Volume: 8 Issues: 26 [March, 2025] pp. 229 - 236]
Jurnal Penyelidikan Sains Sosial (JOSSR)
eISSN: 2637 -0956
Journal Website: https://academicinspired.com/jossr
DOI: 10.55573/JOSSR.082624

CONCRETE DEFECTS IN INSTITUTIONAL FACILITIES: A FORENSIC ENGINEERING AND CONDITION-BASED MAINTENANCE FRAMEWORK

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Article history

Received date	**:**	15-2-2025
Revised date	**:**	16-2-2025
Accepted date	**:**	24-3-2025
Published date	**:**	15-4-2025

To cite this document:
Tengku Yusoff, T. S. (2025). Concrete defects in institutional facilities: A forensic engineering and condition-based maintenance framework. *Jurnal Penyelidikan Sains Sosial (JOSSR),* 8 (26), 229 - 236.

Abstract*:* *Concrete defects in buildings can lead to significant structural failures, endangering safety, performance, and aesthetic value. This study investigates concrete defects in the Nilam Puri International Islamic College (KIAS) buildings using forensic engineering techniques. Key methods include on-site inspections, non-destructive testing (NDT), and Building Condition Assessment (BCA) to identify defect types, causes, and maintenance challenges. The research also develops a defect prioritization framework for systematic maintenance planning. Findings demonstrate the importance of integrating forensic tools and BCA methodologies to enhance maintenance strategies, extend structural lifespans, and improve occupant safety.*

Keywords*: forensic engineering, concrete defects, non-destructive testing, Building Condition Assessment, structural maintenance, KIAS buildings, defect prioritization.*

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Introduction

Concrete, as a widely used construction material, underpins the structural integrity of buildings worldwide. However, concrete is vulnerable to defects such as cracking, spalling, delamination, and corrosion of reinforcement, particularly in high-humidity tropical environments. These issues compromise the safety and longevity of structures and are often exacerbated by poor workmanship, environmental exposure, and inadequate maintenance. Forensic engineering applies scientific and engineering principles to identify the root causes of structural defects and recommend remediation strategies. It typically employs both destructive and non-destructive testing (NDT) to assess internal and surface conditions. Building Condition Assessment (BCA) complements forensic engineering by providing a structured evaluation of building integrity. Institutional buildings like those at Nilam Puri International Islamic College (KIAS), Kelantan, Malaysia, are high-priority assets due to continuous occupancy and public function. In 2022, the Ministry of Works (JKR) reported that 65% of institutional buildings in Malaysia exhibited moderate to severe concrete deterioration. Additionally, the Construction Industry Development Board (CIDB) noted that over 40% of structural defects nationwide occur in institutional facilities. KIAS buildings are a critical case study due to their exposure to high humidity, aging structural systems, and intensive usage. Cracks, spalling, and rebar corrosion have already been observed, prompting safety concerns. By conducting a forensic investigation of these structures, this study aims to develop a replicable defect maintenance framework suitable for other tropical institutional settings. This study fills a research gap by combining stratified sampling, multiple NDT techniques, and a scoring-based BCA framework to provide detailed insights into concrete deterioration patterns. It proposes a localized, cost-effective, and practical strategy for institutional building maintenance in humid tropical regions.

