IJASCE : Int. J. of Adv. Sci. Comp. and Eng, 8(2) - August 2026 30-38

International Journal of
Advanced Science Computing and Engineering

Journal Homepage www.ijasce.org/index.php/ijasce

Enhancing Material Quality Control in Construction: A Data-Driven Approach Using PDCA and DMAIC

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Abstract*—Quality control is a critical aspect of construction projects, ensuring that materials and implementation align with established standards. This study focuses on the quality control of ready-mix concrete used in the capping beam lining works of the Cipelang Irrigation Modernization Project. Initial observations indicated that some concrete materials did not meet the required compressive strength, potentially compromising structural integrity and durability. To address these concerns, the study applied PDCA and DMAIC methodologies to systematically monitor and enhance material quality. Compressive strength tests were performed in accordance with ASTM C39 and BS EN 12390-3 standards, covering specimen preparation, curing, and testing procedures. Additionally, Statistical Process Control (SPC) techniques, including control charts, were utilized to identify variations in mix composition and implement necessary corrective actions. A deeper analysis using Failure Mode and Effect Analysis (FMEA) revealed that quality issues stemmed from three primary factors: human resources, materials, and methodologies. Through corrective measures, the study achieved significant improvements in concrete quality. The hammer test results showed an increase of 42 kg/cm² (~26.25%), while the compressive strength test results improved by 68.17 kg/cm² (~40%). These enhancements reduced material defects, minimized rework, and ensured adherence to project quality requirements. By adopting a structured, systematic approach, this study presents a scalable quality control framework applicable to similar construction projects. The findings contribute to safer, high-quality, and sustainable infrastructure by optimizing material performance and reducing quality inconsistencies.

***Keywords*—Cipelang irrigation project; compressive strength testing; PDCA and DMAIC methods; ready-mix concrete quality; statistical process control.**

Manuscript received 19 Feb. 2025; revised 28 Dec. 2025; accepted 7 Mar. 2026. Date of publication 31 Aug. 2026.

I. INTRODUCTION

Implementing quality control is critical in construction projects to ensure they progress according to established plans and standards. Quality control plays a pivotal role in ensuring the effective execution of construction activities, enabling timely completion and compliance with the required quality benchmarks. Besides, the selection and use of construction materials must strictly adhere to predefined specifications to guarantee the durability of the structure and meet client expectations[1]. Effective construction quality processes can provide a competitive advantage by reducing defects and improving project outcomes [2], [3], [4]. The rigorous implementation of quality control measures, including standardized material testing and monitoring, is crucial to maintain structural integrity over time.

Continuous monitoring and quality control are essential to ensure the consistent performance and reliability of ready-mix concrete in construction projects. This process involves thoroughly evaluating the concrete's compressive strength, a critical property that significantly influences structural integrity and overall quality. The compressive strength test typically involves preparing concrete specimens, curing them under controlled conditions (temperature, humidity), and then applying axial loads until failure. The maximum resistance achieved before failure directly measures the concrete's strength. This standardized testing procedure, such as ASTM C39 or BS EN 12390-3, ensures that the concrete meets the specified design strength and functional requirements [5].

The centralized procurement approach in construction projects emphasizes standardized material selection processes to maintain quality and durability. Moreover, quality control in construction companies plays a crucial role in preventing costly rework and project delays caused by discrepancies in material properties. By systematically monitoring production processes and material quality, companies can identify and address potential issues early [6], [7]. For example, using

Statistical Process Control (SPC) techniques, such as control charts (e.g., Shewhart charts), can help track variations in concrete mix composition and detect deviations from target values. This allows for timely adjustments to maintain the required quality standards.

Based on observations at the Cipelang Irrigation Modernization Project, not all materials met the specified requirements. Some concrete materials exhibited compressive strength values below the established standards. Materials that do not meet specifications are undesirable for the company and can affect the integrity and longevity of the structures. Therefore, implementing quality control measures for the concrete materials used in the Cipelang Irrigation Modernization Project is crucial. This study specifically focuses on the quality control of materials used for the capping beam lining works. Product defects stem from five main factors: human (man), raw materials, machinery, methods, and environment. These factors interact in complex ways, affecting the quality and performance of construction materials and processes. To better understand and address these variables, this study examines how each factor affects the quality of ready-mix concrete used in the Cipelang Irrigation Modernization Project. The research focuses on identifying and controlling defects caused by these elements to ensure the durability, safety, and longevity of the concrete structures.

Therefore, this research aims to systematically apply the Plan-Do-Check-Act (PDCA) and Define-Measure-Analyze-Improve-Control (DMAIC) methodologies to monitor and improve the quality of the ready-mix concrete materials [8], [9]. By doing so, the research seeks to reduce defects, prevent rework, and ensure compliance with the project's quality standards. These methods could help to address issues related to human error, variations in raw material quality, machinery issues, process inefficiencies, and environmental factors. The goal is to establish a robust quality control framework that can be adapted for similar construction projects, ultimately delivering safe, high-quality infrastructure.

