

Doctoral dissertation

Experimental study on cementitious mortars for
repairing RC members

(鉄筋コンクリート部材の補修用セメント系モルタル
の実験的研究)



2026.03

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	Abbreviation
LDCs	Least Developed Countries
RC	Reinforced concrete
OPC	ordinary Portland cement
OPCM	ordinary Portland cement mortar
PF	Polypropylene fiber
PMC	Polymer Modified Concrete
ER.	Epoxy resin
FE	Finite element
ASR	Alkali-silica reaction
HPFRCC	High-performance fiber-reinforced cementitious composites
NDT	Non-destructive testing
FRP	Fiber Reinforced Polymer
ACI	American Concrete Institute
SSD	Saturated surface dry
ASTM	American Society for Testing Materials
JSCE	Japanese Society of Civil Engineering
W/c	water cement ratio
WRA	water reducer Agent
PMCM	Polymer-modified cement mortar
PFRM	Polypropylene fiber-reinforced mortar
LVDTs	Linear variable displacement transducers
UHPC	Ultra-high-performance concrete
PC	Polymer cement
JIS	Japanese Industrial Standards
<i>w/cm</i>	Water-to-cementitious material ratio
<i>s/a</i>	Sand-to-aggregate volume ratio

LCA	Life cycle assessment
LCC	Life Cycle Cost
GWP	global warming potential
GDP	Gross Domestic Product
NPV	Net Present Value

Abstract.

The preservation and rehabilitation of concrete infrastructure are critical for ensuring long-term structural integrity, particularly in developing nations such as Timor-Leste, where resource constraints necessitate cost-effective, locally sourced solutions. This study utilizes an experimental approach to investigate the efficacy of repair materials for reinforced concrete (RC) beams. Ordinary Portland Cement Mortar (OPCM), Polymer-Modified Cement (PMC) mortar, OPCM reinforced with polypropylene fibers (PF), and Epoxy Resin (ER). The experimental findings suggest that OPCM functions as a highly sustainable and viable substitute for more expensive commercial products, exhibiting mechanical performance that is comparable to that of specialized polymer mortars. The integration of PF into the mortar matrix resulted in a substantial enhancement of beam ductility and ultimate load-carrying capacity. While ER treatments demonstrated superior crack width control and improved pre-failure performance, their effectiveness was highly sensitive to application timing, with improper curing leading to marginal reductions in total structural strength. It is noteworthy that all repair methods exhibited robust interfacial bonding, with minimal evidence of shear cracking or debonding. However, failure of all specimens occurred via flexural and shear mechanisms. In order to validate the experimental findings, finite element (FE) models were employed. The numerical simulations demonstrated a high degree of accuracy in replicating the load-deformation behavior of OPCM-repaired beams, exhibiting a strong correlation with physical test data. This research underscores that OPCM is a robust, accessible repair medium that enables the development of resilient infrastructure without sacrificing structural safety. These findings indicate that the optimization of local material constituents represents a viable strategy for enhancing both the structural longevity and the economic sustainability of infrastructure in resource-constrained environments.

Keywords:

Resource constraints, Infrastructure repair, Bond strength, Flexural analysis, optimizing local materials.

I. Introduction.

1.1. Research background

The vital role of modern infrastructure in driving economic development is well-established [1]. Consequently, Timor-Leste, like other Least Developed Countries (LDCs), has made infrastructure development a top national priority to accelerate economic growth and social progress since its establishment in the century [2]. The construction and integrity of modern infrastructure, encompassing essential structures such as buildings and bridges, are critically reliant on reinforced concrete (RC) as a fundamental structural material. The long-term durability of reinforced concrete (RC) structures is compromised by degradation from aging, environmental conditions, and sustained service loads, necessitating significant remediation [3]. This process often begins with surface-level damage, particularly to the concrete cover, which acts as a frequent precursor to deeper structural compromise and underscores the critical importance of prompt intervention.

The fundamental objective of rehabilitating reinforced concrete (RC) structures is to extend their service life by integrating the repair material with the existing substrate into a cohesively functioning system [4, 5]. The success of this endeavor is critically dependent on the bond strength at the repair interface, which is governed by factors such as material stiffness, substrate roughness, and surface geometry. However, restoring structural integrity is a formidable challenge. Defects originate not only from initial design, material, or construction inadequacies but also from a multitude of deterioration mechanisms that act on operational structures—often synergistically with environmental and loading factors. This complexity, especially acute in regions with limited resources, dictates that the application of compatible cementitious repair materials must be preceded by a comprehensive evaluation of the damage and environmental conditions to ensure a lasting and safe restoration.

In pursuit of a durable bond, research has investigated various repair materials and application techniques. While polymer-modified cement (PMC) mortars offer superior bond strength, durability, and crack resistance over traditional ordinary Portland cement mortar (OPCM), the latter remains common in developing countries due to its low cost [6]. The performance of these cementitious systems has been further enhanced by incorporating additives such as epoxy resins, polypropylene fibers, and novel biomaterials to boost mechanical properties in demanding conditions. Beyond the choice of material, the repair's success is governed by procedural factors.

The bond strength is critically influenced by substrate surface preparation, the workability and shrinkage properties of the repair mortar, and the implementation of proper curing protocols, without which the repair may fail prematurely. Consequently, the long-term performance of the repaired structure depends on a comprehensive strategy that addresses all these interdependent variables, from material science to on-site application and environmental exposure, to overcome the central challenge of creating a lasting bond [7].

Building on the challenges of material selection in resource-limited settings, this study focuses on the context of Timor-Leste. In Timor-Leste, the default choice for concrete repair is a general-purpose mortar with ordinary Portland cement (OPC), selected for its availability and simple application. This study evaluates the effectiveness of this common, non-specialized approach by measuring its interfacial strength against that of alternative materials, providing insight into its performance in a resource-constrained environment. by evaluating the bond strength between the interfaces in comparison to other options.

1.2.Objectives

A wide range of methodologies and materials are employed in the rehabilitation and repair of damaged RC members in construction projects. Emerging technologies and advanced materials inform these approaches. However, there is a lack of information specifically addressing the needs of LDCs. This experimental study focuses on the use of cementitious mortars for repairing RC members, aiming to provide essential insights that can support the restoration of damaged RC beams in resource-limited settings.

The primary objective is to investigate the performance of ordinary Portland cement mortar (OPCM) as a repair material for RC structural members, particularly in the context of limited resources regions.

The main objective of the present experimental study is.

- a) Investigate Performance: Evaluate the effectiveness of OPCM as a repair material for RC structure members, specifically when enhanced with polypropylene fiber (PF) and epoxy resin (ER). Its performance will be compared against a standard Polymer Modified Concrete (PMC) mortar.
- b) Assess Bond Strength: Analyze the interfacial bond between the repair materials and the concrete substrate. The performance of this bond will be tested under tension, shear, and mixed compression loads to determine its ability to maintain structural integrity.

- c) **Analyze Failure Mechanisms:** Examine the compatibility, workability, and strength of the different material combinations under varying load conditions. This includes a detailed analysis of crack propagation and failure modes in the repaired specimens.
- d) **Validate Findings:** Validate the experimental results by using a finite element (FE) model analysis.
- e) **Define material:** Define materials for repair within the context of a Least Developed Country, with specific reference to budget constraints and the availability of maintenance resources.
- f) **Life-cycle cost analysis (LCCA)** enables decision-makers to identify the most cost-effective, long-term repair strategy.

