

Risk Analysis of Precast Concrete Pouring Process Using Hazop (Hazard and Operability) Method and Risk Matrix (Case Study at Precast Concrete Company in West Java Area)

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ABSTRACT

This study analyzes risks in the precast concrete pouring process at a West Java company using the HAZOP method and risk matrix. Key hazards identified include low radioactive waste levels, flow issues in feeding pipes, mixer speed absence, high drum transport speed, and added drum placement. These deviations risk leakage and blockages in mixing and disposal systems. The findings emphasize the need for strict monitoring to prevent equipment failure and enhance safety in off-drum mixing operations, supporting safer and more reliable cement compaction.

INTRODUCTION

Human resources and the employment system are inextricably linked to occupational safety and health (K3). In addition to being highly significant for employees, occupational safety and health also affect a job's productivity.

health and safety measures at work that improve productivity. Therefore, occupational safety and health is a necessity that the work system must meet in addition to being a duty that employees must take into account. In other words, workers and the nature of job activities require occupational safety and health, but it is not a requirement.

Occupational safety and health (K3) initiatives must be implemented by businesses in order to lower the number of work-related incidents. Workplace accidents can be caused by a number of circumstances, including as inadequate maintenance, mismaintained equipment, and equipment that is unavailable or inappropriate for usage.

The International Labour Organization (ILO) estimates that occupational illnesses and accidents claim the lives of 2.78 million workers annually. According to Hämäläinen, P., Takala, J., & Boon Kiat (2017), occupational accidents accounted for 13.7% of these deaths, whereas occupational illnesses accounted for about 86.3%. The number of workplace accidents increased from 123,041 in 2017 to 173,105 in 2018, according to data from BPJS Employment. An rise in workplace accidents is seen in this image (BPJS Ketenagakerjaan, 2019).

LITERATURE REVIEW

In the construction industry, especially in the precast concrete casting process, work safety and risk management are the main focus to prevent work accidents and operational losses. Precast concrete is one of the innovations in modern construction that offers high time efficiency and structural quality, but still holds significant potential risks if the production process is not strictly supervised (Gibb et al., 2016).

Risk analysis in construction has come a long way in the last decade. One of the widely used systematic methods is the Hazard and Operability Study (HAZOP), which is known to be effective in identifying potential hazards and inoperability of processes, especially in complex systems such as the production of precast concrete (Khan & Amyotte, 2017). HAZOP works by identifying deviations from normal process parameters and evaluating their causes and consequences, making them suitable for use in industries that demand strict process control (Silva et al., 2019).

In addition to HAZOP, the use of the Risk Matrix as a quantitative and qualitative risk assessment tool is also increasingly widespread. The risk matrix allows the classification of risks based on their likelihood level and impact, making it easier to prioritize mitigation actions (ISO 31000, 2018; Aven, 2016). The combination of the HAZOP method and the Risk Matrix has proven effective in identifying and evaluating operational risks across a wide range of industries including construction (Wang et al., 2020).

In the context of the precast concrete industry, the casting process is a crucial point that contains various potential hazards, such as mold failure, material mixing errors, and unsafe working conditions (Kim et al., 2015).

Research by Rani et al. (2021) shows that human factors, working environment conditions, and supervision of procedures are the main causes of incidents in precast production. Therefore, a system-based analytical approach such as HAZOP is needed to identify failure-prone points in the casting process.

Previous studies have also shown that the application of risk-based approaches in the precast industry in Indonesia is still limited. A study by Prasetyo & Nugroho (2022) emphasizes the importance of integrating international standards-based risk management in Indonesian construction projects. This is in line with the findings of Yuliani et al. (2023) who highlight that many local precast companies have not adopted the HAZOP method or systematic risk evaluation tool, so improving safety standards is still an urgent need.

Thus, this study has an urgency to further examine the precast concrete casting process using a combination of HAZOP and risk matrix, especially in precast companies in the West Java region that have a high level of construction activity. This study is expected to contribute to the improvement of occupational safety standards and process efficiency in the Indonesian precast industry.

