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SUSTAINING CONCRETE STRUCTURAL INTEGRITY: A FRAMEWORK FOR DEFECT IDENTIFICATION AND RECTIFICATION METHODS

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ABSTRACT

One of the key issues that requires substantial attention in existing residential buildings is the occurrence of defects in their concrete structures. Flaws in the structural concrete of these types of buildings are frequently reported in numerous studies. If not rectified early, defects in concrete structures can lead to the collapse of these buildings. This study aims to develop a framework for understanding the identification and rectification methods of concrete defects in existing residential buildings. Thirty-three academic texts generated through a systematic literature review were utilised to collect qualitative data, and content analysis was carried out to meet the research objectives. The findings revealed that cracks are the most prevalent defect in concrete structures. Further, the review explored the most common non-destructive techniques such as the use of Schmidt hammer and ultrasonic for concrete defect detection. Moreover, rectification methods including epoxy treatment and concrete jacketing were identified. Finally, a framework that maps concrete defects with their identification and rectification techniques has been developed. The framework can help building inspectors, property managers, and other stakeholders involved in building maintenance to understand the alternative techniques for the identification and rectification of concrete defects.

Keywords: *Buildings; Concrete Defect; Rectification Techniques; Retrofitting.*

1. INTRODUCTION

Concrete plays a crucial role in residential construction, providing structural support and foundation. However, over time, concrete structures may develop flaws due to various factors such as subpar building techniques, environmental conditions, and ageing (Mehta, 2004). These flaws or defects can compromise the quality, service life, and structural integrity of buildings, posing safety risks to occupants and necessitating costly repairs for building owners (Gurmu et al., 2023). Previous studies revealed the impact of concrete defects on health and safety. For instance, a study conducted by Grillone et al. (2020) showed 26 accidents per 1000 workers due to the collapse of the beam, column, slabs, or other weak parts of the building which may be a result of poor construction or lack of retrofitting on those parts. To prevent impending failures of concrete structures during

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their service life, continuous surveying, monitoring, and rectifying the defects are needed (Obiora et al., 2022).

Various rectification methods have been proposed to strengthen and restore existing concrete structures, involving the addition of new components or structural pieces to enhance functionality and extend lifespan. However, the complexity of concrete flaws and the multitude of available retrofitting options make it challenging to select the most suitable strategy for each specific issue (Austin et al., 2022). Therefore, frameworks or tools for quickly examining concrete faults, pinpointing their origins, and figuring out the best rectification techniques must be developed. To the best of the authors' knowledge, no research has yet developed a framework linking concrete defects, detection techniques, and rectification processes. Additionally, Georgiou (2010) noted that there is a lack of studies guiding the selection of the most suitable and efficient retrofitting method to address generated defects. Therefore, the purpose of this study is to develop a system for figuring out several approaches to recognising concrete defects and comprehending how to correct the flaws in existing residential buildings. The specific objectives of this research are to (i) identify the most typical defects in the concrete structure of the existing buildings, (ii) explore the suitable methods of defect identification and rectification, and (iii) develop a framework that includes defects, causes, method of identification and the rectification process.

2. RESEARCH METHODOLOGY

As essential components of the study technique, a systematic literature review and qualitative analysis of secondary data are employed in the creation of a framework for rectifying concrete defects in existing residential buildings. Gathering, analysing, and summarising all pertinent materials (including articles, journals, case studies, websites, and process evaluations) is the goal of the systematic literature review (Nathan et al., 2023). A pre-planned search strategy is used to guarantee the thorough evaluation of relevant sources, and the procedure is documented to improve openness and repeatability (Nathan et al., 2023). This method entails a thorough examination of case studies, literature, and other relevant sources to develop a framework for fixing concrete flaws in residential buildings.

Data collection is a crucial component of secondary research, necessitating the collection of various theories and research papers to effectively conduct the study. This process involves browsing multiple websites and sources to gather the requisite data. The information-gathering endeavour encompasses retrieving relevant journal articles, conference papers, and other relevant resources from diverse outlets, including academic databases such as Scopus and Web of Science, business reports, government publications, and other online resources. A comprehensive analysis of secondary sources about concrete flaws in existing residential structures was conducted during the data collection phase of this research (Ullrich et al., 2020).