The primary objective is to demonstrate that OPCM, particularly when enhanced with PF and ER, is an effective repair solution for RC structures. This study seeks to validate that this composite system provides sufficient mechanical strength, establishes a durable bond with the substrate, mitigates crack propagation, and successfully restores the flexural capacity of damaged beams. While the general advantages of OPCM are recognized, this research focuses on confirming its long-term durability, thereby offering a practical and cost-effective framework for infrastructure maintenance.

1.3. Structure of thesis

The flowchart of the experimental study on the application of experimental study on cementitious mortars for repairing RC members in LDCs is displayed in Figure 1.1. The structure of this dissertation is based on the flowchart, and the outline can be summarized as follows:

Chapter I: Introduction

This chapter introduces the background and significance of repairing RC structures, emphasizing the importance of selecting suitable materials to ensure durability and cost-effectiveness. The chapter defines the research objectives, outlines the scope of the study, and describes the thesis's overall structure. References relevant to the research context are also presented.

Chapter II Review of previous studies: Repair method for damaged RC structures.

This chapter provides a comprehensive review of existing literature on RC repair materials and methodologies. It discusses the historical development of repair materials, various repair techniques, cost-performance evaluations, and the durability of different materials. The chapter concludes by identifying research gaps and the need for further experimental and analytical

investigation into the performance of conventional and advanced cementitious repair materials. References relevant to the research context are also presented

Chapter III: Methodology and material of application for the repair of RC beams in LDSc.

This chapter presents the methodology and material for applying repair techniques to RC structures members. Specifically, this chapter explains the approach utilized in this thesis for the RC beam repair program or methodology, including the use of both conventional materials and some advanced materials such as PF, PMC, and ER. References relevant to the research context are also presented

Chapter IV: Experimental study on the bond strength between the repairing mortar and the concrete substrate

This chapter presents an experimental investigation of the bond strength between concrete substrates and various repair mortars, including OPCM, PMC mortar, and combined with ER. The chapter explains the experimental procedures slant shear test, the double shear test, and surface roughness, including a description of the materials used. The results and discussion focus on how surface conditions and material types of influence bond behavior after repair. The chapter concludes with a summary of the key findings. References relevant to the research context are also presented

Chapter V: A Comparative Study of the Flexural Behavior of Reinforced Concrete (RC) Members Repaired with Various Cementitious Mortars.

This chapter compares the flexural performance of RC members repaired with different cementitious mortars using four-point bending tests. The chapter describes the materials, mixed designs, repair procedures, and experimental setup. The analysis covers crack formation, deflection behavior, strain distribution, and load-bearing capacity. Finite element (FE) method simulations were performed to validate the experimental results and analyze stress and strain distribution. The findings highlight differences in the structural performance of the repair materials. References relevant to the research context are also presented

Chapter VI focuses on the flexural performance of RC beams repaired with conventional cementitious mortar.

This chapter focuses on the structural performance of RC beams repaired with conventional cementitious mortar. It describes the experimental program, material properties, specimen preparation, and testing procedures in detail. The experimental results are then compared with the

outcomes of finite element analysis to evaluate flexural behavior, crack propagation, and ultimate load capacity. The chapter concludes with a discussion of the efficiency and limitations of cementitious materials for repair in restoring the performance of RC beams. References relevant to the research context are also presented

Chapter VII: Conclusions and Future Research.

This chapter summarizes the major findings obtained throughout experimental and analytical studies. Key conclusions are drawn regarding the bond strength, flexural behavior, and performance of the repair materials. Recommendations for future research include developing and testing sustainable repair materials, taking an advanced modeling approach, and validating laboratory results on a field scale.

Appendix: Life cycle cost analysis (LCCA) of conventional cementitious materials for repairing RC beams.

This chapter describes how to use LCCA to evaluate the economic and environmental implications of using conventional cementitious materials for RC structure repair. The analysis includes cost components such as production, transportation, execution of repairs, maintenance, and service life. The results are discussed in terms of long-term cost-effectiveness and sustainability, providing a comprehensive understanding of the financial calculation method of repair materials under realistic conditions. References relevant to the research context are also presented

Acknowledgments:

The final section expresses gratitude to the supervisors, academic advisors, collaborators, and funding agencies whose support made the research possible.

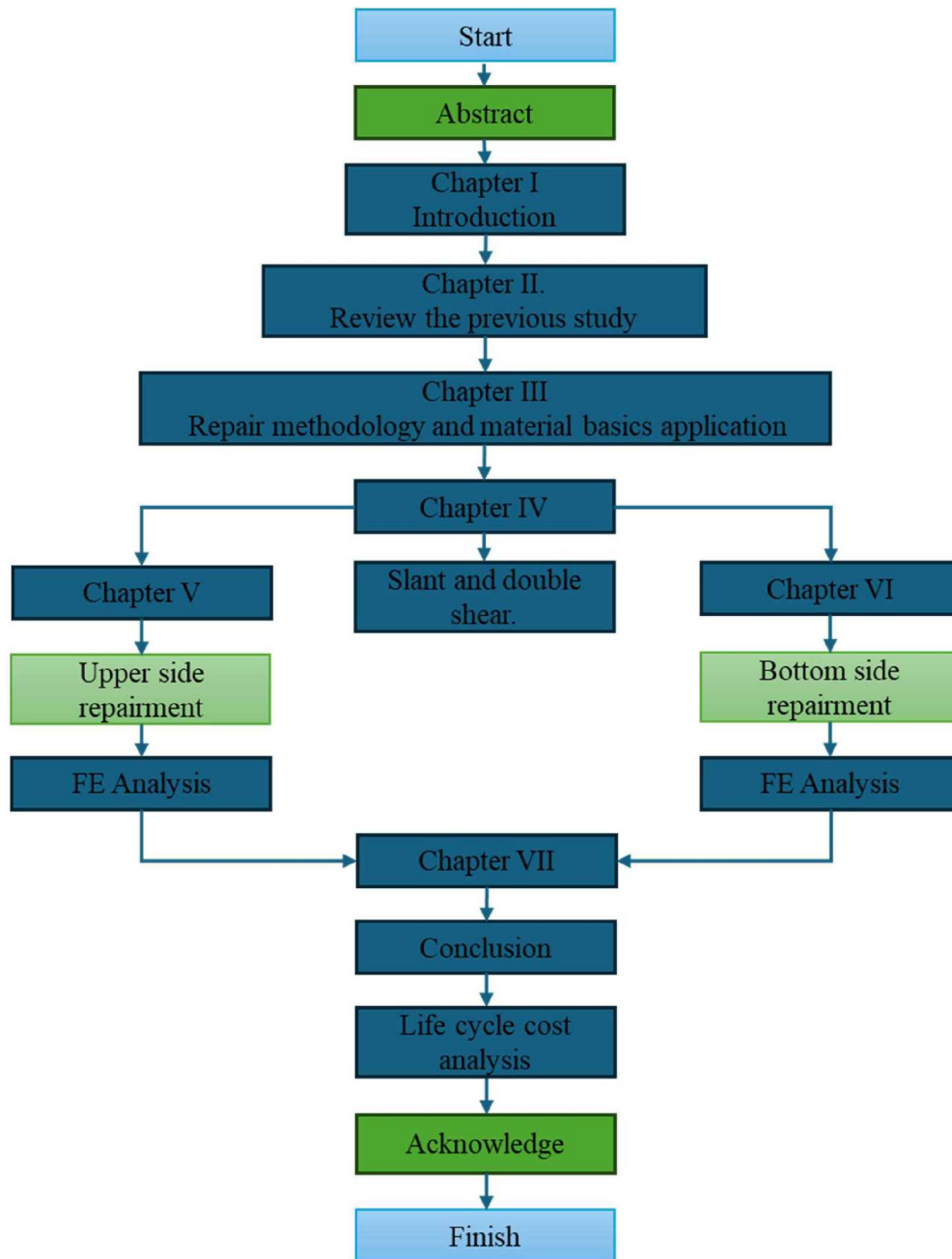


Figure 1.1. Flowchart of experimental study on cementitious mortars for repairing reinforced concrete (RC) members

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II. Preview studies: Repair method for damaged RC structures.

