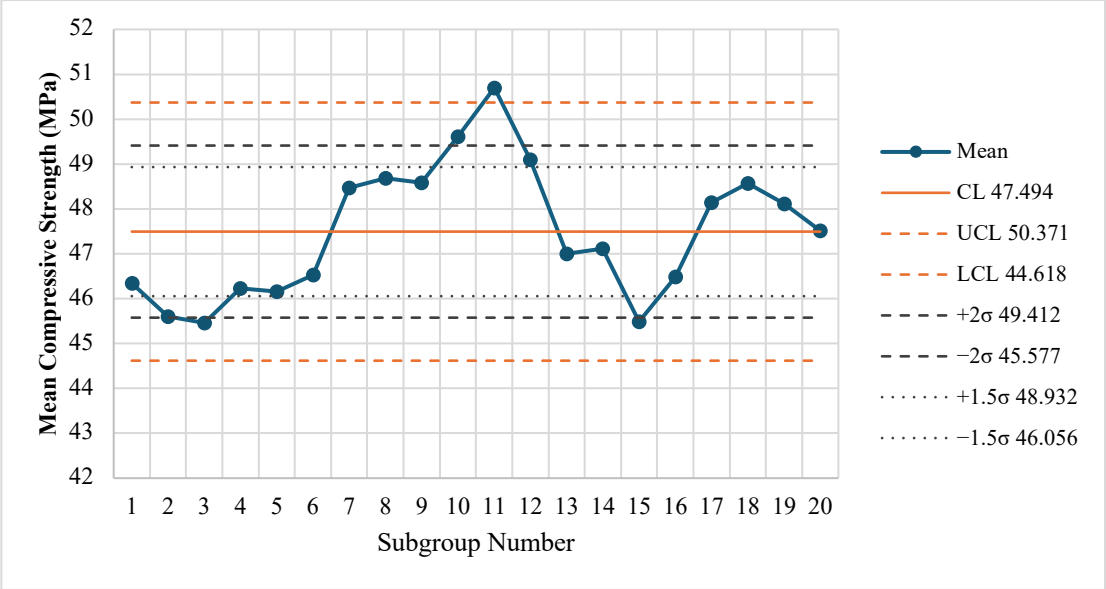

Figure 2. $\overline{x}$ Control Chart Before Improvement

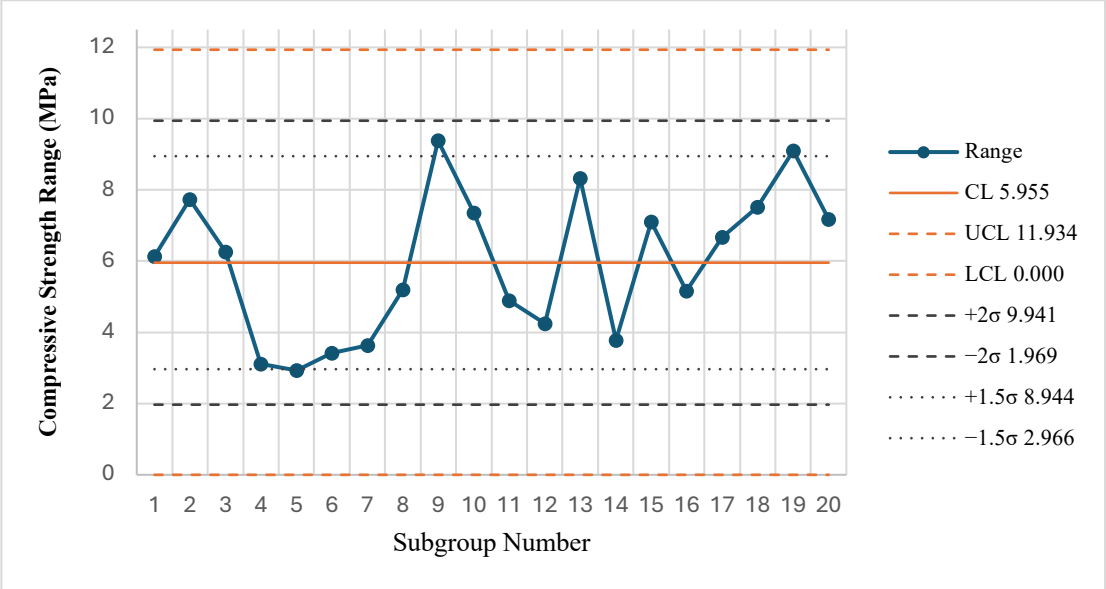

Figure 3. $\overline{R}$ Control Chart Before Improvement

The initial process capability index for the lower specification limit (Cpl) was calculated as 1.77. This index used a lower specification limit of 35 MPa and an estimate of the within-subgroup standard deviation. The value remained below 2.0 and indicated potential process capability relative to the lower specification limit. However, it needs to be interpreted alongside the control chart results because one subgroup mean remained outside the control limits. Thus, the initial production process did not demonstrate sufficient statistical stability to ensure consistent concrete quality over the long term (Montgomery, 2020).

Analysis of the Slump–Compressive Strength Relationship

The relationship between slump and concrete compressive strength is shown in Figure 4. The scatter plot reveals a clear negative relationship: increasing slump was accompanied by decreasing concrete compressive strength. Simple linear regression yielded Equation (1).

$$y = -2.1714x + 71.615 \quad (1)$$