A thematic analysis, which involves identifying patterns and themes within the data, was employed first. Thereafter, content analysis was carried out to extract detailed information regarding the concrete defects, methods of identifying concrete flaws, and techniques for fixing the defects. The PRISMA framework was adopted to extract articles using keywords such as defect, concrete, retrofitting, and rectification (refer to Figure 1). The most popular databases such as Web of Science, Scopus, and Google Scholar were used to retrieve relevant articles (Gurmu et al., 2022). Initially, 223 articles were retrieved and then reduced to 171 articles after excluding articles published in languages other than English. Further screening was carried out to exclude studies addressing defects in non-residential building structures. Finally, the full texts of 33 articles were downloaded and analysed.

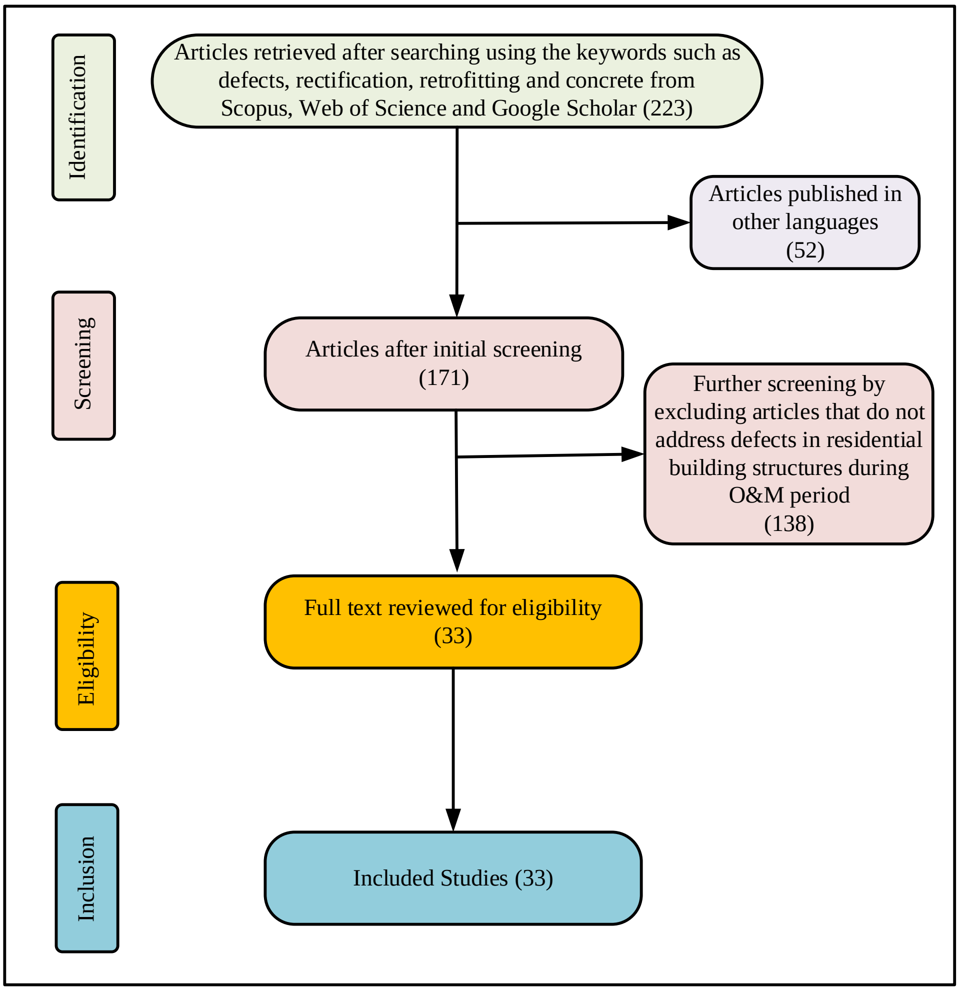

Figure 1: PRISMA framework

3. FINDINGS

3.1 BREAKDOWN OF SYSTEMATICALLY REVIEWED LITERATURE

The findings obtained in this paper are based on qualitative data which were obtained from the 33 academic studies that were selected using the PRISMA framework. As shown in Figure 2, most articles obtained through the systematic literature review were from 2021, comprising seven papers, followed by five papers from 2020, and four each from 2019, 2022, and 2023. These articles employed various research methods, including case studies, literature reviews, questionnaires/surveys, statistical analysis, and qualitative content analysis, to address the research aims and objectives.