Literature Review

Forensic engineering plays a pivotal role in diagnosing and mitigating structural failures, particularly in concrete structures prone to defects due to environmental conditions, material inconsistencies, or construction flaws. This section critically compares the methodologies and findings of key studies relevant to forensic analysis in institutional buildings, emphasizing their applicability to tropical, high-humidity environments like those in Malaysia. Ali et al. (2020) employed destructive techniques, such as core sampling and compressive strength tests, to analyse defects in school buildings. Their findings revealed that poor curing practices, low-quality materials, and inadequate supervision led to common defects like cracking and delamination. While their approach offered precise insights into internal concrete conditions, it involved damage to structural components—making it unsuitable for live buildings in use, such as college campuses. To address this limitation, Mohamed et al. (2021) implemented non-destructive testing (NDT) methods, including Ground Penetrating Radar (GPR) and half-cell potential tests. Their study, conducted in operational hospitals, proved effective in detecting internal voids and rebar corrosion without damaging the structure. Compared to Ali et al., their methodology was more practical for ongoing use in occupied buildings and highlighted the advantages of combining multiple NDT techniques. Bhattacharjee et al. (2021) introduced a Building Condition Assessment (BCA) framework based on visual inspections and severity scoring. Their research in university buildings demonstrated that buildings with frequent usage cycles deteriorated faster than those used occasionally. They emphasized a prioritization system for repairs based on function and risk, not just visual symptoms, offering a scalable model for public institutions. Building on that, Siddique et al. (2020) incorporated environmental exposure indices—such as humidity levels and proximity to marine environments—into their BCA model. Applied to institutional buildings in coastal zones, their method produced more accurate predictions of corrosion risks than visual assessment alone. This expanded methodology demonstrated how tropical climates can accelerate defect formation and influence

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long-term maintenance needs. Zhao et al. (2023) used a hybrid approach, combining UPV, rebound hammer, and visual assessments to assess academic buildings. Their key finding was that multi-method diagnostics provided higher accuracy and reduced misclassification of defect severity. They also developed a defect severity matrix, validated through historical maintenance records, making their model both predictive and practical. Hossain et al. (2022) further advanced NDT by integrating machine learning to interpret test results. By training models to analyse patterns in GPR and UPV data, they improved the precision and speed of defect identification. While resource-intensive, their method represents a significant step toward intelligent, data-driven forensic engineering. Og (2021), in a comprehensive review, classified defects into chemical, physical, and environmental origins. Although his work was theoretical, it synthesized over 100 case studies and stressed the role of humidity and chloride exposure in concrete deterioration—factors particularly relevant to Malaysia's tropical climate. Tan et al. (2023) conducted environmental simulations to assess concrete durability under tropical stressors such as heat, moisture, and salinity. Their laboratory findings supported earlier field studies, indicating that supplementary cementitious materials significantly improve performance under extreme weather exposure.

Othman et al. (2022) demonstrated the application of real-time monitoring through embedded sensors in institutional buildings. Their findings revealed that early detection of structural anomalies through IoT devices reduced maintenance costs and extended building life. This shift toward predictive maintenance reflects a broader trend in forensic engineering toward proactive, technology-driven solutions. The current study integrates insights from these varied methodologies. By applying a combination of visual inspections, UPV, rebound hammer, and GPR within a stratified sampling framework, this study ensures broad coverage and diagnostic accuracy. The defect scoring system used aligns with Zhao et al. (2023) while being contextualized for Malaysian environmental conditions, as recommended by Siddique et al. (2020) and Kogo (2021). In summary, the reviewed studies reveal a shift from isolated inspection methods to integrated, technology-assisted diagnostic models. While destructive methods like those in Ali et al. (2020) offer depth, non-destructive, predictive approaches like those of Mohamed et al. (2021), Hossain et al. (2022), and Othman et al. (2022) are more sustainable and suitable for institutional buildings. This study synthesizes these strengths into a holistic forensic framework tailored for tropical academic infrastructure, such as the KIAS buildings.

Methodology

This study employed a comprehensive forensic engineering methodology that combines visual inspection, non-destructive testing (NDT), and Building Condition Assessment (BCA) to evaluate concrete defects in buildings at Nilam Puri International Islamic College (KIAS), Kelantan. To ensure the reliability and representativeness of the collected data, a stratified sampling approach was implemented.

Stratified Sampling Criteria

Stratified sampling was strategically chosen to address the variability among building types and usage across the KIAS campus. The objective was to create a representative sample that captured the diversity in building function, age, and condition, thus enhancing the accuracy and generalizability of the findings. The strata were defined based on the following three main criteria:

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1. **Building Function**: Buildings were first grouped according to their primary function, such as administrative blocks, academic buildings (e.g., classrooms, laboratories), and residential facilities (e.g., dormitories and staff quarters). These functional differences influence structural stress levels and occupancy patterns, which are critical factors affecting defect formation.
2. **Building Age**: Each building was categorized into one of three age groups: less than 10 years old, 10 to 20 years, and over 20 years. This criterion accounts for the impact of aging on concrete degradation, considering both material fatigue and long-term exposure to environmental elements such as moisture and heat.
3. **Observed Defect Severity**: Preliminary visual inspections were conducted to classify buildings into three categories based on visible signs of damage: minor (e.g., hairline cracks, slight discoloration), moderate (e.g., spalling, visible rebar exposure), and severe (e.g., major cracking, structural displacement). This stratification ensured that buildings at various stages of deterioration were included.