METHODOLOGY

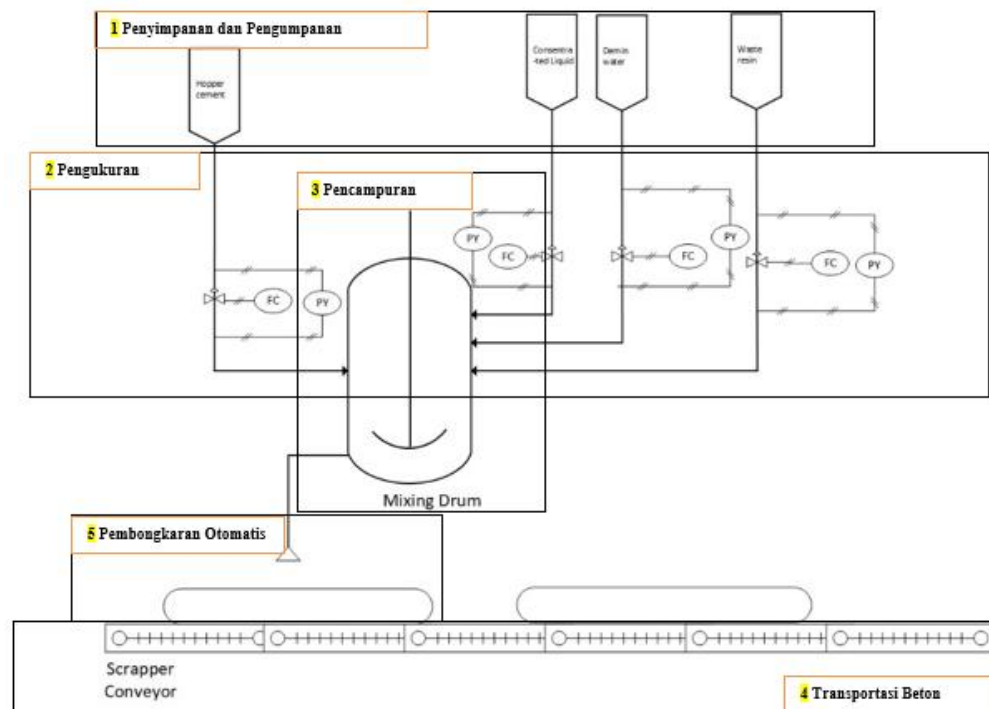


Figure 1. P&ID Process Pouring

System Description

Concrete production systems start from four main components of material storage. The cement hopper stores the cement at a controlled temperature of 20-25°C with a maximum relative humidity of 65% to prevent clumping. Concentrated liquid tanks for liquid additives are kept at room temperature (25-30°C), demineralized water tanks for demineralized water are controlled at 20-25°C, and waste resin tanks are kept at room temperature.

The feeding system uses an operational pressure of 2-3 bar to ensure a stable flow of material. Each line is equipped with Flow Control (FC) to regulate the flow speed and a pressure control sensor (PY) that monitors operating pressure. The control valves on each line operate at a maximum pressure of 4 bar to precisely control the flow of material.

The mixing drum operates under the following conditions:

- Operating temperature: 25-32°C
- Operating pressure: 2-3 bar
- Rotation speed: 15-20 rpm
- Mixing duration: 3-5 minutes per batch
- Capacity: 2-3 m³

The resulting concrete mixture has the following specifications:

- Mixing temperature: 28-32°C
- Slump: 150-180 mm
- Pump pressure: 5-6 bar for material transfer

Scraper conveyors operate with:

- Speed: 20-25 meters/min
- Operating temperature: Room temperature (25-35°C)
- Transfer capacity: 30-40 m³/h

The system is designed for continuous operation with a production capability of 20-25 m³/h, depending on the specifications of the mixture and operating conditions. The operating parameters can be adjusted within the specified range to optimize the quality of the final product.

In the process of making concrete, there are many components that can cause hazards if not controlled properly, such as temperature and pressure in various tanks and mixing systems. For example, if the pressure in the feeding or mixing drum system exceeds the specified limit (4 bar or more), then there can be a failure of components such as valves or hoses that risk causing accidents or equipment damage. HAZOP can help identify potential failures in pressure systems and propose mitigation measures.

RESEARCH RESULT AND DISCUSSION

HAZOP (Hazard and Operability) Study

Typically, HAZOP analysis is used to find and evaluate any risks from essential equipment or the system as a whole. In order to assure important process or device analysis, the fundamental implementation of HAZOP involves logically dividing research items into several nodes, each of which is dependent on distinct requirements. After that, changes in process parameters and deviations from the process index across various nodes are analyzed by combining the guiding words and process parameters. It is possible to identify the root cause of the deviation as well as its effects on system security. In the end, the risks and detrimental elements in the manufacturing process are explained, and safety precautions are suggested based on the outcomes and reasons for the deviation (Fuentes-Bargues et al., 2017).