2.1. History of repairing materials for reinforced concrete (RC) beams

The development of modern concrete began with Joseph Aspdin's invention of Portland cement in 1824, later supplemented by Joseph Monier's RC in the mid-19th century, establishing concrete as the dominant global construction material throughout the 20th century [1]. Despite innovations such as prestressed and high-performance concrete and the current focus on low-carbon, self-healing, and geopolymers to promote sustainability, RC structures remain vulnerable to degradation.[2]. There are various damage mechanisms, including severe issues such as reinforcement corrosion, which is often caused by chloride or carbonation and results in cracking and spalling. Other mechanisms include chemical attacks, such as sulfate attack or alkali-silica reaction (ASR), as well as physical deterioration from freeze-thaw cycles and mechanical overloading.[3]. The impairment of the concrete is attributable to the installation method and the construction process, which are results of unprofessional behavior by the laborers. This issue will inevitably lead to long-term problems in the utilization of the concrete structure, as shown in Figure 2.1.



Figure 2.1. Initial damage and repair application to the concrete structure.

The fundamental principles of repair application efforts were traditionally elementary, often relying on simple cementitious mortars composed of ordinary cement, water, and fine aggregates.

These mortars frequently exhibited premature failure due to insufficient bond strength and incompatibility with the underlying concrete, underscoring the ongoing imperative for advanced and effective durability and repair strategies. However, the efficacy of these strategies is contingent upon the availability of limited resources, a situation that remains prevalent in many regions.

The incorporation of polymer-modified cementitious mortars, comprising styrene-butadiene rubber (SBR) and acrylics, has been demonstrated to result in substantial enhancements in the adhesion, tensile strength, and water resistance of repair mortars [4].

This innovation signified a substantial advancement, facilitating more resilient and dependable repairs. A significant advancement has been made in the field of epoxy-based resin development for concrete repair applications. Epoxy injection represented a revolutionary development due to its capacity to repair damaged concrete structures, thereby restoring their structural integrity and enhancing their compressive and tensile strength [6]. Concurrently, fiber-reinforced polymers (FRP) emerged as a viable material for strengthening and retrofitting RC beams, exhibiting high strength-to-weight ratios and exceptional corrosion resistance. Recent research has centered on the development of advanced and sustainable repair materials. This encompasses high-performance fiber-reinforced cementitious composites (HPFRCC), geopolymers derived from industrial byproducts, and materials with self-healing capabilities. The objective of this research is to extend the service life of repaired structures while minimizing environmental impact [7]. The initial phase of RC repair served as an important learning period, highlighting the complex material science required for effective, long-lasting structural restoration, all while considering the constraints of the structure's condition, budget, and available resources

2.2. Methodology for repairment.

As Figure 2.2 illustrates, the selection of a repair methodology for RC structure members depends on the type, extent, and cause of the damage. A systematic approach is essential to ensure the effectiveness and longevity of the repair. The first step in any repair process is a thorough condition assessment to identify the cause and damage intensity. The procedure generally entails a visual inspection, as well as non-destructive testing (NDT) that may include ultrasonic pulse velocity or rebound hammer tests. In certain instances, core sampling is also employed to ascertain the compressive strength and chemical composition of the concrete [8].

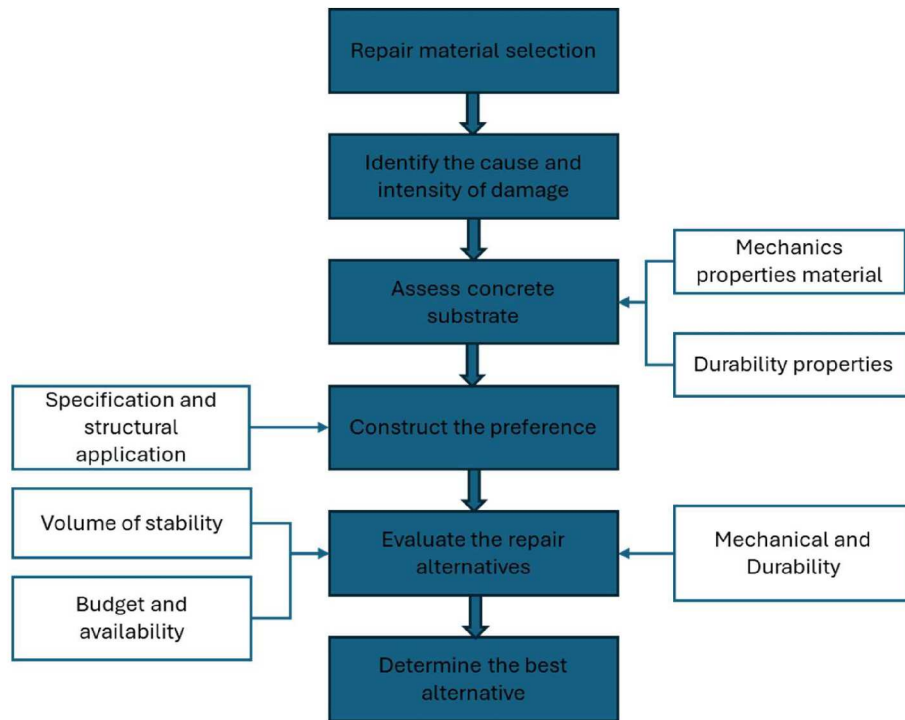


Figure 2.2. Process flow chart for selection of repair material.

In the next step, the area to be repaired must be evaluated before the designated repair material is applied. In the event of surface defects, such as spalling, the standard procedure is to remove all damaged and unsound concrete, thereby exposing a clean, solid substrate. Concurrently, all exposed steel reinforcements are meticulously cleaned of corrosion and subsequently treated with an anti-corrosion coating. In the final stage of the repair process, a bonding agent is typically applied to the prepared concrete surface. This agent facilitates the adhesion of the repair material, ensuring a robust, integrated bond between the existing and new materials. The application of a bonding agent is frequently implemented before the placement of the repair material. This can be accomplished through hand-packing, form-and-pour, or spray application techniques [9].

The subsequent phase in the remediation of structural damage entails the selection of the most prevalent application technique, a decision informed by the dimensions and the spatial disposition of the impairment. A prevalent repair technique involves the implementation of patches, which are utilized to address localized damage, including spalling and delamination. The process entails the removal of deteriorated concrete, the cleaning of exposed steel reinforcement, the application of a

bonding agent, and the filling of the void with a suitable repair mortar. The efficacy of this method is contingent upon meticulous surface preparation and the compatibility of the materials. [10]. In order to achieve a substantial increase in load-bearing capacity, section enlargement or jacketing is employed. This process involves the incorporation of an additional layer of concrete or mortar around the existing beam, often accompanied by supplementary reinforcement. This technique has been demonstrated to enhance the flexural and shear strength of members; however, it concomitantly increases dimensions and deadload.