II. Materials and Method

The study focused on identifying factors that affect the quality of concrete used in the project's capping beam lining, specifically by analyzing and addressing challenges in maintaining optimal quality. The research variables consisted of independent and dependent variables. The independent variables included five key factors: man (X_1), machine (X_2), material (X_3), method (X_4), and environment (X_5). These factors were hypothesized to affect concrete quality. The dependent variable was concrete quality (Y), measured by its performance in casting the capping beam lining. Data were collected from both primary and secondary sources. Primary data were obtained via direct field observations and structured interviews with project personnel involved in the concrete casting processes. Observations focused on identifying operational practices and any deviations that might affect quality. Secondary data were collected from various sources, including laboratory compressive strength test results, material composition data from the concrete plant, and relevant project-related literature and technical documentation.

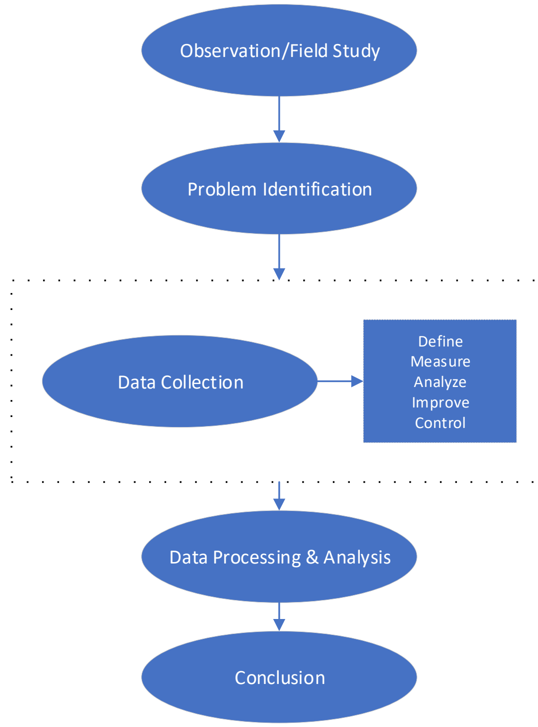

Fig.1 Research Methodology

The research methodology followed a systematic procedure. First, field observations documented and analyzed the concrete casting process. These observations aimed to identify variables influencing quality issues in the capping beam lining. Next, the team identified problems based on discrepancies in ready-mix concrete quality, aiming to determine root causes and propose corrective actions. Data collection involved qualitative inputs from interviews and observations as well as quantitative data from laboratory tests and material records. Additionally, a comprehensive literature review examined established quality control methods and their applicability to concrete casting processes. This review included studies on concrete material quality and methodologies such as PDCA (Plan-Do-Check-Act) and DMAIC (Define-Measure-Analyze-Improve-Control).

The analytical framework incorporated both the PDCA and DMAIC methodologies. The PDCA cycle began with the planning phase, where we identified goals and hypothesized causes of quality issues using the 5W framework (What, Who, Where, When, Why). This was followed by the "Do" phase, involving laboratory tests to measure compressive strength. In the "Check" phase, we compared actual field conditions with theoretical benchmarks. Finally, the "Act" phase implemented corrective measures, including improved curing techniques and the use of vibrators for better compaction.

The DMAIC approach complemented the PDCA cycle with its structured problem-solving steps. The "Define" phase involved developing a problem framework, incorporating SIPOC diagrams and customer requirements. The "Measure" phase analyzed compressive strength test data and used Pareto charts to identify defect trends. During the "Analyze" phase, fishbone diagrams identified root causes, and Failure Mode and Effects Analysis (FMEA) evaluated risks and prioritized corrective actions. In the "Improve" phase, the team implemented solutions such as updating standard operating procedures (SOPs) and training workers. In the "Control" phase, the team monitored outcomes over three months, validated results through additional testing, and established standardized procedures to ensure sustainability.

Evaluation and continuous improvement were integral to the research process. We assessed corrective actions through focus group discussions (FGDs) and worker training sessions. The team evaluated the effectiveness of these measures using compressive strength tests and hammer tests conducted during the observation period. These evaluations informed the development of standardized processes to ensure the long-term sustainability of quality improvements in concrete casting practices.