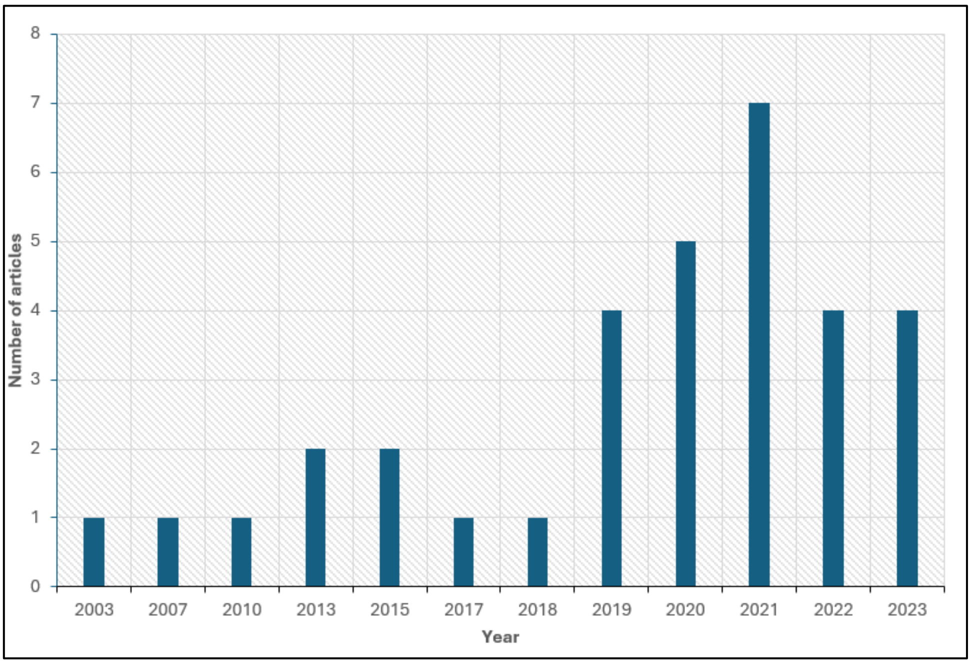

Figure 2: Yearly distribution of the studies

As shown in Figure 3, most of the selected articles were from the Journal of Construction and Building Materials, reflecting the study's focus on concrete. Other texts include the Journal of Applied Science, Journal of Building Engineering, and Journal of Civil Engineering, among others. In total, there are 14 different sources of the texts, providing a diverse range of perspectives relevant to this study.