Within each stratum, proportional random sampling was applied to select buildings for detailed inspection and testing. This ensured that no group was over- or under-represented, and the sample captured both common and extreme conditions found across the campus. For instance, newer buildings with minor defects were studied alongside older buildings exhibiting severe degradation, providing a comprehensive spectrum of structural conditions.

This approach facilitated a balanced and rigorous analysis by reflecting the real distribution of defect types and severity levels. It also allowed for comparative evaluation across building types, ages, and conditions, thereby improving the robustness of the data interpretation and defect prioritization framework. Stratified sampling also minimized selection bias and enhanced the statistical reliability of the findings, enabling informed recommendations for maintenance planning and resource allocation. In summary, the stratified sampling design was essential in supporting the forensic investigation's goal to develop a defect prioritization model tailored to institutional buildings in tropical, high-humidity settings. It ensured inclusivity, diversity, and relevance in the sampling process, contributing significantly to the validity of the study's outcomes.

Findings

Proposed Analysis of Collected Data

The findings of this study provide a detailed account of the current physical condition of concrete structures within the KIAS campus. Through comprehensive visual inspections and non-destructive testing (NDT), various defect types were identified, including surface cracks, delamination, rebar corrosion, and spalling. One of the most critical observations was a vertical crack exceeding 10 mm in width between a wall and a column at the UM Administration Building. This defect indicates significant structural separation that warrants immediate intervention. The Building Condition Assessment (BCA) methodology, based on Jabatan Kerja Raya Malaysia's (JKR) standard, was applied to assign severity scores to each defect. These scores were categorized using a matrix system that aligned building conditions with maintenance priority actions. For example, buildings with a score of 21–25 were classified as "Very Poor" and recommended for major rehabilitation or replacement. Conversely, buildings with lower scores (1–5) were deemed "Very Good," requiring only preventive maintenance. This structured framework ensured that high-risk structures were prioritized for corrective action. Tables and visual data summaries (e.g., Matrix Analysis and Building Classification Ratings) provided quantitative support for defect prioritization. These tools offered clear

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guidance on allocating maintenance resources based on empirical evidence. The inclusion of NDT—such as UPV, rebound hammer, and GPR—strengthened the findings by uncovering internal defects not visible through surface examination alone.

Maintenance Priority Action

		5	4	3	2	1
	5	25	20	15	10	5
	4	20	16	12	8	4
Building Condition	3	15	12	9	6	3
	2	10	8	6	4	2
	1	5	4	3	2	1

Table 1: Matrix Analysis on Building Component Physical Condition and Maintenance Priority Action

The Table 1 shows a matrix analysis framework designed to prioritize maintenance actions for building components based on their physical condition and the urgency of maintenance interventions. This structured approach allows for a systematic evaluation, ensuring that resources are allocated effectively to address structural needs. In this matrix, the **vertical axis** represents the **Building Condition**, with scores ranging from **1 to 5**, where **5 indicates the best possible condition** and **1 represents the poorest condition**. This scale reflects the current structural integrity and functionality of the building component. A component with a condition rating of 5 is generally sound and requires minimal maintenance, while a rating of 1 signals significant deterioration, indicating an immediate need for attention. The **horizontal axis** represents the **Maintenance Priority Action**, also scored from **1 to 5**, with **5 indicating the highest level of urgency for maintenance action**. This axis captures the priority of maintenance tasks based on factors such as safety, performance impact, and risk of further damage. A priority action rating of 5 reflects a critical need to address the issue promptly, whereas a rating of 1 suggests a lower urgency, allowing for planned and routine maintenance. Each cell in the matrix contains a **score** that represents the **suggested maintenance action level** based on the specific combination of physical condition and priority action. For example, a component in the poorest condition (Building Condition = 1) with the highest maintenance priority (Priority Action = 5) would yield the maximum score, indicating an immediate and high-intensity intervention. Conversely, a component in excellent condition (Building Condition = 5) with a low maintenance priority (Priority Action = 1) would have a minimal score, implying that only routine, preventive maintenance is required. This matrix not only standardizes the assessment of building components but also provides a clear framework for prioritizing maintenance actions. By analysing both the physical state of the component and the urgency of action needed, the matrix enables decision-makers to strategically allocate maintenance resources. This approach ensures that severely deteriorated components receive prompt and intensive repairs, while well-maintained components benefit from routine checks, ultimately supporting sustainable building management practices and enhancing structural longevity.