In Equation (1), y is concrete compressive strength (MPa), and x is slump (cm). The coefficient of determination, $R^2 = 0.896$, indicates that approximately 89.6% of the variation in compressive strength can be explained by variation in slump. Slump is therefore strongly associated with compressive strength in prestressed concrete pile production. For a lower specification limit of 35 MPa, the equation gives an upper slump threshold of approximately 16.86 cm. The recommended operating range remains 12–16 cm, rather than the 10–14 cm interval specified in the previous working procedures. This requires a change to the standard quality control procedures at PT Varia Usaha Beton.

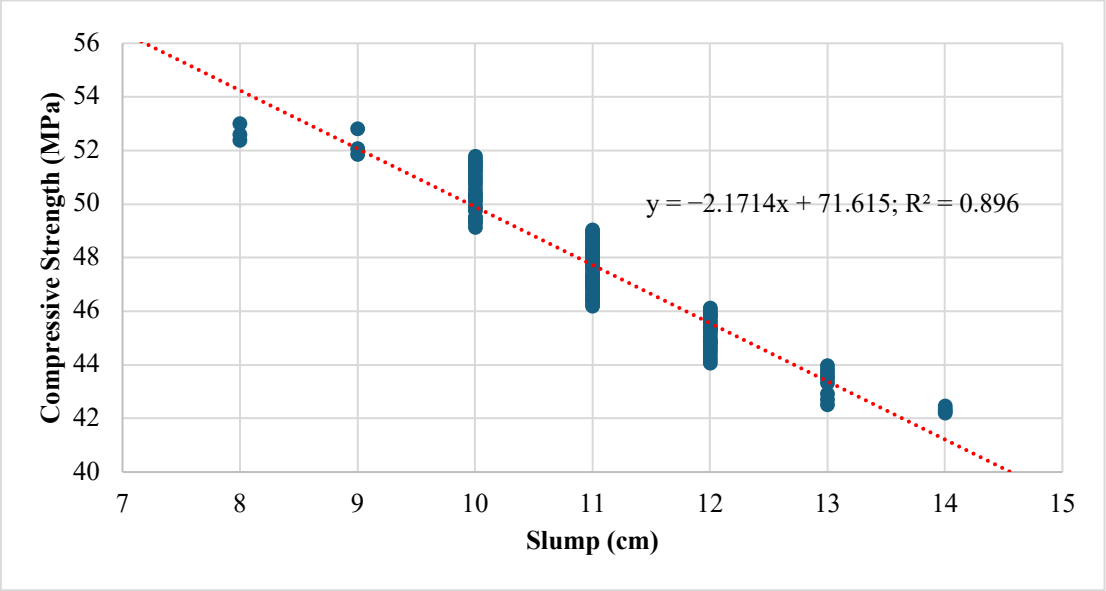

Figure 4. Scatter Plot of Compressive Strength

Analysis of the Causes of Quality Variation

The causes of nonconformities were identified using the fishbone diagrams shown in Figures 5 and 6. The fishbone analysis of concrete production (Figure 5) grouped potential causes into five main factors: materials, personnel, methods, machinery, and the environment. Material factors included aggregate size and grading, cement quality, and water testing standards. Personnel factors concerned operator skills and experience in