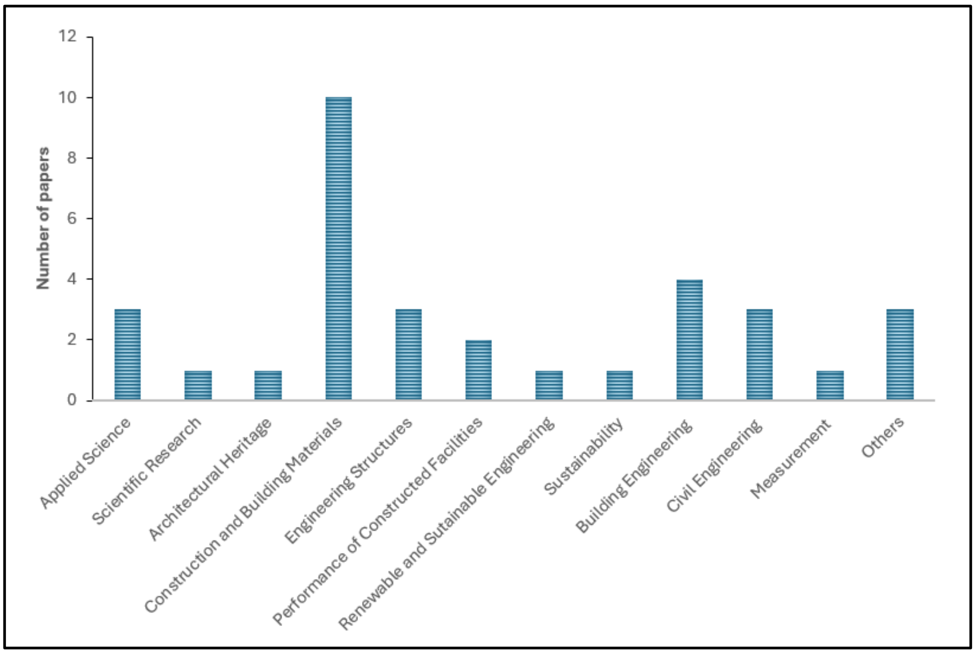

Figure 3: Distribution of articles based on their sources

3.2 DEFECTS IN CONCRETE STRUCTURES

As summarised in Table 1, blisters, cracking, crazing, curling, delamination, discolouration, dusting, efflorescence, low spots, pop-outs, scaling, and spalling were found to be some of the common defects in concrete structures. Among the various types of defects listed in Table 1, cracks have been identified as the predominant defect observed in numerous research papers.

Table 1: Summary of defects in concrete structures

Category	Description	Author
Cracks in concrete	Cracks can develop due to several causes, including drying shrinkage, temperature variations, incorrect curing, overloading, or subgrade settling.	Li et al. (2018)
	Insufficient depth of concrete overbends in reinforcement and lack of expansion joints may cause cracks.	Shaikh (2018)
Curling of concrete structure	This can become worse due to inadequate curing, inadequate subgrade preparation, or the use of inferior-quality materials.	Oh et al. (2016)
Scaling of concrete	This flaw may be due to poor finishing, repeated freeze-thaw cycles, or contact with chemicals such as dicing salts.	Yang et al. (2021)
Spalling of concrete	Occur due to overloading, freeze-thaw cycles, chemical actions, inadequate curing, poor finishing, or the use of poor-quality materials.	Shannag and Higazey (2020)
Delamination	Inadequate surface preparation, insufficient bonding, or the use of inferior materials.	Oh et. al. (2016)
Pop-out and discoloration	Poor quality control during the manufacture	Yang et al. (2021)
	Placing concrete can also cause popouts.	Shannag and Higazey (2020)
	Variations in the aggregate, fluctuations in the quantity of water used during mixing, or exposure to sunshine can all contribute	Shaikh (2018)

3.3 DEFECT IDENTIFICATION TECHNIQUES

Through a systematic review of the literature, four different categories of Non-Destructive Testing (NDT) i.e. (i) ultrasonic testing, (ii) GPR technique, (iii) IE, and (iv) Schmidt hammer were identified (refer to Table 2).

Table 2: Data summary obtained in the study.

Category	Description	Author
Ultrasonic testing	To identify the thickness and state of the concrete structure.	Gupta et al. (2022)
Ground Penetrating Radar (GPR) technique	To find changes in the concrete's material composition	Metwaly (2015)
Impact Echo (IE) test	To find cracks, delamination, thickness, and other flaws	Baggens and Ryden (2015)

Category	Description	Author
Schmidt Hammer	To assess the compressive strength	Kumavat et al. (2021)
Visual Inspection	Provides valuable initial information and serves as the first step in evaluating the overall condition of concrete structures	Shannag and Higazey (2020)

3.4 RECTIFICATION PROCESS OF CONCRETE DEFECTS

The most common rectification methods for flaws in concrete are outlined in Table 3. A review of relevant studies revealed that epoxy treatment and Carbon fibre reinforcement are the most suitable methods to be applied to fix concrete flaws.