III. Results and Discussion

A. PDCA Method - Plan Stage

In concrete work, various issues may arise, such as cast concrete materials failing to meet specified requirements, worker negligence or disregard for established regulations, and incomplete adherence to work methods or standard operating procedures (SOP). To address these issues, we conducted field observations at the Cipelang Irrigation Modernization Project by visually inspecting the results of ready-mix concrete casting in the irrigation channel areas. The field observations revealed several locations with substandard casting results, as detailed in the table below:

TABLE I
CONCRETE CASTING RESULTS ON CAPPING BEAM LINING WORK

No	Location	Photo of Casting Results	Notes
1	*Capping beam lining:* CP 182 KA		Honeycomb defects
2	*Capping beam lining:* CP 184 KA		Cracks observed

Table I shows the results of concrete casting for the capping beam lining work, highlighting construction defects at two distinct locations. At location CP 182 KA, the accompanying photograph and notes reveal "honeycomb defects," which appear as rough, pitted areas on the side of the poured concrete. At the second location, CP 184 KA, the visual evidence and corresponding notes indicate that visible "cracks" ran across the surface of the concrete beam.

The issues related to the quality of the cast concrete materials in the capping beam lining were identified using the 5W approach (what, who, where, when, why), as follows:

TABLE II
IDENTIFICATION OF CAST CONCRETE ISSUES

No	What	Who	Where	When	Why
1	Substandard visual quality of ready-mix concrete	Contractor	Capping beam lining CP 182 KA	08 Feb 2023	Honeycomb defects in cast concrete
2	Substandard visual quality of ready-mix concrete	Contractor	Capping beam lining CP 184 KA	17 Feb 2023	Cracks in cast concrete

The table highlights defects such as honeycomb and cracks in the cast concrete observed on February 8, 2023, at CP 182 KA and February 17, 2023, at CP 184 KA. These defects deviate from the required specifications, which require a smooth, even concrete surface. Therefore, we analyzed the causes of the honeycomb and cracks and developed corrective measures to prevent recurrence.

B. PDCA Method - Check Stage

The third stage of the PDCA method involves checking. Field inspections were conducted on the capping beam lining works to compare theoretical standards with practical implementation. Inspections of the concrete casting at CP 182 KA on November 17, 2023, revealed the following analysis:

TABLE III
INSPECTION OF CAPPING BEAM LINING WORK BASED ON THEORETICAL REVIEW

No.	Required Action	Field Observations
1	Finishing should be performed meticulously using appropriate tools	Finishing done using "ruskam"
2	Concrete slump should meet specifications	Slump met specifications (12 cm, within 5–12 cm)
3	Concrete curing should be conducted properly	Curing not performed
4	Concrete should be compacted properly using appropriate tools	Compaction done without a vibrator
5	The workability of the concrete used must meet the requirements (concrete slump must meet the specifications) The concrete slump meets the specifications.	The slump value obtained is 12 cm, where the slump requirement in the specifications is 5-12 cm

Based on the table above, several deficiencies were identified: no concrete curing and improper compaction without using a vibrator.

C. PDCA Method - Action Stage

The Action stage involved implementing corrective measures for concrete casting based on findings from the Check stage. Improvements included applying proper curing techniques and using vibrators to compact the concrete.

TABLE IV
NECESSARY ACTIONS FOR CONCRETE CASTING IMPROVEMENTS

No.	Issue	Correctional Action
1	Curing not performed	Implement proper curing for a minimum of 7 days
2	Vibrator not used for compaction	Ensure vibrators are used during concrete casting

D. DMAIC Method - Define Stage

1) Problem Framework Development

This stage defines the scope of work, team resources, problems, stakeholder requirements, quality targets, and project goals. Table V outlines the development of the problem framework for casting the capping beam lining, involving an Engineer, a Quality Control Technician, and casual laborers. The framework addresses two main issues: non-conformant construction practices and substandard cast concrete. Critical stakeholder needs include thorough preparation, strict SOP adherence during pouring, proper curing, routine testing, and a high-quality surface finish. To meet these needs, the concrete must be crack-, honeycombing-, and porosity-free, with a smooth surface, and meet slump and strength standards. The project aims to eliminate material defects, meet customer expectations, and ensure consistent SOP implementation.

TABLE V
PROBLEM FRAMEWORK DEVELOPMENT

Category	Description
Scope of work	Casting process of *capping beam lining*
Team resources	1. Engineer 2. Quality Control Technician 3. Daily workers / Casual laborers
Problem/case to be solved	1. Non-conformity of work with standard operating procedures 2. The quality of the cast concrete material does not meet the required specifications
Stakeholder needs	1. Good concrete surface finish 2. Concrete curing is performed 3. Concrete testing is performed 4. Preparation is done before casting 5. Casting according to SOP (Standard Operating Procedure)
Quality	1. No cracks 2. No honeycombing/porosity 3. Surface is not rough 4. Slump and compressive strength meet requirements
Project goal	1. No material defects in the finished work 2. Customer desires are fulfilled 3. Work SOP is implemented

2) SIPOC Diagram

The SIPOC diagram provides information on the suppliers, Inputs, Processes, Outputs, and Customers involved in the production process.