A detailed description of the HAZOP analysis processes is provided. The HAZOP analysis may be made more efficient by first deciding on the purpose

and extent of the study. In the manufacturing process, the research object mostly consists of pipelines, instruments, control systems, and mechanical equipment. Second, the primary data on the study item is gathered, such as the raw materials' physical and chemical characteristics, process flows, safety operating guidelines, equipment manufacture manuals, accident reports, and other pertinent data. Third, the study item is separated into many analysis nodes, such as significant devices or particular process units, based on the information gathered. Node division can simplify the intricacy of HAZOP analysis and make clear the primary purposes and operational characteristics of each unit. Generally speaking, the primary manufacturing equipment—such as storage tanks, disintegration towers, and reactors—is separated into many nodes. The node deviations are then examined in detail. This mostly covers the reasons of the divergence as well as its effects. The cause of the deviation can be identified by examining how process parameters (like high temperatures, high pressures, and equipment failures) vary during production and operation, as well as how the deviations and potential outcomes (like fire, explosion, and poisoning) affect the system. The reasons and effects of deviations are then noted, compiled, and examined. All potential risks and detrimental elements in the manufacturing system can be identified based on this kind of study. Additionally, a rational and scientific approach to safety management is suggested. Figure 2.2 displays a flowchart of the HAZOP analysis process.

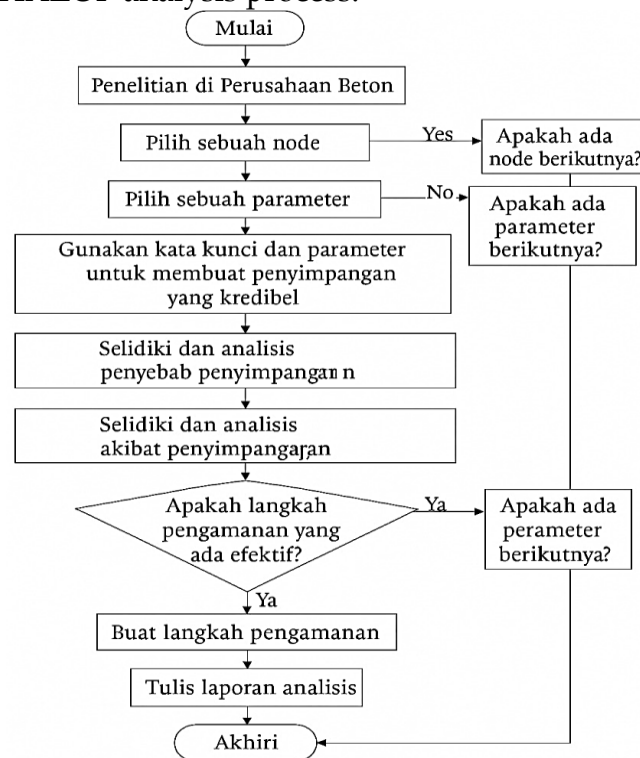


Figure 2. Stages of HAZOP Analysis

General terminology for HAZOP analysis

1) Node

Nodes are discrete components of the production process. Nodes, like vital machinery or vital procedures, serve a single purpose. During the HAZOP analysis, each node has to be given an identity number (Zou et al., 2018).

2) Parameter

Refers to the process's related chemical and physical characteristics. Two distinct types exist. Among them are generic parameters like reactivity, composition, and additives that characterize the node's condition. Temperature, pressure, and velocity are examples of particular characteristics that can be monitored or detected (Dunjó et al., 2011).

3) Guidewords

In HAZOP analysis, guidewords are a collection of straightforward terms or expressions that are used to characterize qualitative departures from the design purpose. An aberrant node state may be indicated by this. A thorough comprehension of each rule is necessary for the proper production of deviations. Table 1 lists guiding words and their common meanings.

4) Deviation

A collection of potential theories that depart from the design objective is called a deviation. Applying the proper process parameters and guideword to every node in HAZOP analysis creates a significant deviation. "Guideword + Parameter" is the typical format for the deviation. Table 2 below lists a few typical variances (DOE-HDBK-1100-2004, Chemical, 2004).

5) Cause

The several reasons why deviations might happen are known as causes. The deviation is shown to be a considerable deviation if its cause has been shown as credible. Following research and analysis, strategies and actions to address the deviation might be suggested if the reason of the departure is identified. Equipment malfunctions, human mistake, erratic process conditions (such as compositional changes), outside interference (like power outages), etc. are some examples of these reasons.