Table 3: Rectification methods for concrete defects

Category	Description	Author
Epoxy treatment	Epoxy injection is used to repair and reinforce concrete structures with cracks or cavities. The epoxy injection assists in stopping additional deterioration and extends the life of the structure.	Kaarthik and Mandurachalam (2022)
Carbon fibre reinforcement	Carbon fibre strips or sheets to the surface of the concrete structure provide additional strength and stiffness. It provides strength and rigidity to the structure while reducing the extra weight or thickness.	Liu et al. (2020)
Grout Injection	By injecting a particular resin into the fractures, the crack injection technique may fix cracks in concrete.	Kim et al. (2013), Jiang et al. (2019)
Steel and concrete jacketing	Provide additional support and thickness to members to carry more load.	Mahmoud (2022)

4. DISCUSSION

4.1 DEFECTS IN CONCRETE

Concrete structures are susceptible to cracking over time, which can compromise their structural integrity and longevity. Cracks affect the load-carrying capacity and overall performance of the structures. Moisture and aggressive chemicals can penetrate concrete through cracks, further deteriorating it and reducing its durability. Depending on their size, orientation, and location, cracks can affect the behaviour of structures. Cracks can be divided into several categories, including structural cracks, thermal fractures, settlement cracks, and plastic cracks. Several factors can cause concrete cracking, including shrinkage, thermal stresses, excessive loading, and inadequate reinforcement. Moreover, faulty design or construction methods including inadequate joint spacing, and incorrect control joint placement can cause cracks (Li et al., 2018).

Besides cracks, delamination, which is the separation of a thin surface layer of concrete from an existing concrete surface, was identified as another defect in concrete structures. Concrete paste separates along a plane parallel to the surface of the concrete in the case of delamination. This type of concrete flaw typically forms because of concrete properties, daily temperature increases, and the finishing procedure used (Lacroix et al., 2021). Variations in the aggregate, fluctuations in the quantity of water used during mixing, or exposure to sunshine can all contribute to this. Inadequate curing, poor finishing, or the use of contaminated materials can also cause it.

In concrete, curling refers to the lifting or curling of the corners or edges of a slab, typically for a flat surface. Concrete structures can be adversely affected by this deformation. Moisture gradients or differences in moisture content are one of the major causes of concrete curling. When concrete cures and dries, the top surface dries faster than the bottom, causing shrinkage. This differential shrinking causes the slab edges to curl upward. Curling can be caused by temperature changes, restricted mobility at joints, and poor building practices (Oh et al., 2016). Moreover, pop-out is another defect found in structural elements in this review. In concrete, pop-out occurs when small cone-shaped or circular fragments break away from the surface. The size of these pop-outs can vary from a few millimetres to a few centimetres, and they can affect the appearance, durability, and functionality of concrete structures. Pop-outs, from an aesthetic perspective, form unattractive craters or depressions on the surface of concrete, reducing its visual attractiveness. In terms of durability, pop-outs can undermine the concrete surface's integrity, resulting in increased permeability, probable moisture infiltration, and decreased resistance to freeze-thaw cycles.

4.2 DEFECT IDENTIFICATION TECHNIQUES

The concrete surface can be visually examined to identify visible defects. It can detect apparent cracks, spalling, scaling, pop-outs, crazing, discolouration, honeycombing, and other surface abnormalities that could suggest a problem. In addition to detecting surface defects, the visual inspection also helps to assess concrete uniformity, inspect reinforcement conditions, detect surface contamination, ensure proper surface preparation, and provide documentation for future reference.

The Non-Destructive Testing (NDT) method does not damage materials, components, or structures while identifying defects or assessing potential failures. To examine the properties of an object, these methods typically involve specialised equipment and techniques. One of the most useful NDT techniques is ultrasonic testing. In this technique, ultrasonic pulses are transmitted through concrete and their travel time is measured. The test analyses the velocity of sound waves to determine the concrete's quality, uniformity, and potential defects. Concrete is exposed to sound waves via a transducer that is positioned on the concrete's surface. The transducer analyses the waves after they bounce off the material surfaces to identify the thickness and state of the structure.