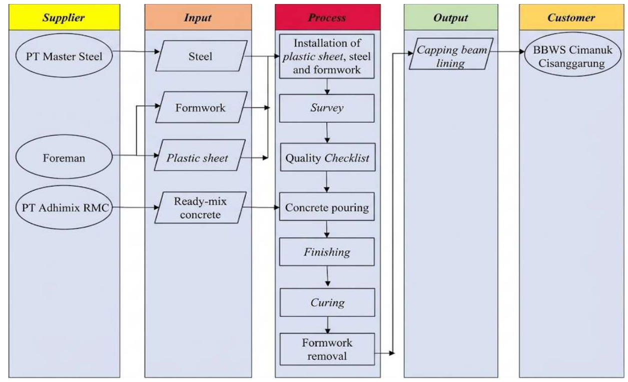

Fig. 2 SIPOC Diagram for Capping Beam Lining Casting

E. DMAIC Method - Measure Stage

The Measure stage is focused on evaluating current performance. Data from compressive strength tests on concrete materials were collected and analyzed using a Pareto diagram. Data from compressive strength tests conducted from February to April 2023 are presented as follows:

TABLE VI
COMPRESSIVE STRENGTH TEST RESULTS - FEBRUARY 2023

No.	Date of Sampling	Sampling Position	28 Days (Kg/cm^2)			
			X_1	X_2	X_3	Average
1	01- Feb- 2023	Partition flooring CP 79 Ka	190.43	193.89	189.27	191.20
2	02- Feb- 2023	Parapet Lining CP 30 Ki	178.89	182.35	184.66	181.97
3	03- Feb- 2023	Parapet Lining CP 30 Ki	188.12	191.58	189.27	189.66
4	08- Feb- 2023	Capping beam lining CP 102 Ka	184.08	183.50	186.97	184.85
5	08- Feb- 2023	Capping beam lining CP 182 Ka	169.08	170.23	171.96	170.42
6	11- Feb- 2023	Capping beam lining CP 185 Ka	185.81	191.58	191.00	189.46
7	11- Feb- 2023	Capping beam lining CP 188 Ka	192.16	187.54	189.85	189.85
8	12- Feb- 2023	Capping beam lining CP 112 Ki	191.00	192.74	194.47	192.74
9	14- Feb- 2023	Capping beam lining CP 114 Ka	194.47	195.62	196.78	195.62
10	14- Feb- 2023	Capping beam lining CP 114 Ki	195.62	197.93	191.58	195.04
11	17- Feb- 2023	Capping beam lining CP 184 Ka	173.69	172.54	174.85	173.69
12	20- Feb- 2023	Excluder building shelter wall	174.27	167.92	170.81	171.00
13	21- Feb- 2023	Capping beam CCSP CL CP 99	193.89	189.85	186.97	190.24
14	23- Feb- 2023	Capping beam CCSP CL CP 104	197.93	198.51	194.47	196.97
15	26- Feb- 2023	Capping beam CCSP CL CP 146	195.62	194.47	193.31	194.47

Source: Cipelang Irrigation Modernization Project Laboratory

TABLE VII
COMPRESSIVE STRENGTH TEST RESULTS MARCH 2023

No.	Date of Sampling	Sampling Position	28 Days (Kg/cm^2)			
			X_1	X_2	X_3	Average
1	04- Mar- 2023	Capping beam CCSP CP 80 Ki	190.54	187.65	187.65	188.61
2	05- Mar- 2023	Partition flooring CP 99 Ka	181.88	170.60	171.20	174.56
3	06- Mar- 2023	Capping beam lining CP 227 Ka	178.89	181.19	214.66	191.58
4	07- Mar- 2023	Capping beam lining CP 190 Ki	173.12	174.27	171.96	173.12
5	08- Mar- 2023	Partition flooring CP 118 Ka	188.11	191.58	192.73	190.81
6	11- Mar- 2023	Capping beam lining CP 239 Ki	250.00	244.30	251.45	248.58
7	15- Mar- 2023	Capping beam lining CP 190 Ka	161.40	167.10	159.00	162.50
8	17- Mar- 2023	Partition flooring CP 95 Ka	195.04	200.81	203.12	199.66
9	18- Mar- 2023	Capping beam lining CP 237 Ki	193.88	197.35	205.43	198.89
10	20- Mar- 2023	Capping beam lining CP 235 Ki	234.72	238.01	233.80	235.51
11	20- Mar- 2023	Partition flooring CP 97 Ka	229.70	239.33	231.89	233.64
12	21- Mar- 2023	Capping beam lining CP 190 Ki	163.10	164.40	166.30	164.60
13	23- Mar- 2023	Partition flooring CP 97 Ka	195.04	190.43	197.35	194.27
14	24- Mar- 2023	Capping beam lining CP 239 Ka	222.74	181.19	183.50	195.81
15	25- Mar- 2023	Partition flooring CP 98 Ka	172.90	174.30	169.40	172.20
16	26- Mar- 2023	Tapping floor 1.1CP 134 Ki	181.77	196.20	200.81	192.93
17	27- Mar- 2023	Capping beam lining CP 236 Ki	161.90	162.40	165.20	163.17
18	28- Mar- 2023	Capping beam lining CP 229 Ka	197.35	199.66	193.89	196.97
19	30- Mar- 2023	Capping beam lining CP 223 Ki	190.43	208.12	198.51	197.35