batching, transportation, and casting. Method factors included standard mixing and quality testing procedures, while machinery factors concerned the performance of the batching plant, truck mixer, and testing equipment.

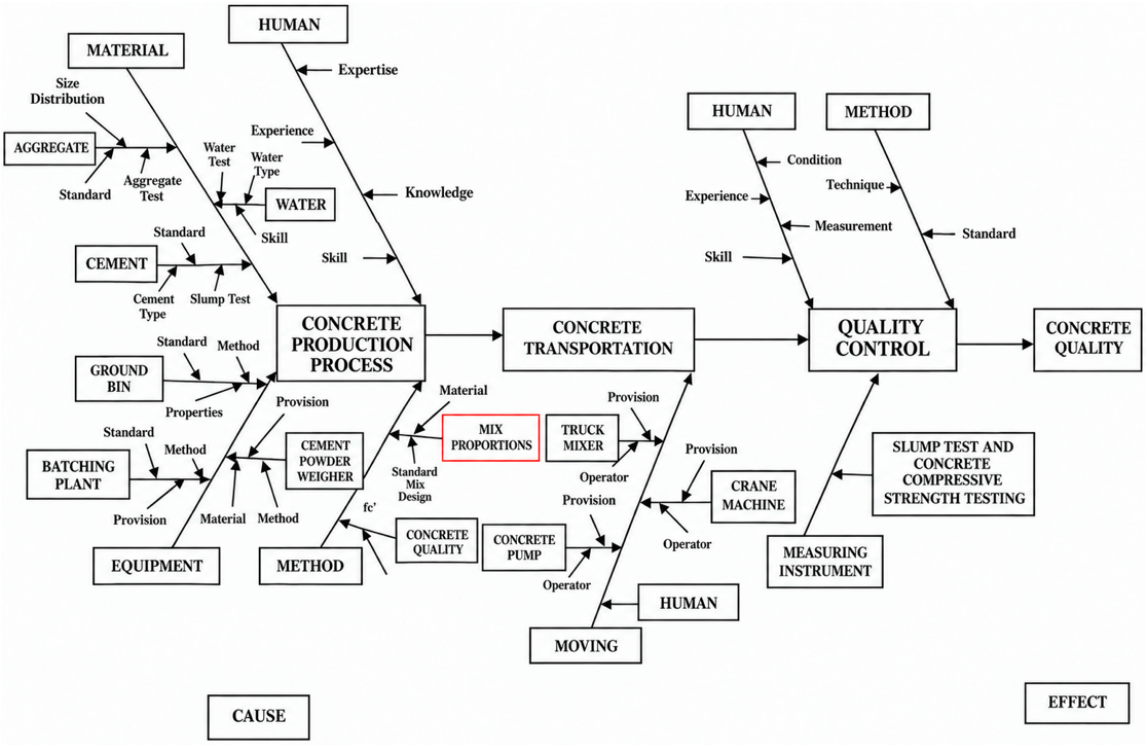

Figure 5. *Fishbone* Diagram of the Production Process

Further analysis focused on material factors through the mix design fishbone diagram (Figure 6). The results identified the water–cement ratio (w/c) as the dominant factor influencing concrete quality. Fine aggregates, coarse aggregates, fly ash, and additives also contributed to quality variation, in addition to water and cement. However, the greatest sensitivity remained associated with w/c. Small changes in w/c were found to strongly affect the resulting concrete compressive strength.