6) Consequences

The repercussions are the different effects that anomalies have on the surroundings, machinery, and workers. The foundation of consequence analysis is the presumption that deviations will cause the current safety protection systems to malfunction.

Table 1. Guidewords and their meanings

Guidewords	Meaning
Not	Total elimination of design functions
Less	Quantitative decline
Other	Quantitative enhancement
The Opposite	The logical opposite of Intent

Table 2. Common deviations

Parameter	Deviation
Flow	No flow, high flow, low flow, backflow
Pressure	High pressure, Low pressure, high temperature, low temperature
Composition	Missing components, High concentration, low concentration, too long time, too short, too slow, too fast
Ph	High pH, low pH

Matriks Risiko

A two-dimensional matrix graph is called a risk matrix. The risk matrix's vertical and horizontal coordinates have distinct meanings. The risk's severity (S) is shown by the horizontal coordinates. The frequency of risk, also known as the probable risk (L), is shown by the vertical coordinates. Tables 3 and 4 classify the severity and potential compaction of cement outside the drum according to the standard.

Calculating the value between severity (S) and likelihood (L) using the formula Risk (R) = S * L (Duijm, 2015) yields the risk matrix based on the severity and probability categorization criteria in Tables 3 and 4. A risk matrix from the cement compaction process of out-drum mixing was created using the worldwide standard risk assessment approach (ISO/IEC 3, 2009) and the computation R findings. Table 5 and Figure 3 display the risk matrix and risk classification.

Table 4 and Figure 3 demonstrate that a risk matrix may be used to evaluate the degree of risk as long as the severity and potential risk of mixing cement compaction outside the drum can be identified.

Table 3. Severity Classification

Severity (S)	Level	Definition of loss and hazard
Negligible	S1	Can be negligible or have no impact on equipment, workers and the environment.
Minor	S2	There is a potential impact on the equipment during the safety operation process. Nevertheless, there is no safety threat to workers and the environment.
Keep	S3	There was some damage to the equipment that resulted in the partial malfunction of the cement compaction, but there was no uncooling effect on the operator and the environment.
Serious	S4	Serious damage to cement compaction pavement causes total or minimal waste leakage.
Disaster	S5	Catastrophic damage from cement compaction of waste or low waste equipment to workers.

Table 4. Classification of possibilities

Description	Level	Probability (L)	Definition
Impossible	L1	$10^{-6} > L$	Events are almost impossible to occur during the life of the facility.
Distance	L2	$10^{-4} > L > 10^{-6}$	This event is unlikely to occur during the life of the facility.
Impossible	L3	$10^{-2} > L > 10^{-4}$	Such events may not occur during the life of the facility.
Kemungkinan	L4	$L > 10^{-2}$	Events may occur several times during the operation of cement compaction

Table 5. Risk matrix

Risk description	Risk level	Risk definition
Acceptable reduced risk	I	No action is required.
Acceptable with controls	II	It is acceptable once safety protection measures are implemented.
Almost unacceptable	III	Compliance protection measures should be implemented to reduce risks below Level II.
Unacceptable	IV	Risk control methods should be taken to reduce risks below level II.

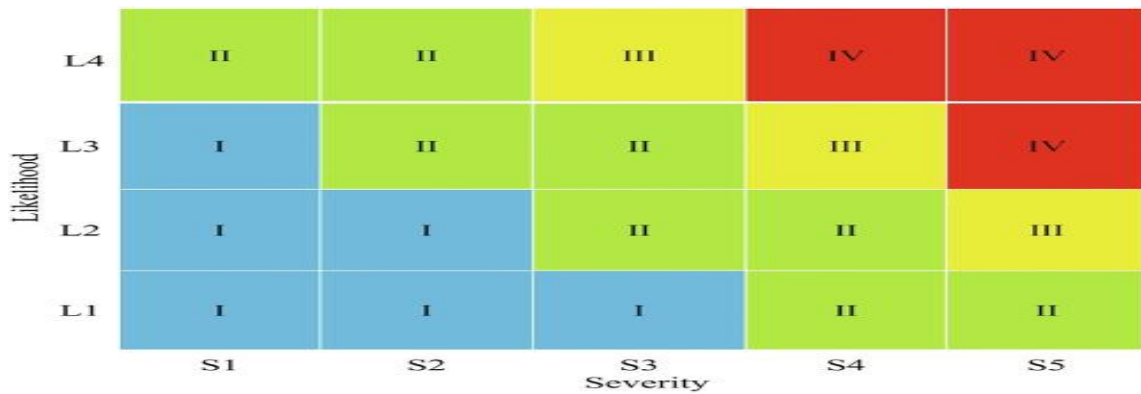


Figure 3. Risk matrix of cement compaction of mixing outside the drum

Various safety precautions are taken in light of the evaluation results. When risk levels are intolerable, suitable corrective actions must be developed in order to lower or remove the risk.