Source: Cipelang Irrigation Modernization Project Laboratory

TABLE VIII
COMPRESSIVE STRENGTH TEST RESULTS APRIL 2023

No.	Date of Sampling	Sampling Position	28 Days (Kg/cm2)			
			X1	X2	X3	Average
1	05- Apr- 2023	CP 99 Ki Capping beam CCSP	196.20	203.12	200.81	200.04
2	06- Apr- 2023	Capping beam lining CP 237 Ka	189.27	192.74	199.66	193.89
3	08- Apr- 2023	Capping beam lining CP 235 Ka	183.50	188.12	192.74	188.12
4	09- Apr- 2023	CP 99 Ki Capping beam CCSP	201.97	197.35	177.73	192.35
5	11- Apr- 2023	CP 118 Ka Lantai Partisi	196.20	199.66	201.97	199.28
6	11- Apr- 2023	CP 102 Ka Lantai Partisi	200.81	196.20	193.89	196.97
7	12- Apr- 2023	Capping beam lining CP 229 Ki	195.97	205.83	200.90	200.90
8	13- Apr- 2023	CP 98 Ki Capping beam CCSP	182.99	182.27	182.63	182.63
9	14- Apr- 2023	Capping beam lining CP 227 Ki	156.94	161.04	156.65	158.21
10	15- Apr- 2023	Capping beam lining CP 223 Ka	189.27	192.74	190.43	190.81
11	16- Apr- 2023	Capping beam lining CP 214 Ki	196.20	193.89	191.58	193.89
12	17- Apr- 2023	CP 98 Ki Capping CCSP	174.60	171.80	173.50	173.30
13	17- Apr- 2023	Capping beam lining CP 210 Ki	175.06	187.70	176.22	179.66
14	19- Apr- 2023	CP 105 Ki Capping CCSP	200.91	171.83	224.28	199.01
15	20- Apr- 2023	Capping beam lining CP 239 Ka	178.07	205.12	202.99	195.39
16	21- Apr- 2023	Capping beam lining CP 236 Ka	182.79	187.18	183.35	184.44
17	22- Apr- 2023	CP 120-121 Ki Capping beam CCSP	178.76	202.93	165.08	182.26
18	23- Apr- 2023	Capping beam lining CP 198 Ka	181.52	213.14	186.72	193.79
19	24- Apr- 2023	CP 105 Ka Lantai Partisi	171.80	173.40	175.10	173.43
20	25- Apr- 2023	CP 118 Ka Lantai Partisi	195.54	186.25	212.97	198.25
21	26- Apr- 2023	Capping beam lining CP 196 Ki	164.70	158.90	164.40	162.67
22	27- Apr- 2023	Capping beam lining CP 230 Ki	198.70	181.90	168.30	182.97
23	28- Apr- 2023	CP 105 Ka Lantai Partisi	220.47	187.81	191.45	199.91
24	30- Apr- 2023	Capping beam lining CP 230 Ka	179.10	199.10	201.40	193.20

Source: Cipelang Irrigation Modernization Project Laboratory

Based on the data collected from February to April 2023, the following defects were observed. The following is a Pareto diagram of concrete work that did not meet the minimum compressive strength value for February-April 2023.

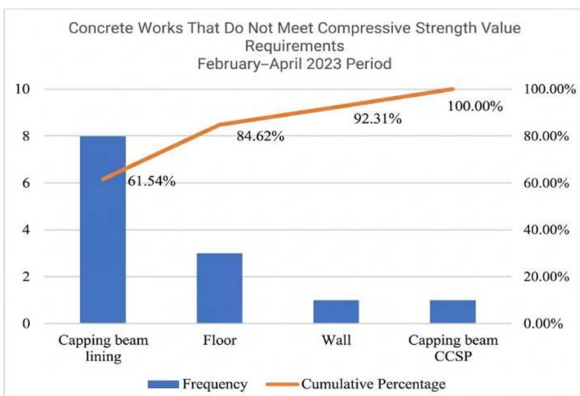

Fig. 3 Pareto diagram of concrete materials that do not meet the minimum concrete compressive strength value. Source: Data Processing

The Pareto analysis showed that the highest number of defects occurred in the capping beam lining work (61.54%), followed by floor work (23.08%) and wall work (7.69%).