The other rationale for addressing crack repair is that the methodologies for doing so are clearly delineated in Table 2.1 [11, 12].

Table 2.1. Crack evaluation and repair method

Crack Characteristic	Recommended Methodology	Mechanism & Purpose
Fine, Dormant Cracks (Static, no future movement)	Low-Pressure Epoxy Injection	Injects low-viscosity epoxy resin to "glue" the concrete
Wider or Active Cracks (Dynamic, subject to movement)	Routing and Sealing	A V-shaped groove is cut and filled with a flexible sealant (e.g., polyurethane or silicone). However, it does not restore structural strength.
Active Cracks Requiring Structural Fix	Stitching	U-shaped steel staples are grouted into holes drilled across the crack, physically pinning the sections together
Significant Structural Degradation (Compromised load capacity)	Section Enlargement (Jacketing)	Adds a new layer of concrete and steel reinforcement around the existing member

The most contemporary approach to strengthening involves the implementation of externally bonded Fiber Reinforced Polymer (FRP) composites. Fiber-reinforced polymer (FRP) sheets or laminates are bonded to the tension face of the beam to enhance its flexural strength. Alternatively, they are applied as U-wraps to the web to improve its shear capacity. This method offers the advantage of adding significant strength with minimal increase in weight or size, making it ideal for retrofitting applications where clearance is a concern [13]. In the context of restoration, the

process of curing assumes paramount importance. Proper curing is pivotal in ensuring that the newly installed material attains its maximum strength and durability, thereby bringing the restoration process to a successful conclusion.

The final step in the process is to define the type of material and repair method that is suitable for the condition of the site repair. Two practical constraints primarily influence this crucial decision: the availability of suitable repair materials in the surrounding area and the allocated budget for repair. The selection of appropriate materials and methods is of paramount importance, as it is directly linked to the enhancement of the concrete and the assurance that the repair meets the requisite strength and durability standards.

2.3. Cost performance of repairing materials.

The economic viability of a given repair strategy is a pivotal factor in its selection. A cost-performance analysis is an economic assessment that extends beyond the initial costs of materials and labor. It incorporates the anticipated lifespan of the repair and the projected maintenance costs to ensure the long-term value and sustainability of the investment.

Traditional cementitious mortars remain the most cost-effective option for non-structural, cosmetic repairs. Their low material cost and ease of application make them suitable for large-scale patching where structural performance is not the primary concern. However, their lower durability may lead to higher life-cycle costs due to the need for repeated repairs.[14]

Although polymer-modified mortars and epoxy-based materials have a higher upfront cost, they are more cost-effective in the long term due to their superior bonding, strength, and durability. However, their superior bonding, strength, and durability can result in a longer service life, making them more cost-effective in the long run, particularly for critical structural repairs [15, 16]. Cost performance analysis compares the balance between the initial cost of repair materials and their long-term effectiveness and durability. For concrete crack repair, epoxy injections typically have a higher initial material cost than conventional mortar repairs, often higher in cost for the same length of crack. Labor costs also tend to be higher for epoxy, partly due to specialized handling and equipment. While mortar repair is seen as a cost-effective, fast fix for superficial damage, its longer service life and superior performance mean epoxy injection often lowers the overall life-cycle expense. Epoxy injections restore or enhance the strength and integrity of structural concrete, offering a service life often three times longer than mortar-based repair. In contrast, mortar repairs patch the surface but may not address underlying structural issues, resulting in more frequent

repairs and higher cumulative costs over time. Studies and industry estimate consistently report that even though epoxy has higher upfront costs, its long-term durability makes it more cost-effective for critical repairs where longevity is essential. Therefore, while mortar remains a reasonable, inexpensive fix for minor, non-structural cracks, epoxy injection's cost performance is superior for structural cracks.

In the context of rehabilitation, fiber-reinforced polymer (FRP) strengthening systems are often regarded as a costly solution, particularly with regard to the initial financial investment required. The material cost for carbon or glass fibers and specialized resins is substantial, and the application requires skilled labor. Nevertheless, when compared to the alternative of member or full-structure replacement, FRP retrofitting is often the most economically viable option for extending the life of a structure that has suffered significant strength loss.

2.4. Durability of repairing materials

The durability of a repair is defined by its ability to perform its intended function over a desired period without significant degradation [17]. A critical component of this durability is the compatibility between the repair material and the existing concrete substrate. Discrepancies in properties, including but not limited to modulus of elasticity, thermal expansion coefficient, and drying shrinkage, have been shown to generate stress concentrations at the bond line. These stress concentrations, in turn, have been demonstrated to result in delamination and failure [18].

The structural deterioration of RC members is predominantly attributed to the oxidative corrosion of steel reinforcement. Therefore, an effective repair material must demonstrate the capacity to impede the ingress of chloride and carbon dioxide while concurrently establishing a high-alkaline environment to facilitate the passivation of the embedded steel. Research has demonstrated that polymer-modified and epoxy-based materials exhibit superior resistance to aggressive environments in comparison to conventional mortars [19].

The long-term performance of FRP systems has also been the subject of extensive research. While the FRP itself is corrosion-resistant, the durability of the bond between the FRP and the concrete substrate is critical. Exposure to moisture, system strengthening, and freeze-thaw cycles has been demonstrated to degrade the epoxy adhesive, with the potential to compromise the effectiveness of the system. Therefore, proper surface preparation and the application of protective topcoats are imperative to ensure long-term durability [20].

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III. Methodology and material of application for the repair of RC beams in the least developed countries.

3.1. Methodology for application repair of RC beams.

An experimental study conducted relevant methodologies to apply repair material to RC structure members, which involves a systematic procedure to ensure the bonding, durability, and restoration of structural integrity [1]. The specific steps of the methodology depend on the nature of the damage and the available material in the area. However, the general methodology followed in this research is the initial application to repair the country with limited resources, as shown in Figure 3.1. In the case of available material and budget for repairment, follow these phases.