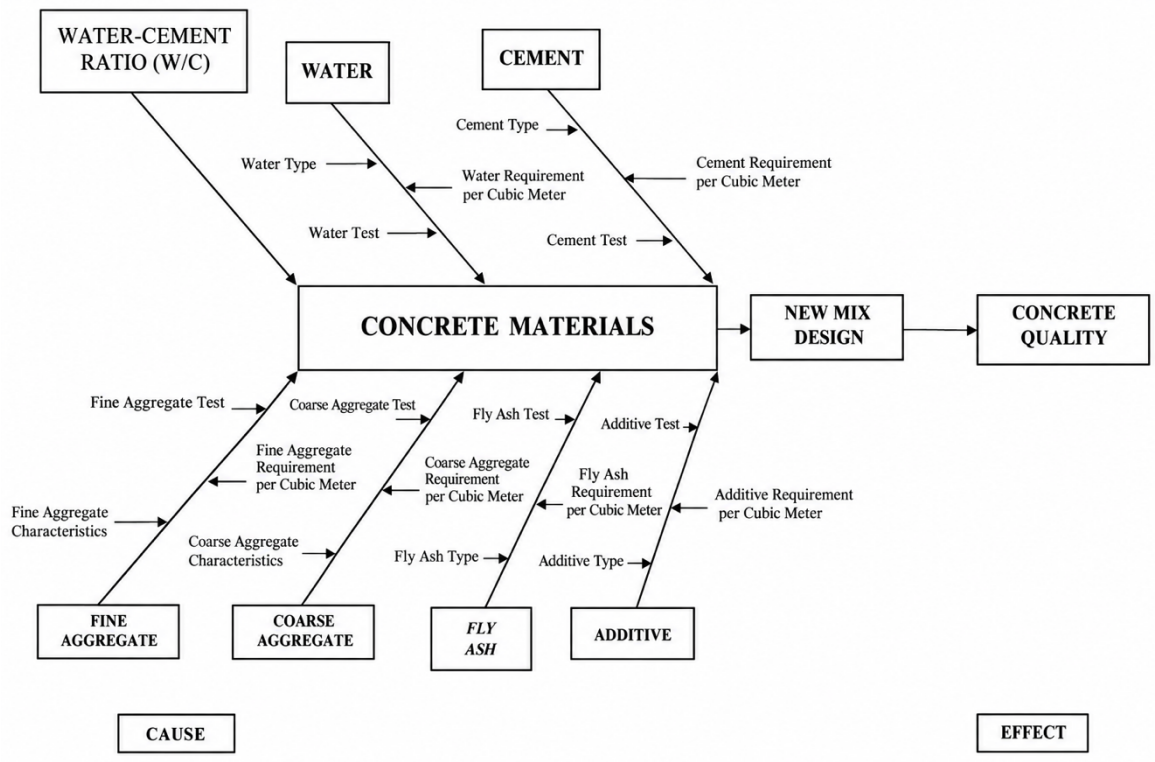

Figure 6. *Fishbone* Diagram of *Mix Design* Factors

Results of Production Process Improvement

Concrete quality improvement involved two main measures: adjusting the water–cement ratio from 0.36 to 0.38 and changing the standard slump range from 10–14 cm to 12–16 cm based on the regression results. The subsequent evaluation showed reduced within-subgroup variation, with the average range decreasing from 5.955 to 1.195 MPa. In Figure 7, the mean control chart has a CL of 37.874 MPa, a UCL of 38.451 MPa, and an LCL of 37.297 MPa. Subgroups 2, 6, 9, 12, and 16 remained outside the control limits. The range control chart in Figure 8 has a CL of 1.195 MPa, a UCL of 2.395 MPa, and an LCL of 0 MPa; subgroups 8 and 17 were above the UCL. Cpl increased from 1.77 to 2.03. This increase indicates improved potential process capability relative to the lower specification limit of 35 MPa. However, the process after improvement was not fully under statistical control and requires continued monitoring.