Another commonly used technique in concrete defect identification is the use of the Schmidt hammer (rebound hammer) which measures the rebound of a spring-loaded mass striking a sample's surface. The test hammer strikes the concrete with a predetermined amount of force. Its rebound is determined by the hardness of the concrete and assessed by test equipment. The rebound value may be used to calculate the compressive strength of concrete using a conversion chart. The rebound value is then connected to the compressive strength of the concrete, indicating its total strength.

Furthermore, Ground Penetrating Radar (GPR) is another NDT method commonly employed for inspections. It is used in concrete testing to assess the condition of concrete structures by providing information about reinforcement bars, voids, cracks, and delamination. Typically, GPR antennas are moved over concrete surfaces and reflected signals are recorded and analysed in real-time or during post-processing. Radar waves are used in the GPR technique to find changes in the concrete's material composition. An image of the inside of the slab is produced by sending waves into the material and then analysing the signals that reflect.

Additionally, the impact echo test, as an NDT technique, is employed for identifying defects in concrete structures. This method detects voids, honeycombing, cracks, and delamination. A mechanical impact or impulse is applied to the surface of the concrete structure using a specialised impact device, (Baggens & Ryden, 2015). The impact can be generated by striking the surface with a hammer or using a mechanical excitation device. A concrete thickness gauge is typically used to measure concrete elements from one side.

4.3 RECTIFICATION METHODS FOR CONCRETE STRUCTURE DEFECTS

One of the dominant and efficient rectification methods is the use of carbon fibre reinforcement. It is a popular retrofitting technique for strengthening and reinforcing concrete buildings that have been damaged owing to cracking, settling, or other types of damage. Carbon fibre strips or sheets are used on the surface of the concrete structure to offer extra strength and stiffness (Draganic et al., 2021). Carbon fibre reinforcement can help to increase the structure's strength and stiffness while decreasing the reinforcement's excess weight or thickness, making it a long-lasting and efficient method of retrofitting concrete structures (Liu et al., 2020). Grout injection was also highlighted as another important technique. Concrete cracks, voids, and porous areas are injected with grouts, resins, or other materials to improve performance and restore integrity. Epoxy injection has been identified as another important method. It is frequently employed as a retrofitting procedure to repair and reinforce concrete structures afflicted with cracks or voids (Kaarthik & Mandurachalam, 2022). Many advantages can be gained from epoxy treatments, including high strength, excellent adhesion, chemical resistance, durability, and ease of maintenance. Concrete surfaces can be significantly improved in terms of performance, appearance, and longevity with these treatments.

The application of steel or concrete jacketing is another NDT method. Using epoxy adhesive or mechanical fasteners, steel plates are affixed to existing concrete structures. This integration of steel plates enhances both strength and stiffness, effectively serving as external reinforcement (Kim et al., 2013). A steel jacket provides additional strength and stability by covering columns and beams with steel angles, channels, or bands. By forming a new reinforced concrete section around the existing member, concrete jacketing adds a new layer of concrete to it. Shotcrete is more often used than cast-in-place concrete. In addition to improving load-carrying capacity, the jacketed section provides additional resistance against seismic forces. As part of this method, a layer of reinforced concrete is added outside the perimeter of the existing member using longitudinal steel reinforcements and transverse steel ties. By using reinforced concrete jackets, the member's strength, both flexural and shear, as well as its vertical bearing capacity, can be substantially increased. Through the confinement and anti-buckling action of the new stirrups, the member's ductility and deformation capacity can also be increased significantly. By adding longitudinal reinforcement, the member's bearing capacity and flexural strength are enhanced, while the addition of transverse reinforcement improves its shear strength and ductility.

4.4 DEVELOPMENT OF THE FRAMEWORK

By linking the defects, their identification methods, and rectification techniques discussed in previous subsections, a framework shown in Figure 4 is developed. The framework provides the link between each defect, its identification techniques, and the remediation process. For instance, from the findings discussed above, one of the major defects in concrete is crack, and the techniques to identify are visual inspection, ultrasonic testing, impact echo, and Schmidt hammer. The methods that can be utilised to remedy the cracks are Carbon fibre reinforcement, epoxy treatment, and grout injection. Using a similar procedure, the methods for identification and rectification processes for other defect types can be easily obtained from the framework.