HAZOP and risk matrix for safety analysis of drum mixer cement compaction
Identification of analysis objects

Mixing cement powder and radioactive waste in a designated mixing container is the primary step in the cement compaction process of out-drum mixing. container that produces stable, compacted cement. The majority of radioactive waste comes from the operation and maintenance of nuclear power plants and takes the form of low- and medium-level radioactive liquid waste, waste resin,

and waste filter cartridges. It is challenging to thoroughly examine every piece of manufacturing machinery and process unit because of the intricacy of cement compaction using drum mixing. Therefore, for HAZOP analysis, the primary process unit and significant equipment other than drum mixing cement compaction are chosen.

Dividing nodes, specifying parameters and guidewords

The primary process unit or cement compaction equipment must first be divided into many nodes in order to conduct an efficient HAZOP analysis for out-drum mixing cement compaction. A thorough examination of the node's composition and function is then used to identify the parameters and guiding words. According to Ojovan et al. (2005) and Nagasaki (2015), the primary nodes are drum transport, weighing and measuring, storage and feeding, mixing outside the drum, and automatic capping and opening. Table 6 lists the nodes, parameters, and keywords for mixing cement compaction outside of a drum.

Results of HAZOP analysis and risk matrix

To get a semi-quantitative risk analysis for mixing solid cement outside of the drum, a combination of HAZOP and risk matrix was used. Table 6 displays the findings of the assessment of the degree of deviation risk. According to the HAZOP research, the metal drum's conveying speed can be both low and high. Three high-frequency deviations are another site for the drum. The primary causes of abnormal conveying speed include defective drive motors, improper speed regulation, and inconsistent conveyor roller maintenance. Furthermore, incorrect drum placement resulted from positioning sensor and locking device failure. The production efficiency of cement compaction using drum mixing is impacted by the high-frequency variation mentioned above. Therefore, regular inspections, maintenance, and servicing are recommended to reduce high-frequency deviations.

The most serious issue for deviations that have disastrous effects is the direct emission of radioactive materials. As a result, workers who operate and maintain cement compaction equipment may be exposed to radiation, and equipment and workshops may get contaminated by radiation. According to Table 6, moist sewage measuring tanks and discharge pipes, burst pipes, wet waste storage containers and discharge pipes, and no mixing speeds can all result in catastrophic deviations. Furthermore, it has been discovered that the radioactive cement waste mixture leak and equipment failure can cause major anomalies like the measurement tank and discharge pipe rupturing, high drum transport speeds, extra drum locations, and robot manipulators. There is a big difference between a catastrophe and major repercussions. due to the fact that cement slurry has a comparatively lower quantity of radioactivity than liquid and resin waste.