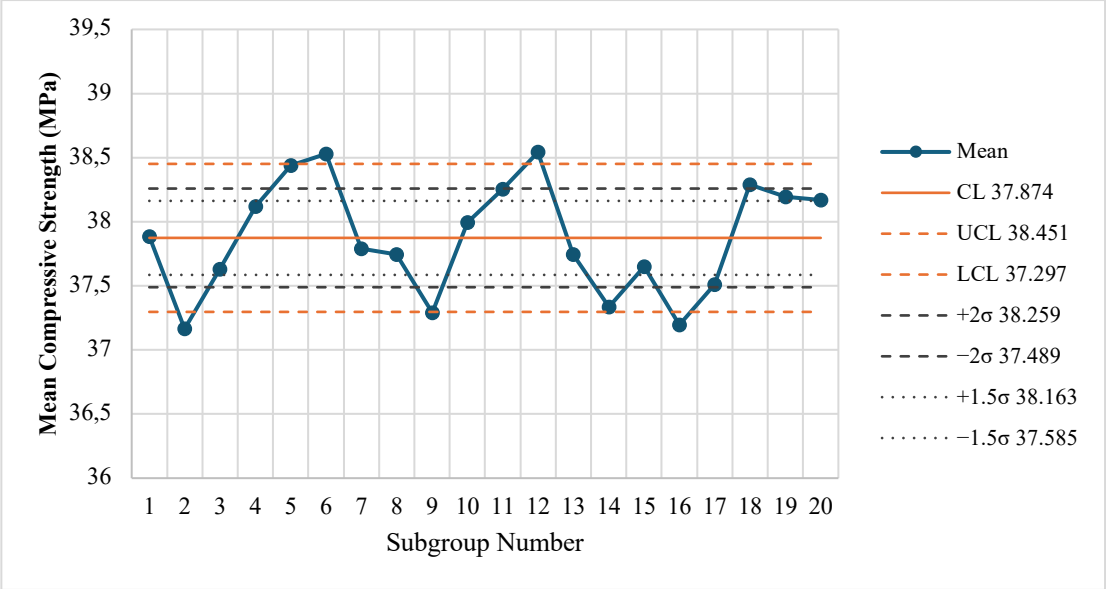

Figure 7. $\bar{x}$ Control Chart After Improvement

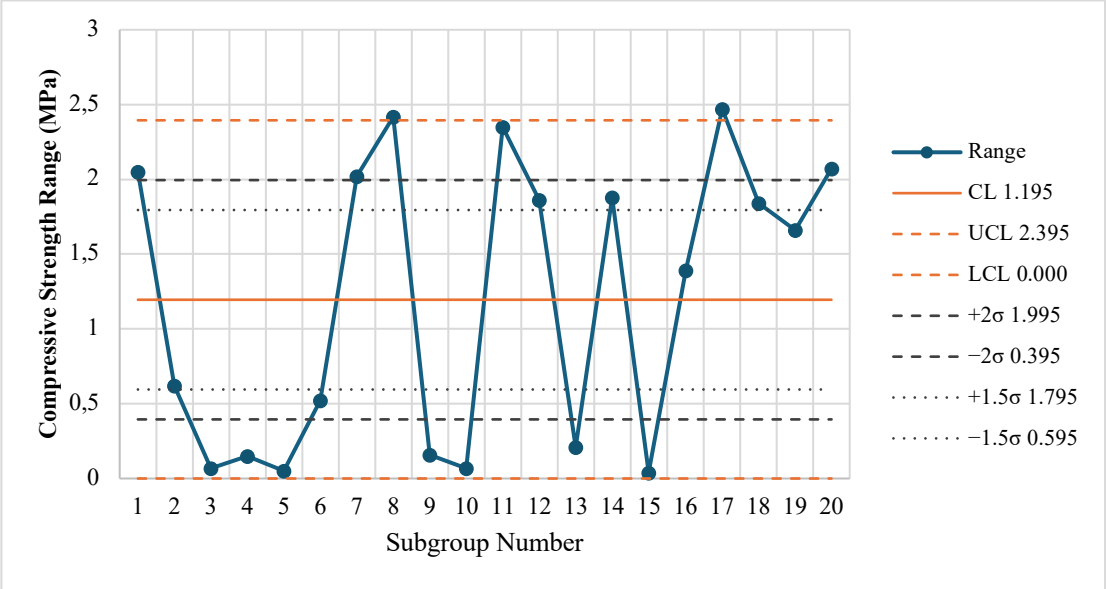

Figure 8. $\bar{R}$ Control Chart After Improvement

Production Cost Analysis

Production costs before and after SPC implementation are presented in Table 1. Overall, there were no significant changes in the main cost components, including tie wire, wire rod, PC wire, primer paint, and formwork; their unit prices and total costs per meter remained unchanged. The main difference involved concrete, whose unit price increased from Rp 853,000/m³ to Rp 897,895/m³. Consequently, the concrete cost per meter increased

from Rp 53,313/m to Rp 56,118/m. This change increased total production costs from Rp 135,649/m before SPC implementation to Rp 138,454/m afterwards. The total increase was Rp 2,805/m, or approximately 2.07% of the previous total cost.

Table 1. Production Cost Analysis

No.	Item	Unit	Qty. /m	Before SPC (Rp)		After SPC (Rp)	
				Unit Price	Cost /m	Unit Price	Cost /m
1	Tie wire	kg	0.045	12,300	557	12,300	557
2	Wire rod	kg	1.008	11,500	11,592	11,500	11,592
3	Concrete	m^3	0.063	853,000	53,313	897,895	56,118
4	PC wire	kg	1.254	14,300	17,939	14,300	17,939
5	Primer paint	kg	0.017	1,617,360	27,459	1,617,360	27,459
6	Formwork	m^2	0.170	145,802	24,789	145,802	24,789
Total					**135,649**		**138,454**

Note: Totals are the sums of the displayed costs per meter; material quantities are reported to three decimal places.

DISCUSSION

The 95.24% share of compressive strength nonconformities in Figure 1 provides the basis for discussing product quality. This finding indicates that concrete production at PT Varia Usaha Beton was relatively capable of maintaining consistent fresh concrete workability but still faced substantial challenges in ensuring that the final compressive strength met the required specifications. This is important because compressive strength is a key indicator of concrete structural quality and strongly determines the safety and performance of piles as foundation elements (Solís-Carcaño et al., 2008).