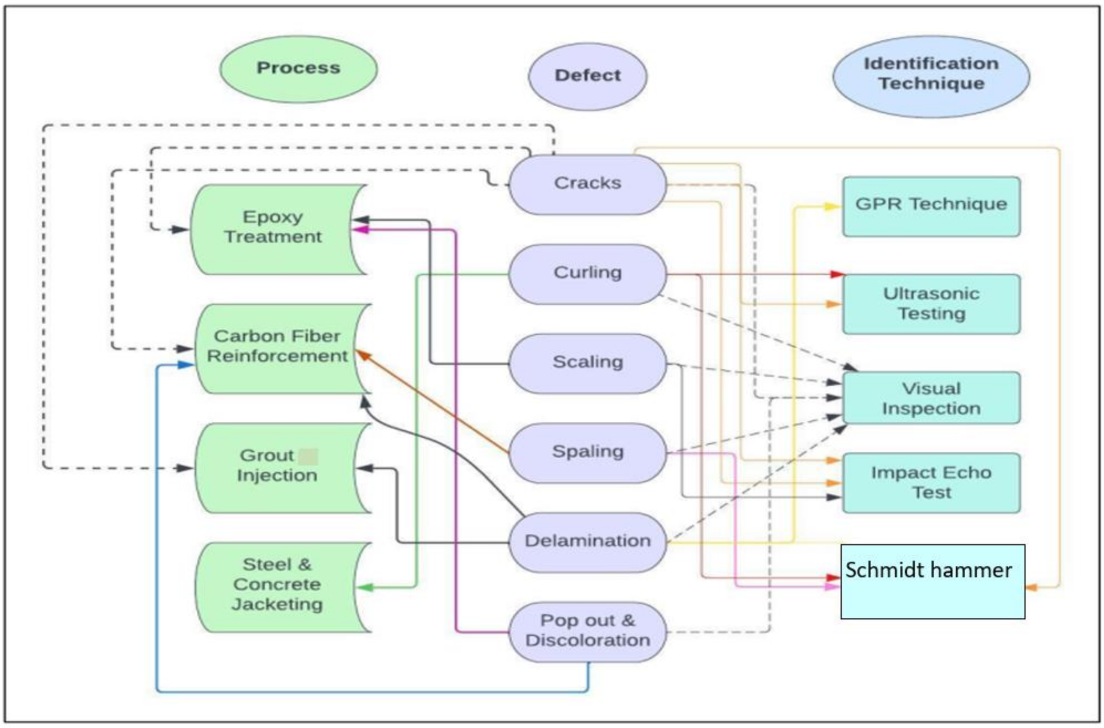

Figure 4: Framework to detect defects, identification techniques, and rectification process

5. CONCLUSIONS

This study aimed to analyse defects in the concrete structures of residential buildings via a systematic review of the literature. The findings obtained in this research revealed several defects associated with concrete structures; however, cracks are the most dominant and severe problem. Additionally, the study has shown that while several techniques were used for the identification of defects in concrete, the Schmidt hammer and ultrasonic methods are the most widely used. The means to rectify these identified flaws can be done through epoxy treatment, fibre-reinforced treatment, grout injection, and jacketing. It was found that epoxy and fibre-reinforced treatment are capable of remedying most of the defects.

This research has managed to establish a framework that provides links between defects, identification techniques, and rectification processes. Various stakeholders involved in the building maintenance and operation can benefit from the output of this research. By retrofitting using the suggested techniques, owners or property managers of residential buildings can maintain the structural integrity of their concrete structures. Moreover, the framework can be used by future researchers interested in investigating defects in other structures and materials such as steel or masonry for comparison purposes. Despite its contributions, there were certain limitations associated with this research. The study used secondary data only and field tests were not carried out to verify the proposed framework. Further, due to the complexity of building defects, the developed framework may not capture all the causes and their interrelationships. Hence, it is suggested that future researchers should conduct field tests and employ triangulation methods to verify the proposed techniques. Additionally, separate frameworks for low-rise and high-rise buildings can be developed by future researchers since the causes of defects may vary based on the types of buildings.

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