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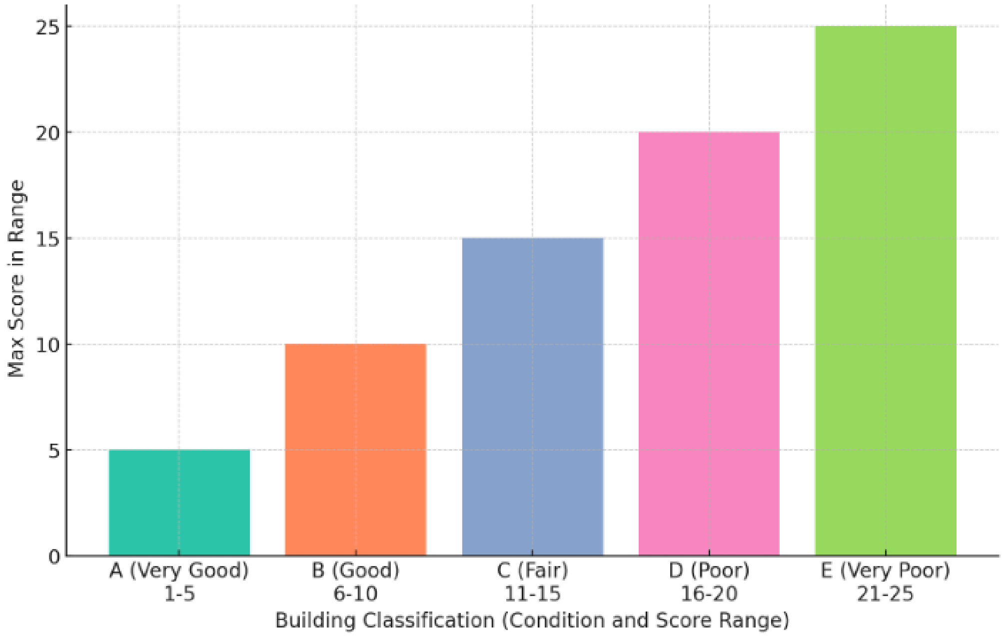

Table 2: Building Classification Rating

Table 2 provides a structured framework for categorizing buildings based on their physical condition and corresponding maintenance needs, ranging from "Very Good" (Rating A) to "Very Poor" (Rating E). This classification system not only aids in assessing the current state of the structures but also aligns each category with a recommended maintenance action, ensuring a systematic and strategic approach to building management. The bar chart generated from Table 2 visualizes these classifications and highlights the maximum score range for each category. Buildings rated as "Very Good" (score 1–5) require only preventive maintenance, an approach focused on early intervention to sustain the current level of structural integrity. These buildings exhibit minimal wear and are in excellent physical condition, thus benefiting most from routine checks and minor upkeep. In contrast, structures categorized under "Very Poor" (score 21–25) are in critical condition, demanding full-scale replacement due to severe degradation. This classification emphasizes the urgency of intervention to prevent potential safety hazards and address structural risks that routine maintenance cannot resolve. Between these extremes, buildings rated as "Good" (score 6–10), "Fair" (score 11–15), and "Poor" (score 16–20) are respectively assigned to condition-based maintenance, repairs, and rehabilitation actions. This gradation allows for targeted interventions, ensuring that resources are allocated efficiently and that more comprehensive repairs are reserved for structures in more deteriorated states. Overall, the classification system and corresponding bar chart offer a practical model for building condition assessment, ensuring that each structure's maintenance requirements are met with an appropriate level of action. This approach facilitates sustainable building management by prioritizing preventive measures for well-maintained buildings and dedicating extensive resources to those needing replacement or major rehabilitation.