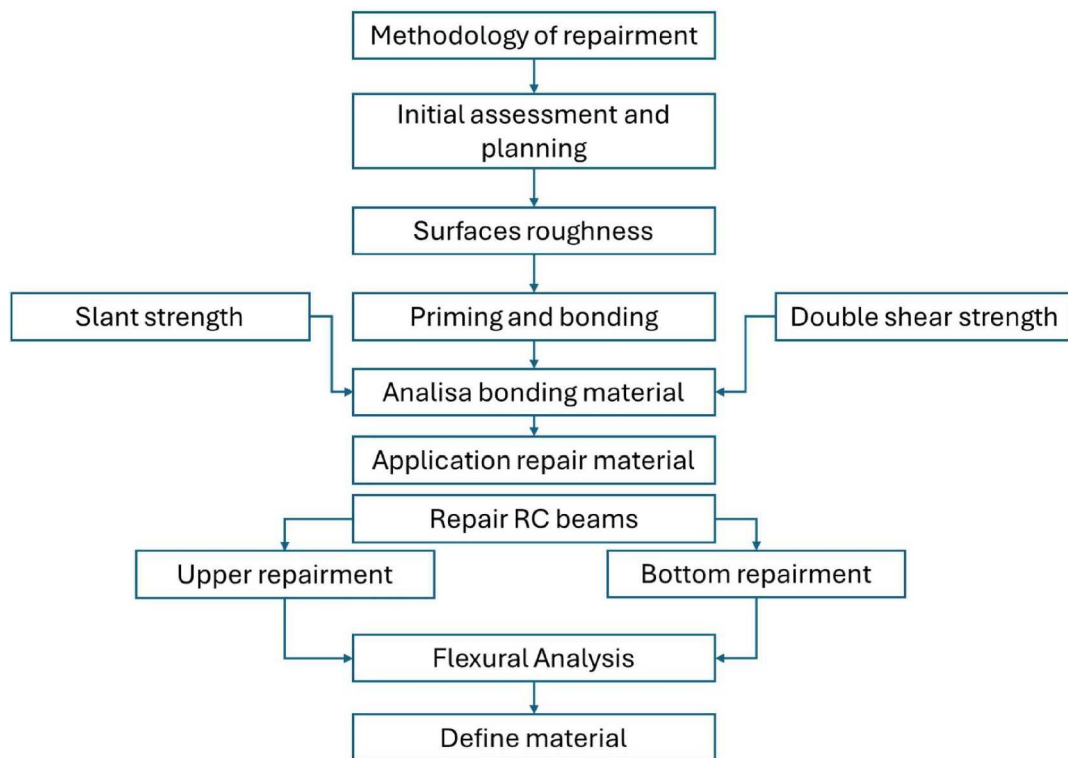


Figure 3.1. Flowchart of repairment and define the material

3.1.1. Initial assessment and planning.

It is essential to understand the root cause of structural damage before undertaking any repair work. An initial assessment and repair strategy must be formulated in accordance with relevant American Concrete Institute (ACI) standards (including ACI 562[2], ACI 563[3], ACI 546R [4], and ACI 224.1R[5]) to determine subsequent procedures.

This assessment begins with inspecting the structure's condition to determine the type, cause, and extent of damage (e.g., cracks, spalling, corrosion, honeycombing), as shown in Figure 3.2. The poor condition of the concrete structure requires immediate attention for repair [6]. This research also involves investigating the availability and price of conventional and advanced repair materials within the country, factoring in the repair budget and long-term planning. The main materials being evaluated are Ordinary Portland Cement (OPC), Polymer Modified Cement (PMC), polypropylene fibers (PF), and epoxy resin (ER) bonding agents [7].

Finally, a solution must be defined that aligns with the structural requirements and environmental conditions in the area or regions.



Figure 3.2. Poor concrete structure condition

3.1.2. Surface preparation or treatment

Proper preparation is essential to achieving good adhesion of the repair material to the existing concrete substrate. The first step is concrete removal. Deteriorated concrete must be mechanically removed using tools such as light chipping hammers, scabblers, or hydro demolition equipment until sound, dense concrete is exposed. The edges of the repair area often need to be defined by saw-cutting perpendicular to the surface. This prevents the repair material from being applied too thinly at the edges, a condition known as feathering. If reinforcing steel is exposed, reinforcement treatment is required. The corroded bars must be fully exposed and thoroughly cleaned of all rust, scale, and debris using mechanical wire brushing or sandblasting. After cleaning, apply a rust-converting primer or a corrosion-inhibiting coating to the steel, following the manufacturer's instructions. Finally, surface cleaning involves removing all residual dust, debris, and contaminants, such as oil or grease. This is typically done via abrasive blasting, blowing with oil-free compressed air, or vacuuming. The prepared concrete surface must be clean and have an adequate rough texture to promote strong mechanical interlocking with the new repair material.

The roughness of the concrete substrate is considered a key factor in the bonding performance between the concrete substrate and the cement-based repair mortar. A rough surface provides a larger surface area and mechanical interlocking for the repair mortar to adhere, resulting in a more durable and enduring connection [8].

The rough surface in this experiment for the concrete substrate was acquired by spraying water over the concrete surface after casting the concrete to delay the hardening of the concrete and removing the soft concrete surface by brushing until coarse aggregates were exposed, as shown in Figure 3.4.



Figure 3.3. concrete surfaces with different roughness [9]



Figure 3.4. Surface roughness preparation in this research

3.1.3. Pairing and bonding

This step is critical because it creates a strong chemical and mechanical bond between the existing concrete substrate and the new repair material. There are two main actions involved: substrate dampening/sealing and application of a bonding agent. The concrete surface must be dampened frequently to reach a saturated surface dry (SSD) condition. This prevents the porous substrate from rapidly drawing water out of the fresh repair mortar, which would severely inhibit its curing and adhesion otherwise. After this preparation, apply an epoxy bonding agent or a polymer-modified slurry primer to the entirely cleaned concrete area according to the product's specific instructions. The subsequent repair material must then be placed while the bonding agent is still tacky or wet to ensure proper adhesion.

3.1.4. Repair material application

The application method depends heavily on the repair material selected and the size and orientation of the damaged area. First, the material, whether mortar, grout, or concrete, must be mixed precisely according to the manufacturer's instructions. Typically, a mechanical mixer is used to achieve a homogeneous, lump-free consistency. For placement (patching/troweling), standard patch repairs require applying the mortar with a hand trowel or spatula. Press it firmly against the primed substrate and into the cavity to eliminate air pockets. For overhead or vertical repairs, it is crucial to use thixotropic (non-sagging) materials to prevent slumping. When grouting or pouring is necessary, such as for larger voids or structural jacketing, secure formwork must first be installed. Flowable materials are then typically poured or pumped, starting from the lowest access point and moving upward, to ensure proper consolidation and prevent air entrapment within the repair zone, as shown in Figure 3.5.



Figure 3.5. Application repair material

3.1.5. Final stage

The final stage of the repair process involves achieving the desired aesthetic and ensuring long-term performance through proper aftercare. For Finishing, the required surface texture is achieved using tools like floats, trowels, or sponges. Curing is essential; the repaired area must be kept moist and shaded from direct sun while curing for the period specified by the relevant standards and material manufacturer. This diligent curing ensures the repair material develops its specified strength and durability. Finally, Post-Repair Testing is performed after the specified curing time. Quality control checks, such as flexural testing and analysis, should be conducted to confirm the repair meets the initial design specifications by using the finite element method.

3.2. Materials for applying repair

3.2.1. Conventional concrete applications for the main structure.

A substrate concrete structure is an original concrete layer that has been modified or added to with materials like coatings or repair mortars; it acts as the necessary base for these subsequent additions. The substrate concrete used a conventional mix design as its foundational material. It was composed primarily of OPC, which acted as the main binder. The cement was mixed with water to initiate the chemical reaction (hydration) necessary for hardening. Void spaces were filled with fine aggregates (sea sand) and coarse aggregates (crushed gravel ranging from 5–20 mm), which provided structural mass. The material was used as shown in Figure 3.6. A crucial addition was a water reducer admixture, a chemical agent that allows for a lower water-to-cement ratio while maintaining sufficient workability, or ease of placement. This ultimately leads to denser, stronger, and more durable finished concrete.