F. *DMAIC Method - Analyze Stage*

In this stage, we analyzed the factors contributing to the quality issues observed in the capping beam lining work. We did this by comparing the ongoing fieldwork with the results of the theoretical review (including previous PDCA research), the required material specifications, VOCs, and process maps.

1) Fishbone Diagram and FMEA Analysis

The Fishbone diagram identified potential causes of defects in concrete quality, categorized as Man, Machine, Material, Method, and Environment. The FMEA (Failure Modes and Effects Analysis) method was then applied to assess which factors posed the highest risk for defects. Table IX outlines the observations of quality indicators during capping beam lining concrete work, evaluating the construction process across five fundamental factors

TABLE IX
OBSERVATIONS OF QUALITY INDICATORS IN CAPPING BEAM LINING CONCRETE WORK

No	Factor	Ideal Condition	Observed Condition	Notes
1	Man	Competent workers, adequate supervision	Workers not inducted, lack of knowledge	High impact on quality
2	Machine	Proper machine usage to ensure efficient work	Concrete pouring controlled by mixer truck speed	No quality issue identified
3	Material	High-quality materials with proper specifications	Clean formwork, correct material composition	Formwork material residuals present
4	Method	Clear, complete work methods (SOP)	Incomplete method application, lack of vibration, no curing	Significant impact on quality
5	Environment	Favorable environmental conditions (weather)	Mild weather, no adverse conditions	No impact on concrete quality

Man, Machine, Material, Method, and Environment. For each factor, the table contrasts the theoretical ideal conditions required for optimal results against the actual conditions observed on-site, followed by notes on how these discrepancies impacted overall quality. The most severe deficiencies were identified within the "Man" and "Method" factors, both of which were noted to have a high or significant impact on quality. Ideally, the workforce should consist of competent workers under adequate supervision. However, observations showed that workers lacked the necessary knowledge and had not been properly inducted. Similarly, the construction methods fell short of the ideal, clear standard operating procedures. They applied these methods incompletely, omitting critical quality-control steps such as concrete vibration and curing.

Conversely, the remaining three factors did not present major quality issues. The "Machine" factor, which ideally involves proper use for efficiency, was observed as the mixer truck's speed controlling the concrete pour; this was deemed to have no identified negative impact. For the "Material" factor, the ideal standard is high-quality materials matching specifications. While the observed material composition was correct and the formwork was mostly clean, minor residue remained. Finally, the "Environment" factor met the ideal condition, as mild weather provided favorable circumstances with no adverse effects on concrete quality. Based on the table above, a fishbone diagram was made regarding the factors that cause defects in the capping beam lining concrete material, namely as follows:

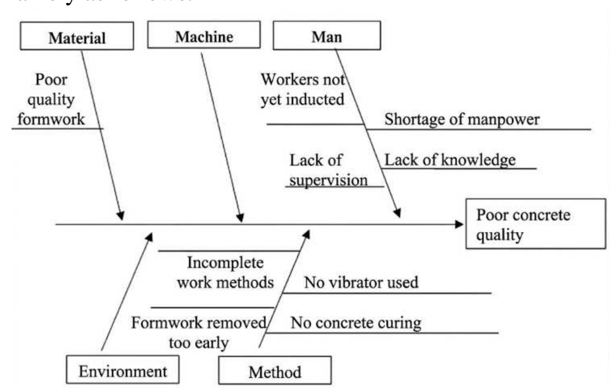

Fig. 4 Fishbone Diagram Analysis of Concrete Defects

2) FMEA Analysis of Defects in Capping Beam Lining

FMEA was applied to assess the risk of defects associated with each factor, focusing on identifying critical failure modes. Based on the analysis, the highest-risk factors were Method, followed by Man and Material.

TABLE X
FMEA ANALYSIS FOR DEFECTIVE CONCRETE IN CAPPING BEAM LINING WORK

No.	Factor	Defect Cause	Severity (S)	Occurrence (O)	Detection (D)	RPN (Risk Priority Number)	Criticality Level
1	Man	Unindicted workers	8	7	3	168	High
2	Man	Lack of knowledge of SOP	8	7	3	168	High
3	Man	No engineer on-site	6	6	3	108	High
4	Man	Insufficient workers	6	5	5	150	High
5	Material	Poor formwork material	5	5	3	75	Low
6	Method	There is a working method, but it is incomplete	8	7	4	224	Very high
7	Method	Not using a vibrator	8	7	3	168	High
8	Method	Not doing all standard work stages (Curing work is not done)	5	6	4	120	High
9	Method	The formwork is dismantled too quickly	8	7	3	168	High

The analysis concluded that the highest risk was associated with the Method (RPN 224), followed by Man (RPN 168) and Material (RPN 75).