The predominance of compressive strength nonconformities indicates substantial process variation during mix design development and implementation. This variation may be influenced by fluctuations in the water–cement ratio, aggregate quality, or inconsistent mixing procedures. According to (Neville & Brooks, 1987) concrete compressive strength is highly sensitive to small changes in water content, aggregate grading, and compaction procedures. (Park et al., 2024) reported similar conditions, identifying inadequate control of the water–cement ratio as a major cause of concrete quality deviations in mass production.

Before improvement, the Cpl value of 1.77 indicated potential process capability relative to the lower specification limit. This finding is consistent with (Aprilia & Suryanto Hs, 2020) who reported that the Cp of floor panels was only 1 before improvement and increased after production parameters were adjusted. (Jannah & Dani, 2018) likewise showed that a low Cp indicated substantial quality variation in concrete roof tiles. In the present study, the increase in the index needs to be interpreted alongside the control chart results because one subgroup mean before improvement remained outside the control limits. Controlling the causes of variation therefore remains necessary to maintain consistent quality.

The negative slump–compressive strength relationship in Figure 4 provides a basis for setting the slump range at 12–16 cm. The regression results reinforce the importance of slump control in maintaining concrete quality. Slump below 12 cm produces concrete with limited workability, creating a risk of workmanship defects despite high compressive strength. Conversely, slump above 16 cm results in excess water in the mixture, increasing concrete porosity and significantly reducing compressive strength (Neville & Brooks, 1987).

Investigation of the causes of quality variation complements the analysis of the slump–compressive strength relationship. The fishbone analysis confirmed that quality variation in prestressed concrete piles was primarily caused by the water–cement ratio. This factor is directly related to the regression results in Figure 4, which show a very strong negative correlation between slump and compressive strength. Thus, w/c is a critical variable that requires strict control. According to (Neville & Brooks, 1987) even small fluctuations in w/c can produce significant differences in concrete compressive strength and durability. This finding is consistent with (Robertson & Ley, 2020) who stated that concrete quality depends heavily on the control of material parameters such as w/c.