Table 6. HAZOP Results and Risk Matrix

Node	Deviasi	Kemungkinan Penyebab	Konsekuensi	Pengamanan	S	L	R	Rekomendasi
1	1. Level rendah di tangki penyimpanan semen	1.1 Pecahnya hopper semen. 1.2 Semen mengeras sebagian. 1.3 Sensor pemantau abnormal.	1. Serbuk semen mencemari peralatan dan lingkungan kerja.	1. Inspeksi rutin.	S2	L3	II	
	2. Tidak ada aliran di pipa umpan semen	2.1 Saluran keluar tangki penyimpanan sepenuhnya tersumbat. 2.2 Fungsi konveyor ulir tidak tersedia. 2.3 Konveyor ulir kehilangan pasokan listrik.	1. Pemadatan semen tidak dapat diselesaikan.	1. Pasokan daya siaga. 2. Inspeksi rutin.	S3	L2	II	1. Pemantauan aliran otomatis dan peringatan.
	3. Aliran kurang di pipa umpan semen	3.1 Pipa pembuangan pecah. 3.2 Saluran keluar tangki penyimpanan sebagian tersumbat.	1. Serbuk semen mencemari peralatan dan lingkungan kerja.	1. Vibrator diterapkan untuk mendorong pengumpulan.	S3	L3	II	1. Pemantauan aliran otomatis dan peringatan.
	4. Level limbah basah rendah	4.1 Tangki penyimpanan limbah cair pecah. 4.2 Tangki penyimpanan resin limbah pecah. 4.3 Sensor pemantau abnormal.	1. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh cairan limbah radioaktif dan resin. 2. Pekerja mungkin terpapar radiasi dosis rendah saat membersihkan limbah.	1. Level dipantau oleh indikator level.	S5	L3	IV	1. Alarm level otomatis. 2. Pemantauan konsentrasi radioaktif.
	5. Tidak ada aliran di pipa pengumpan limbah basah	5.1 Katup kontrol kehilangan fungsi.	1. Kegagalan pemadatan semen.	1. Pemantauan aliran.	S3	L2	II	1. Alarm aliran abnormal.
	6. Aliran kurang di pipa pengumpan limbah basah	6.1 Fungsi katup kontrol abnormal. 6.2 Pipa pembuangan pecah.	1. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh cairan limbah radioaktif dan resin. 2. Pekerja mungkin terpapar radiasi dosis rendah saat membersihkan limbah.	1. Pemantauan aliran.	S5	L3	IV	1. Alarm aliran abnormal.
	1. Level rendah di tangki penimbangan semen	1.1 Terjadi kesalahan pada sensor pemantau. 1.2 Tangki pengukur pecah.	1. Ruang kerja dan peralatan terkontaminasi semen. 2. Jumlah pembuangan semen kurang dari kebutuhan.	1. Level dipantau oleh indikator level.	S3	L3	II	1. Alarm level abnormal.
2	2. Tidak ada aliran di pipa umpan semen	2.1 Saluran keluar tangki penimbangan sepenuhnya tersumbat. 2.2 Katup kontrol rusak.	1. Kegagalan proses peny.	1. Pemantauan aliran.	S3	L2	II	1. Peringatan aliran otomatis.
	3. Aliran kurang di pipa umpan semen	3.1 Pipa pembuangan sebagian tersumbat. 3.2 Pipa pembuangan pecah.	1. Bentuk pemadatan semen yang tidak memenuhi syarat. 2. Semen mencemari peralatan dan lingkungan kerja.	1. Pemantauan aliran.	S3	L3	II	1. Alarm aliran abnormal.
	4. Level limbah basah rendah di tangki penimbangan	4.1 Terjadi kesalahan pada sensor pemantau. 4.2 Tangki pengukur pecah.	1. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh limbah cair radioaktif dan resin. 2. Pekerja mungkin terpapar radiasi dosis rendah saat membersihkan limbah.	1. Level dipantau oleh indikator level.	S5	L3	IV	1. Alarm level abnormal.
	5. Tidak ada aliran di pipa pengumpan limbah basah	5.1 Katup kontrol rusak.	1. Kegagalan sementasi.	1. Pemantauan aliran.	S3	L2	II	1. Alarm aliran abnormal.
	6. Aliran kurang di pipa pengumpan limbah basah	6.1 Katup kontrol abnormal. 6.2 Pipa pembuangan pecah.	1. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh limbah cair radioaktif dan resin. 2. Pekerja mungkin terpapar radiasi dosis rendah saat membersihkan limbah.	1. Pemantauan aliran.	S5	L3	IV	1. Alarm aliran abnormal.
	7. Level air demineralisasi rendah di tangki penimbangan	7.1 Terjadi kesalahan pada sensor pemantau. 7.2 Tangki pengukur pecah.	1. Kualifikasi bentuk pemadatan semen lebih rendah dari standar. 2. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh air demineralisasi.	1. Level dipantau oleh indikator level.	S3	L3	II	1. Alarm level abnormal.
	8. Tidak ada aliran di pipa air demineralisasi	8.1 Katup kontrol rusak.	1. Kegagalan sementasi.	1. Pemantauan aliran.	S3	L2	II	1. Alarm aliran abnormal.
	9. Aliran kurang di pipa air	9.1 Katup kontrol abnormal. 9.2 Pipa pembuangan pecah.	1. Kualifikasi bentuk pemadatan semen lebih rendah dari standar.	1. Pemantauan aliran.	S2	L3	II	1. Alarm aliran abnormal.