G. DMAIC Method - Improve Stage

To minimize defects in concrete work, a focus group discussion (FGD) was conducted to address field issues related to the poor final condition of cast concrete materials. Based on prior analyses using the Fishbone Diagram and FMEA, improvements were targeted at the identified critical factors contributing to defects: man, method, and material.

The FGD resulted in several corrective measures to be implemented, including:

- Developing detailed process maps for each phase of the work;
- Updating work methods and standard operating procedures (SOP) to ensure comprehensiveness, followed by worker induction on the revised procedures;
- Ensuring that fieldwork adheres strictly to the SOP;
- Improving supervision during fieldwork;
- Increasing the number of field workers as needed.

1) Worker Induction:

This activity was designed to educate workers on the SOPs required to implement quality improvements in fieldwork. The induction for daily workers emphasized the following points:

- Reusable formwork materials must be cleaned of concrete residue, and unfit formwork should be replaced immediately;
- During concrete casting, proper compaction must be carried out using a vibrator;
- Curing must be performed for at least 7 days after casting;
- Formwork removal should occur no sooner than 7 days post-casting.

For supervisors, quality control personnel, and engineers, the induction highlighted these roles:

- Supervisors must be present and oversee critical stages such as site preparation, land checklists, and concrete casting;

- Quality control personnel must monitor at least the site checklist and casting phases;
- Engineers must supervise key tasks, including joint surveys, site checklists, and casting operations.

Observations indicated that the induction process significantly improved worker awareness of the SOPs and ensured adherence to previously neglected or unimplemented requirements. This was further validated during implementation.

2) Implementation of Improvements:

The team implemented corrective actions to enhance quality control in capping beam lining work by applying all recommendations from the improvement stage. This included ensuring SOP compliance, addressing identified shortcomings, and strengthening monitoring and supervision.

H. DMAIC Method - Control Stage

The Control stage aims to maintain and sustain the improvements achieved during the previous phases. This stage involves disseminating standardized improvements to capping beam lining work and monitoring the outcomes of implemented corrections. Standardizing the improvements is critical to ensure consistency and ongoing adherence to quality enhancements. As part of the control phase, we comprehensively disseminated updated regulations and standard operating procedures (SOPs) for capping beam lining. This included detailing enhancements made to work methods and establishing standardized procedures as a critical improvement to the capping beam lining workflow. These enhancements require full support and implementation by all employees involved in capping beam lining activities to ensure sustained progress and continuous improvement.

Concrete testing was carried out to monitor and evaluate the impact of the implemented improvements. Tests included compressive strength tests and field hammer tests. The hammer test served as an additional measure to assess on-site concrete strength. Comparing pre- and post-improvement test results showed significant increases in concrete quality. Hammer test values rose from 162 Kg/cm² to 204 Kg/cm², reflecting an increase of 42 Kg/cm² or approximately 26.25%. Similarly, compressive strength test results increased from 170.42 Kg/cm² to 238.59 Kg/cm², a rise of 68.17 Kg/cm² or approximately 40%.

TABLE X
HAMMER TEST RESULTS BEFORE AND AFTER IMPROVEMENTS

Test	Before Improvement	After Improvement	Change (%)
Hammer Test	162 Kg/cm²	204 Kg/cm²	+26.25%
Compressive Strength	170.42 Kg/cm²	238.59 Kg/cm²	+40%

These improvements demonstrate the effectiveness of the corrective measures implemented in the capping beam lining work. The results highlight the critical importance of standardized procedures, proper supervision, and adherence to updated SOPs to achieve and sustain high-quality outcomes. The standardization process is crucial to ensure that the implemented improvements are sustained and continually applied in the Cipelang Irrigation Modernization Project. This standardization serves as a foundation for continuous improvement, addressing the key factors contributing to material defects in concrete work-namely, man, material, and method. The following table summarizes the standardization measures applied to the capping beam lining process, comparing conditions before and after the improvements and detailing the recommended standardized practices.

TABLE XI
STANDARDIZATION OF IMPROVEMENTS IN CAPPING BEAM LINING WORK

No.	Cause	Before Improvement	After Improvement	Standardization Recommendations
1	Man	Insufficient number of workers in each group, working alternately	Increased number of workers per group	The number of workers per group must comply with the requirements outlined in the process map.
2	Man	Engineers did not participate in all stages of work	Engineers are present during critical stages	Engineers must be present during work. If no engineer is available, work cannot proceed.
3	Man	Formwork was removed within less than one day	Formwork removal occurred after at least 3 days	Remove formwork only after the concrete has hardened, and do not remove it within 3 days.
4	Man	No induction provided to workers	Induction provided to workers	Induction must be conducted for all workers, especially for new worker groups.
5	Material	Formwork material had significant residual concrete	Formwork material cleaned	Formwork material must be clean, and damaged or unfit formwork must be replaced.
6	Method	Curing was not performed	Curing was implemented	Curing must be performed for at least 7 days.
7	Method	Vibrators were not used during concrete compaction	Vibrators were utilized during compaction	Vibrators must be available and used during compaction. Work cannot proceed without them.
8	Method	Work methods and SOPs were incomplete	Improved and completed work methods and SOPs	Work methods and SOPs must be fully detailed and comprehensive.
9	Method	Formwork removal occurred too quickly	Removal occurred only after curing for 7 days	Delay formwork removal until at least 7 days after casting to ensure proper curing.