Figure 3.6. Material for conventional substrate concrete

The substrate concrete composition was determined using the ACI method for mix design. The ACI mix design method is generally used in Timor-Leste. The concrete was cast, and the fine aggregate and cement were combined in the mixer. Then, add an admixture (water reducer) to the water. Next, add half of the water mixture to the mixer. Followed by the coarse aggregate and the remaining water mixture. The mixing process was allowed for three minutes before being discharged from the mixer for placement in the form. The mixer was continuously operated throughout the mixing procedure. The molds were formed in different shapes depending on the purpose of testing: a rectangular form with dimensions (100 mm × 100 mm × 70 mm) for double shear and a cylindrical prismatic form with an angle of 30° for slant shear, including cylinder specimens for the compressive strength (diameter 100 and height 200 mm). Additionally, RC beam samples were prepared. The samples were cured for 28 days before the experiment.

3.2.2. Conventional cement mortar for repair.

The conventional cement mortar for repair is a standard mix of cement, sand, and water, as a crucial building material, particularly noted for its high usage in Timor-Leste. This preference is driven by several key attributes: its excellent bonding properties make it reliable for applying finishes like plastering and for performing repairs on existing structures. Furthermore, it offers dependable

strength and is highly versatile, meaning the mix can be adjusted for various construction needs, ranging from simple filling to more substantial surface applications. Compounding these performance benefits is its affordability relative to more specialized materials, ensuring it remains the cost-effective standard for the majority of general construction and maintenance applications within the region.

The materials utilized in this investigation are similar to conventional substrate concrete. The cement mortar was designed with a water-to-cement (w/c) ratio of 30%, and a mixing ratio of 1:2.2 by volume. In the mixing procedure, fine aggregates and cement were added to the mixer, followed by admixture and water. The mixing process was allowed for three minutes before being discharged. Prepare samples for compressive strength (diameter 50 mm and 100 mm height), slant shear, and double shear. In addition, all specimens were cured for 28 days to ensure proper strength development.

3.2.3. Advanced material for repairing

A. Polymer-modified cement mortar

Polymer-modified cement (PMC) mortars are important construction materials owing to their exceptional properties. The excellent characteristics of this substance make it a widely favored option for repairing damaged concrete.

The typical repair cement mortar used in this study for polymer-modified cement is a commercial PMC (RepairmixJ1 produced by Tokuyama Company, Japan), which is a form of repair material for concrete structures, as shown in Figure 3.7.

PMC is composed of a combination of Portland cement (which contains crystalline silica), silica sand (which contains silica, aluminum oxide, and iron oxide), admixtures (which contain calcium oxide), and fibers. The PMC mortar mix proportions were based on the manufacturing guidelines. The mixing process was allowed for three minutes before being discharged. Prepare samples for compressive strength and flexural test for RC beams after repairing.

Furthermore, all specimens designed for testing the compressive strength, slant shear, and double shear strength were properly cured for 28 days to guarantee optimal strength development.



Figure 3.7. Polymer-modified cement

B. Epoxy resin

Epoxy resin (ER) is a class of thermosetting polymers known for its exceptional adhesive properties, high strength, and strong resistance to chemicals and heat. These characteristics make epoxy resin one of the most versatile and widely used resins across various industries. It is typically sold as a two-part system consisting of the resin (part A), which contains epoxy prepolymers, such as diglyceryl ether of bisphenol A (DGEBA), featuring a highly reactive epoxy group (a three-membered ring containing oxygen), and the hardener/curing agent (part B), which contains a reactive compound, often an amine or anhydride. When thoroughly mixed, the two parts undergo a chemical reaction called curing. This reaction causes the epoxide rings to open, creating extensive cross-linking between the polymer chains and transforming the liquid mixture into a rigid, durable solid. In this study, epoxy resin was used as a component of the specimens and functioned as the interface connection between the concrete substrate before the repair materials were poured onto the surfaces. Specifically, the study used epoxy resin XL-800 (Epotherm), for which the resin and hardener were mixed at a weight ratio of 4:1 and had a density of approximately 1.10–1.30 g/cm³. The laminating epoxy (XL-800) was manufactured by Mitsubishi Chemical Institute Co., Ltd., and the manufacturer provided its mechanical properties.

c. Polypropylene fibers

The incorporation of Polypropylene Fibers (PF) is anticipated to significantly enhance the mechanical properties of the mortar matrix by promoting three key effects: improving mortar-aggregate bonding, reducing porosity, and increasing the ductility of the resulting composite material [10]. The PF used in this study, supplied by a commercial company, exhibits the following approximate properties: a low density of 0.91 g/cm^3 , a length of 12 mm, a small diameter of $42.6 \text{ }\mu\text{m}$, and a high tensile strength of 390 N/mm^2 . These fibers are introduced to act as a bridging mechanism, particularly to control and resist cracking, which is essential for achieving a tougher and more durable material.

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IV. Experimental study on the bond strength between the repairing mortar and the concrete substrate.

4.1. Outline

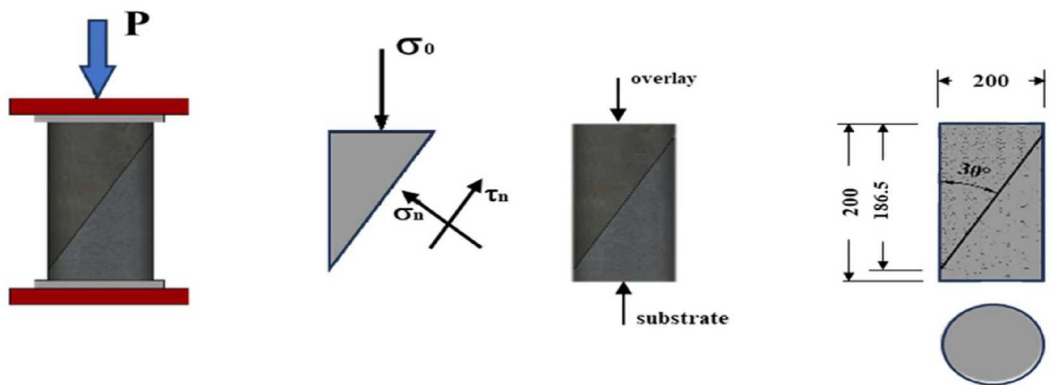
An investigation into structural repair methodologies was conducted, focusing on the applicability of Ordinary Portland Cement Mortar (OPCM) supplemented by a proprietary material as a repair medium for reinforced concrete structures. This research is particularly relevant to Least Developed Countries (LDCs) due to existing economic constraints and the limited availability of specialized repair products.

The core objective was to experimentally determine the performance of OPCM, specifically its ability to maintain bond integrity with the concrete substrate under external loading. The study compared OPCM against benchmark repair systems, including polymer-modified cement mortar and epoxy resin bonding agents.

Recognizing that substrate surface preparation is paramount for optimizing adhesion, the study rigorously assessed interfacial bond performance under tension, shear, and mixed compression. These tests accounted for the intentional roughness of the concrete substrate. An optimal mix design procedure was employed to evaluate workability and mechanical characteristics, ultimately establishing a correlation between available local materials (OPC and PMC) and the requirements for long-term durability in repair applications within LDCs.