	demineralisasi		2. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh air demineralisasi.					
3	1. Tidak ada kecepatan pencampuran	1.1 Motor penggerak mixer rusak 1.2 Mixer kehilangan pasokan listrik.	1. Bilah padat campuran mengeras di mixer. 2. Pekerja mungkin terpapar radiasi dosis rendah saat membersihkan campuran yang mengeras.	1. Motor penggerak ganda untuk mixer. 2. Pemantauan pengoperasian pencampuran.	S5	L3	IV	1. Catu daya darurat siaga.
	2. Kecepatan pencampuran rendah	2.1 Motor penggerak mixer abnormal. 2.2 Kesalahan pengaturan kecepatan motor penggerak.	1. Kualifikasi bentuk pematatan semen lebih rendah dari standar. 2. Efisiensi produksi bubuk rendah membuatnya sulit dibersihkan.	1. Pemantauan jarak jauh untuk pengoperasian pencampuran.	S2	L3	II	1. Inspeksi rutin dan pemeliharaan.
	3. Kecepatan pencampuran tinggi	3.1 Motor penggerak mixer abnormal. 3.2 Kesalahan pengaturan kecepatan motor penggerak.	1. Percikan. 2. Pencampuran tidak homogen. 3. Kualifikasi bentuk pematatan semen lebih rendah dari standar.	1. Pemantauan jarak jauh untuk pengoperasian pencampuran.	S2	L3	II	1. Inspeksi rutin dan pemeliharaan.
	4. Waktu pencampuran terlalu singkat	4.1 Kesalahan pengaturan waktu.	1. Efisiensi produksi rendah.	1. Pemantauan jarak jauh untuk pengoperasian pencampuran.	S1	L3	I	1. Inspeksi rutin dan pemeliharaan.
	5. Waktu pencampuran terlalu lama	5.1 Kesalahan pengaturan waktu.	1. Efisiensi produksi rendah.	1. Pemantauan jarak jauh untuk pengoperasian pencampuran.	S1	L3	I	1. Inspeksi rutin dan pemeliharaan.
	6. Level rendah di tangki pencampuran	6.1 Wadah pencampuran pecah. 6.2 Sensor pemantau abnormal.	1. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh campuran.	1. Ultrasonik dan probe kontak digunakan untuk pemantauan.	S4	L1	II	1. Inspeksi rutin dan pemeliharaan. 2. Pemantauan konsentrasi radioaktif.
	7. Tidak ada aliran di pipa umpan	7.1 Campuran mengeras sepenuhnya di mixer. 7.2 Pipa pembuangan tersumbat.	1. Kegagalan pematatan semen.	1. Pemantauan aliran.	S3	L2	II	1. Alarm aliran abnormal.
	8. Aliran kurang di pipa umpan	8.1 Fungsi katup kontrol abnormal. 8.2 Viskositas campuran terlalu tinggi untuk dibuang dengan lancar. 8.3 Pasta semen mengeras sebagian di mixer atau pipa. 8.4 Pipa pembuangan pecah sebagian.	1. Saluran keluar mixer mungkin tersumbat. 2. Peralatan dan lingkungan kerja mungkin terkontaminasi oleh campuran.	1. Vibrator diterapkan untuk mendorong pengumpanan.	S4	L3	III	1. Alarm aliran abnormal.
	9. Campuran mengandung komponen lain.	9.1 Mixer dan wadah pencampur tidak dibersihkan sepenuhnya. 9.2 Air pembersih tidak sepenuhnya dibuang.	1. Motor penggerak mixer mungkin rusak. 2. Kualifikasi bentuk pematatan semen lebih rendah dari standar. 3. Mixer terkorosi.	1. Pembilasan bertekanan tinggi diterapkan untuk membersihkan peralatan pencampuran.	S3	L3	II	1. Inspeksi rutin dan pemeliharaan untuk peralatan pematatan semen.
4	1. Tidak ada kecepatan pengangkutan	1.1 Konveyor rol rusak. 1.2 Konveyor rol kehilangan pasokan listrik.	1. Tidak dapat mengangkat drum logam.	1. Motor penggerak siaga untuk konveyor rol. 2. Pemantauan kecepatan.	S3	L3	II	1. Peringatan kecepatan abnormal.
	2. Kecepatan pengangkutan rendah	2.1 Kesalahan pengaturan kecepatan konveyor rol. 2.2 Konveyor rol tidak dirawat dengan baik.	1. Efisiensi produksi rendah.	1. Pemantauan kecepatan.	S1	L4	II	1. Peringatan kecepatan abnormal. 2. Perawatan rutin.
	3. Kecepatan pengangkutan tinggi	3.1 Kesalahan pengaturan kecepatan konveyor rol. 3.2 Motor penggerak konveyor rol abnormal.	1. Masa pakai konveyor rol lebih rendah dari yang dirancang. 2. Drum logam yang diisi dengan limbah padat jatuh.	1. Pemantauan kecepatan.	S4	L4	IV	1. Peringatan kecepatan abnormal.
	4. Posisi drum tambahan	4.1 Sensor fotoelektrik untuk pemosisian mungkin rusak. 4.2 Perangkat pengunci mungkin rusak.	1. Bubur semen tidak dapat ditempatkan di drum. 2. Tutup drum tidak dapat ditutup dan dibuka. 3. Kartrid filter bekas tidak dapat ditempatkan di drum logam.	1. Suku cadang untuk sensor fotoelektrik dan perangkat pengunci disimpan. 2. Pemantauan posisi drum secara real-time.	S4	L4	IV	1. Alarm posisi abnormal.
5	1. Posisi manipulator robot tambahan	1.1 Sistem kontrol manipulator robot mungkin rusak. 1.2 Perangkat penggerak manipulator robot mungkin rusak. 1.3 Kehilangan daya listrik ke manipulator.	1. Tutup drum tidak dapat ditutup dan dibuka secara otomatis.	1. Pemantauan jarak jauh untuk manipulator robot.	S4	L3	III	1. Alarm posisi abnormal. 2. Catu daya darurat siaga.