By adhering to these standardized practices, the project ensures consistent implementation of quality measures, minimizes material defects, and supports a sustainable and efficient workflow. These recommendations serve not only as corrective actions but also as preventive measures for future work. The reevaluation of data conducted from December 2023 to February 2024 aimed to measure the success of the implemented improvement methods in addressing the issues identified in the initial observations. The applied methods included enhancements such as concrete curing processes, the use of vibrators during compaction, and increasing the number of workers.

These measures were designed to address suboptimal compressive strength test results and hammer test values below the required specifications. These substantial improvements are directly attributed to the effective implementation of the following methods:

1) Concrete Curing: Ensuring a curing period of at least seven days post-pouring allowed for optimal hydration, significantly enhancing material strength.

2) Vibrator Utilization: Using vibrators during compaction eliminated air voids, reducing the risk of honeycomb or porosity in the concrete structure.

3) Worker Induction and Supervision: Worker training and enhanced supervision ensured adherence to standard operating procedures (SOPs), reducing procedural errors and improving overall quality

The reevaluation process validates that the implemented methods successfully improved concrete material quality. The significant enhancements in compressive strength and hammer test values confirm that the applied techniques were appropriate for addressing the research objectives. This study highlights the effectiveness of systematic improvements and provides a foundation for future projects seeking to implement continuous quality enhancements in construction practices.

I. Discussion

The primary factors contributing to quality issues in cast concrete fall into three main areas: man, material, and method. Among these, the "man" and "method" factors contribute most to concrete quality defects. Data analysis using Failure Mode and Effect Analysis (FMEA) revealed that the Risk Priority Number (RPN) for the "man" factor reached 168 (high criticality level), the "material" factor reached 75 (low criticality level), and the "method" factor reached 224 (very high criticality level). The team implemented quality control improvements for ready-mix concrete using the PDCA (Plan, Do, Check, Act) and DMAIC (Define, Measure, Analyze, Improve, Control) methodologies. Specific actions included developing a detailed process map for each job stage, revising work methods and SOPs to improve comprehensiveness, implementing worker inductions on updated SOPs, strictly enforcing SOP compliance during fieldwork, boosting supervisory oversight, and increasing field personnel to improve efficiency.

These measures significantly improved concrete quality. This improvement was evident from an increase in hammer test results by 42 kg/cm², equivalent to a 26.25% improvement (from 162 kg/cm² to 204 kg/cm²), and an increase in compressive strength test results by 68.17 kg/cm², equivalent to a 40% improvement (from 170.42 kg/cm² to 238.59 kg/cm²). Observations during the control phase, conducted over three months (December 2023 to February 2024), showed consistent improvements in material quality, with no compressive strength or hammer test results falling below the specified requirements [10]. To sustain these improvements, we recommended standardizing future concrete casting projects [11]. These standards include ensuring the number of workers per task group matches process map specifications, requiring an engineer's presence during work (with work halted if an engineer is unavailable), prohibiting formwork removal before concrete hardening for at least three days, and conducting inductions for all workers, especially new group members.

For materials, formwork materials must be clean and replaced if unsuitable [12], [13], [14]. For methods, cure concrete for at least seven days, and use vibrators during casting; otherwise, do not proceed [15], [16], [17], [18]. Enhancing concrete quality requires attention to five key factors: man, material, machine, method, and environment. Implementing the standardization measures outlined in this study can achieve improvements effectively. To sustain results, all employees and management must consistently uphold the conditions achieved through these improvements [19], [20].

IV. Conclusion

The quality defects in cast concrete were primarily driven by workforce practices ("man") and operational procedures ("method"), which exhibited the highest criticality levels in the FMEA analysis. By applying PDCA and DMAIC methodologies to address these root causes through updated Standard Operating Procedures (SOPs), targeted worker inductions, and enhanced supervision, the project achieved significant measurable improvements. Compressive strength increased by 40% and hammer test results improved by 26.25%, effectively eliminating test failures during the three-month control phase. Sustaining these structural gains requires permanently standardizing the improved practices, such as strict seven-day curing times, mandatory vibrator use, and continuous engineering oversight. Long-term success ultimately depends on the consistent commitment of both management and the workforce to adhere strictly to these refined standards across all five fundamental quality factors: man, material, machine, method, and environment.

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