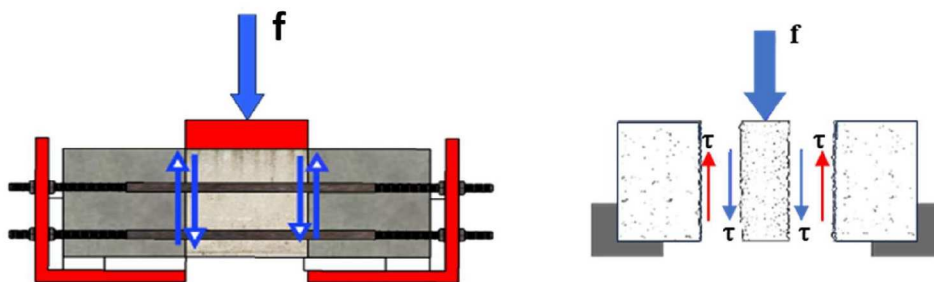
4.2. Experimental procedure

An experimental study was conducted by applying relevant methodologies to determine bond strength. Three main types of materials, OPCM, polymer-modified cement (PMC) mortar, and epoxy resin (ER) bonding, were used and evaluated in combination. OPCM was used as an adhesive, water reducer admixture (to increase the workability and increase the strength of mortar) mixed with fine aggregate through a proper mixed design to achieve high-strength and PMC mortar with a standardized mixing procedure. Epoxy resin bonding was used as an interface border between repair materials and bonding between the OPCM and substrate concrete, and PMC mortar and substrate concrete [1, 2, 3, 4]. The bond strength between the repair mortar and concrete substrate proved to be an essential aspect of this experimental study, which considered the durability of the repair material itself.



(a) Mechanics of testing (b) Cross-section (c) Specimen (d) Cross-section

Figure 4.1. Slant shear test.



(a) Double shear test.

(b) Schematic of the specimen under shear stress

Figure 4.2. Double shear test



Figure 4.3. Slant shear sample



Figure 4.4. Double shear sample

3.2.1. Slant shear test

The American Society for Testing Materials (ASTM) C882 and C1042 for slant shear test schemes were first proposed in 1976 in the form of the Arizona Slant Shear Test, as shown in Figure 4.1(a) [5]. The ASTM standard is often used as an experimental guideline in Timor-Leste. The slant shear test is a mechanical test used to evaluate the shear strength of a material or the bond strength at the interface or joint between two materials.

The application of an axial load to the specimens at an interface angle created a combination of shear and tensile stresses. Based on Figure 4.1(b), the bond stresses were calculated as follows [6]:

$$\sigma_o = \frac{P}{A} \quad (1)$$

$$\tau_n = \frac{1}{2} \sigma_o \sin(2\alpha) \quad (2)$$

$$\sigma_n = \sigma_o \sin^2 \alpha \quad (3)$$

Here, P denotes force (kN), A denotes the area of the specimen (mm^2), and σ_o denotes the stresses applied on the specimen; σ_n and τ_n denote the interfacial normal and shear stresses (bond stress) on the bond plane resulting from σ_o , respectively; α denotes the slant shear angle.

The angle of the slant shear specimen was 30° – 45° from the horizontal plane bonded to the substrate mortar specimen. In this study, the specimen is shown in (Figure 4.1(c)) with the angle used $\pm 30^\circ$ (Figure 4.1(d)) from the vertical axis to form a composite cylinder with a total composition of 100 mm in diameter and 200 mm in height.

After curing the substrate concrete specimen for 28 days and air-drying it for 7 days, use a slightly coarse brush (wire brush) to clean the concrete surface and remove any mortar or dust from the coarse aggregate. In addition, a paintbrush was used to ensure thorough cleaning. Slant shear

specimens were obtained by applying OPCM with and without epoxy, as well as PMC mortar, as shown in Figure 4.3. The samples were cured 28 days before the experiment.

3.2.2. Double shear (pure shear) test

Double shear testing of concrete is a mechanical test method used to determine the shear strength of concrete specimens. The experimental study evaluates the capacity of a concrete specimen to resist shearing forces applied in two planes or along two parallel surfaces. A schematic of the double shear strength (shear friction test) is shown in Figure 4.2(a) as an alternative double-plane shear test design, which was utilized by Tassios and Vintzeleou (1987) on pre-cracked unreinforced specimens, and a similar setup has been proposed by the Japanese Society of Civil Engineering (JSCE) for uncracked fiber-reinforced concrete specimens (JSCE 1990) [7].

Therefore, with no internal reinforcement applied to the experimental samples in this study, the samples directly exhibited shear friction properties in the joint area and assisted in the application of external shear stress. This type of test is essential for understanding the behavior of concrete under shear loads, which is crucial in the design and evaluation of concrete structures.

Based on Figure 4.2(b), the shear stresses were calculated as follows:

$$\tau = \frac{f}{2A} \quad (4)$$

where f denotes applied force (kN), A denotes the contact area of the specimen (mm^2), and τ denotes the shear stress applied on the specimen.

After preparing the substrate concrete for the double shear test, it was cured for 28 days and air-dried for 7 days. Use a hand with a slightly coarse brush (wire brush) to clean the concrete surface, removing any mortar or dust from the coarse aggregate. Use a paintbrush to ensure the surface is clean of dust. Double shear specimens were obtained by applying fresh OPCM with and without epoxy, as well as PMC mortar, as shown in Figure 4.4. This procedure was implemented to guarantee the precision of measurements and test outcomes. The double-shear samples were cured for 28 days before the experiment.

3.2.3. Surface roughness

The roughness of the surface of the concrete substrate is considered a key factor in the bonding performance between the concrete substrate and the cement-based repair mortar [8]. A rough surface provides a larger surface area and mechanical interlocking for the repair mortar to adhere, resulting in a more durable and enduring connection [9]. The rough surface in this experiment for the concrete substrate was acquired by spraying water over the concrete surface after casting the

concrete to delay the hardening of the concrete and removing the soft concrete surface by brushing until coarse aggregates were exposed, as shown in the figures. 4.5 and 4.6 for double shear specimens and slant shear specimens, respectively. The samples were cured 28 days before the experiment.



Figure 4.5. Surface roughness preparation for the slant shear test

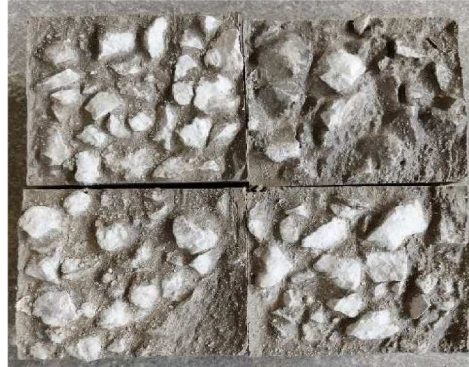


Figure 4.6. Surface roughness preparation for the double shear test

4.3. Materials

4.3.1. Substrate concrete

Substrate concrete refers to the underlying or existing layer of concrete that contains additional materials, such as coatings, overlays of repair mortars, or new concrete layers. Furthermore, it serves as the base or foundation for these additional materials.

The substrate concrete utilized OPC with a density of 3.15 g/cm^3 , fine aggregates (sea sand) with a density of 2.6 g/cm^3 , water with a density of 1 g/cm^3 , crushed gravel (5–20 mm) with a density of 2.71 g/cm^3 , and a water reducer admixture (WRA) with a density of 1.02 g/cm^3 . Table 4.1 shows the substrate concrete composition, which was determined using the American Concrete Institute (ACI) method for mix design [10], mix design with a water-cement ratio (w/c) of 0.5. The ACI mix design method is generally used in Timor-Leste. Concrete was prepared by first combining the fine aggregate and cement in the mixer to ensure a uniform dry blend. Then, add an admixture WRA to the water. Next, add half of the water mixture to the mixer. Followed by the coarse aggregate and the remaining water mixture. The mixing process was allowed for three minutes before being discharged from the mixer for placement in the form. The mixer was continuously operated throughout the mixing procedure. The molds were formed in different shapes depending

on the purpose of testing: a rectangular form with dimensions (100 mm × 100 mm × 70 mm) for double shear and a cylindrical prismatic form with an angle of 30° for slant shear, including cylinder specimens for the compressive strength (diameter 100 and height 200 mm). The samples were cured 28 days before the experiment.