To determine the degree of risk, a risk matrix is created using the HAZOP analysis mentioned above. Table 6 lists seven unacceptable dangers for which risk control techniques are required in order to lower the risk level. The addition of drum locations, the lack of a mixer speed, the high conveying speed of the metal drum, the low level of wet waste in the storage tank, the low level of wet waste in the measuring tank, the low level of wet waste in the storage tank, and the low level of wet waste in the measuring tank are a few examples.

When feeder containers and pipelines fail, storage tanks and gauge tanks experience low levels and decreased flow. Radioactive waste is released uncontrollably as a result. Concentrated liquids and resin waste should be moved right away to emergency storage tanks if this risk is detected. Decontamination techniques must be used in the meantime to lower radioactive levels in feeder pipelines, measurement tanks, and broken storage tanks. Additionally, employees in cement compaction workshops must pay closer attention to the levels of storage tanks and measurement tanks as well as the flow of discharge pipes in order to prevent the release of radioactive waste that contaminates tools and workshops.

Another intolerable danger is the mixer's inability to mix; this is typically brought on by the drive motor failing and the mixer losing power. The cement powder and waste combination might harden the mixer's paddle when it loses its fundamental mixing function, which damages the mixer's drive motor. Moreover, personnel must clean the mixer and mixing container and fix the drive motor while posing a radiation danger once the mixture has solidified in the mixer. In order to solve this issue, backup drive motors and emergency power supplies are ready.

Mixing outside the drum is significantly impacted by the high conveying speed of metal drums. It is challenging to stop a drum carrying a radioactive mixture at the intended location when it is being moved at a fast pace. As a result, a tiny quantity of cement mixture will fall beyond the metal drum, allowing the radioactive mixture to seep. A further intolerable danger is the increase of drum sites. Positioning sensors and locking mechanisms undergo routine maintenance and inspections to avoid this intolerable danger. Additionally, spare components must be ready to handle crises.

CONCLUSIONS AND RECOMMENDATIONS

Numerous noteworthy anomalies in the cement compaction process of drum mixing were found by the results of the HAZOP analysis and risk matrix. These include low levels of radioactive waste in the tank, disruptions in waste flow, and high drum transport speeds, all of which have the potential to cause waste leakage and system clogging. To reduce the danger of equipment failure, these variances must be properly observed and managed. Important recommendations for enhancing the dependability and safety of off-drum mixing facilities are provided by this investigation.

ADVANCED RESEARCH

Building upon the findings of the HAZOP analysis and risk matrix, future research should focus on developing an integrated risk mitigation framework

that incorporates real-time monitoring systems and predictive maintenance technologies specifically tailored for off-drum mixing operations. Advanced sensor networks and data-driven algorithms, such as machine learning models, can be employed to detect early signs of process deviations – such as abnormal flow rates or vibration patterns in drum transport systems – thereby enabling proactive intervention before critical failures occur. Additionally, a comparative analysis of various cement compaction techniques under controlled risk scenarios could provide insights into optimizing process parameters while minimizing exposure to hazardous events. This research direction not only aims to enhance operational safety but also contributes to the design of intelligent, adaptive risk control systems in precast concrete production facilities.

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