The post-improvement evaluation in Figures 7 and 8 showed an increase in Cpl from 1.77 to 2.03 and a decrease in the average within-subgroup range. These results indicate that adjusting the water–cement ratio and establishing a new slump interval were associated with reduced variation in concrete quality. However, five subgroups on the mean control chart and two on the range control chart remained outside the control limits. Therefore, the index of 2.03 indicates potential capability relative to the lower specification limit; it does not establish that the process is fully under control or consistently meets specifications (Montgomery, 2020). With slump controlled within 12–16 cm, efforts to maintain

workability and compressive strength need to be accompanied by monitoring and investigation of the remaining causes of variation. (Hübsch, 2007) also demonstrated the importance of controlling mix design parameters to improve process capability in precast products.

The increase in production costs after SPC implementation was mainly attributable to changes in the concrete mix design: the water–cement ratio was adjusted from 0.36 to 0.38, and the slump range was changed from 10–14 cm to 12–16 cm. These adjustments increased concrete material requirements and directly increased the unit price of concrete. Nevertheless, the cost increase of 2.07% was relatively small compared with the increase in Cpl from 1.77 to 2.03.

This moderate cost increase can be viewed as a long-term investment because controlling concrete quality variation is expected to reduce the risk of nonconforming products, customer claims, and on-site rework. This is consistent with (Lins et al., 2025) who emphasized that, although SPC implementation increases production costs, the long-term benefits of quality control and cost savings from reduced production losses are substantially greater.

CONCLUSION

This study showed that adjusting w/c from 0.36 to 0.38 and the slump range from 10–14 cm to 12–16 cm was associated with reduced variation in concrete quality. The average within-subgroup range decreased from 5.955 to 1.195 MPa, while the process capability index for the lower specification limit of 35 MPa (Cpl) increased from 1.77 to 2.03. However, several subgroups remained outside the control limits after improvement, indicating that process stability needs to be improved through continued monitoring. The production cost increase of Rp 2,805/m, or 2.07%, provides a basis for considering the economic implications of quality improvement. These findings support control of the water–cement ratio and slump as part of efforts to maintain the quality of prestressed concrete piles.

This study was limited to one plant and an evaluation of material costs before and after improvement. Predictions of compressive strength at slump values above the initial observed range also require validation through direct testing. Future research could extend the monitoring period, examine application under other production conditions, and evaluate SPC implementation costs more comprehensively.

Artificial Intelligence (AI) Use Statement

Grammarly was used solely to assist with language refinement, grammar checking, and stylistic editing of the manuscript. It was not used to generate research data, perform statistical analyses, interpret research findings, or formulate scientific conclusions. All suggested revisions were reviewed and verified by the authors, who take full responsibility for the accuracy, integrity, and final content of the manuscript.

Author Contribution Statement

Nurul Kurniawan: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing original draft. Budi Witjaksana: Conceptualization, Methodology, Validation, Supervision, Writing – review & editing. Hanie Teki Tjendani: Validation, Supervision, Writing – review & editing. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for its content.

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Conflict of Interest Statement

The authors declare that they have no financial, professional, institutional, or personal conflicts of interest that could have influenced the design, conduct, analysis, interpretation, or reporting of this study.

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NOMENCLATURE

x	Slump (cm)
y	Concrete compressive strength (MPa)
Cpl	Process capability index for the lower specification limit (dimensionless)

R^2	Coefficient of determination (dimensionless)
w/c	Water–cement ratio (dimensionless)
CL	Control chart center line (MPa)
UCL	Upper control limit (MPa)
LCL	Lower control limit (MPa)
LSL	Lower specification limit for concrete compressive strength (MPa)
$\bar{X}$	Mean compressive strength within a subgroup (MPa)
$\bar{R}$	Compressive strength range within a subgroup (MPa)
σ	Standard deviation of the statistic monitored on the control chart (MPa)