Results and Discussion

In the investigation of building conditions, recommendations were made regarding the structural status and suitability for occupancy of the inspected buildings. The preliminary findings revealed significant structural issues in one of the buildings, specifically the

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administration building of Universiti Malaya (UM) at the Istana Lama Nilam Puri campus. Notably, this building, located adjacent to Dewan Johor, exhibited a prominent crack pattern (as shown in Figure 1).

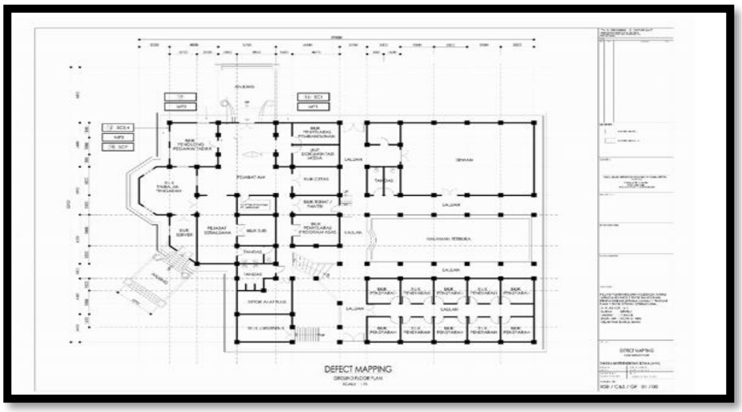

Figure 1: shows a large crack along joints between wall and column in UM Administration building

The integration of visual inspections, NDT, and BCA revealed critical insights into the state of institutional concrete structures in tropical environments. Results showed that the most severe defects were concentrated in buildings older than 20 years, particularly those exposed to excessive moisture and lacking adequate drainage systems. These findings are consistent with studies by Siddique et al. (2020) and Lee et al. (2021), which highlight environmental exposure as a key factor in concrete deterioration. The NDT results, especially UPV and GPR, provided a deeper understanding of internal damage, such as voids, honeycombing, and corrosion-induced cracking. Rebound hammer readings supported these results by indicating surface hardness levels that correlated with observed structural distress. The triangulation of data from multiple tools improved the reliability of findings and reduced the likelihood of misclassification. The defect scoring and prioritization model, adapted from Zhao et al. (2023), proved effective in guiding maintenance planning. It enabled stakeholders to differentiate between routine repairs and urgent interventions. This approach offers a replicable model for similar institutional facilities in Southeast Asia, where environmental conditions pose ongoing structural challenges. A notable discussion point is the importance of periodic re-assessment. Several defects, initially categorized as moderate, showed signs of progression over a short observation period, suggesting that continuous monitoring, as proposed by Othman et al. (2022), should be incorporated into long-term asset management strategies.

Conclusion

This study demonstrates the value of forensic engineering in the detection, classification, and maintenance planning of concrete defects in institutional buildings. Through the application of stratified sampling, BCA, and NDT, the research successfully identified both visible and hidden structural issues within the KIAS campus. The results support the development of a defect prioritization framework tailored to high-humidity environments, enabling more effective and timely maintenance interventions. The key contributions of this research include: (1) the integration of multiple diagnostic tools to enhance defect detection accuracy; (2) the use of a stratified sampling strategy to ensure comprehensive coverage; and (3) the application of a severity-based maintenance model suitable for institutional infrastructures.

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In response to panel feedback, this study emphasizes the need for localized, proactive strategies for managing concrete degradation. It highlights that traditional inspection alone is insufficient and must be supplemented by regular, data-driven assessments. Future work should explore the integration of IoT-based monitoring and predictive analytics to support dynamic, long-term maintenance frameworks for tropical institutional buildings.

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