4.3.2. Ordinary Portland cement mortar (OPCM).

OPCM is a significant construction material in repairing and plastering applications due to its superior bonding properties, strength, versatility, and cost-effectiveness in various construction contexts. The utilization of this material is widespread in the construction industry in the least developed countries, including Timor-Leste.

This investigation utilizes OPC with a density of 3.15 g/cm³, fine aggregates (sea sand) with a density of 2.6 g/cm³, water with a density of 1 g/cm³, and water reducer admixture (WRA) with a density of 1.02 g/cm³ for cement mortar mixtures. The cement mortar was designed with a water-to-cement (w/c) ratio of 30%, and a mixing ratio of 1:2.2 by volume, as shown in Table 4.1.

In the mixing procedure, fine aggregates and cement were added to the mixer, followed by admixture and water. The mixing process was allowed for three minutes before being discharged. Prepare samples for compressive strength (diameter 50 mm and 100 mm height), slant shear, and double shear.

Table 4.1. Mix the proportion of concrete substrates

Mix	w/c (%)	Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	WRA (kg/m ³)	Air content (%)	Slump (cm)
Substrate concrete	50	170	340	741	1067	3.4	4.2	6

Table 4.2. Mix proportions for repairing materials.

Mix	w/c (%)	Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	WRA (kg/m ³)	Flow (mm)
Ordinary Performance cement mortar (OPCM)	30	210	700	1354	7	150
Polymer-modified cement (PMC)		252	1850	-	-	147

In addition, all specimens for compressive strength, slant shear, and double shear strength tests were cured for 28 days to ensure proper strength development.

4.3.3. Polymer-modified cement (PMC) mortar

PMC mortars are important construction materials owing to their exceptional properties. The excellent characteristics of this substance make it a widely favored option for repairing damaged concrete. The typical repair cement mortar used in this study for polymer-modified cement is a commercial PMC (RepairmixJ1 produced by Tokuyama Company, Japan), which is a form of repair material for concrete structures.

PMC is composed of a combination of Portland cement (which contains crystalline silica), silica sand (which contains silica, aluminum oxide, and iron oxide), admixtures (which contain calcium oxide), and fibers. The PMC mortar mix proportions were based on the manufacturing guidelines, as shown in Table 4.2. The mixing process was allowed for three minutes before being discharged. Prepare samples for compressive strength testing with a diameter of 50 mm and a height of 100 mm, as well as for slant shear and double shear tests.

Furthermore, all specimens designed for testing the compressive strength, slant shear, and double shear strength were properly cured for 28 days to guarantee optimal strength development.

4.3.4. Epoxy resin (ER)

ER was employed in this research as part of the specimens and the interface connection between the substrate concrete before pouring the repair materials onto the surfaces. ER is generally created through the combination of two or more substances, such as an epoxy resin and a hardener, before being applied. In particular, the study used the epoxy resin XL-800 (Epo-therm), where the main agent and hardener of XL800 were mixed in a weight ratio of 4:1, and the density was approximately 1.10–1.30 g/cm³. The laminating epoxy (XL800) was manufactured by Mitsubishi Chemical Institute Co., Ltd. The mechanical properties provided by the manufacturers are listed in Table 4.3.

4.4. Results and discussion

4.4.1. Physical properties of materials

The ASTM C39 standard test method was used to determine the compressive strength of the cylindrical samples of substrate concrete [8], and the ASTM C109 standard test for compressive strength of the OPCM and PMC mortar samples [9]. Following a 28-day curing period,

compressive strength tests were conducted on the samples of repair materials and concrete substrates in the laboratory.

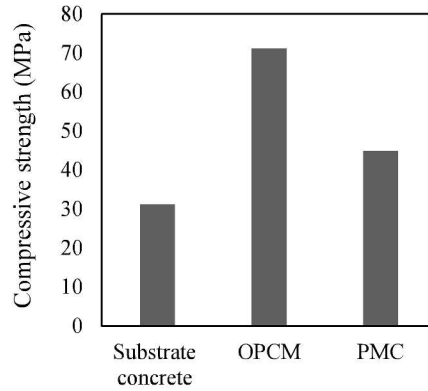


Figure 4.7. Compressive strengths of materials

The three different types of materials resulted in different strength outcomes that correlated with the designed w/c ratios. Figure 4.7 shows the average compressive strength of OPCM and PMC mortar, as well as substrate concrete. OPCM had the highest compressive strength, classifying it as a high-strength cement mortar. Conversely, although the PMC mortar has a high compressive strength, it is significantly lower than that of the OPCM (approximately 37% lower). The performance of the substrate concrete was consistent with normal-strength concrete.

4.4.2. Slant shear strength

The interfacial bond properties between the concrete substrate and repair materials are determined by two forces: the slant shear and compressive strength, as shown in the Figure. 4.8.

Table 3.3 displays the compressive strength results of the sample, as well as the slanted shear and tensile strengths that occurred at the interface of the substrate concrete with the repair materials. The test conducted for this specific experiment also resulted in the compressive strength of the same specimen, which was calculated using Eq. (1). The results obtained from the compressive stress on the surface of the cylindrical specimen caused slanted shear and normal stress on the surface of the rough joint of the concrete substrate with the repair material. The bond strength calculations conducted on the repair materials used at the concrete substrate interface, obtained by Eq. (2), showed OPCM exhibited the highest bond strength, significantly surpassing the

performance of all the other materials tested. The PMC mortar also demonstrated high bond strength; however, introducing epoxy resin in combination with the PMC mortar at the interface caused a significant decrease in bond strength (by approximately 30%), resulting in a lower average strength for this specific composite. Notably, combining the OPCM with epoxy resin caused a dramatic decrease in its slant shear strength, reducing it to the lowest value recorded across all material combinations and representing a substantial reduction from the OPCM's bond strength. Normal stress calculations performed on the repair materials used at the concrete substrate interfaces revealed that the OPCM once again exhibited the highest normal stress, as obtained by Eq. (3). The PMC mortar also exhibited high normal stress strength. However, when epoxy resin and PMC mortar were used together, the normal stress strength decreased by over 30% compared to PMC mortar alone. The OPCM combined with ER had the lowest normal stress strength in the group, with a decrease of approximately 50%.



Figure 4.8. Slant Shear experiment

Table 4.3. Mechanical properties of slant shear

Description	Slant shear (MPa)	Normal stress at surface (MPa)
PMC mortar	14.9	8.6
PMC mortar + Epoxy	10.3	5.9
OPCM	18.0	9.4
OPCM + Epoxy	8.5	4.9

4.4.3. Double shear strength

The specimens produced at the vertical interface were tested against a single axial load. The bonding properties between the concrete substrate and repair materials are shown in Figure 4.9, and the experimental results as shown in Table 4.4.

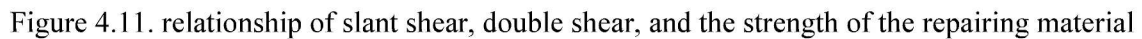
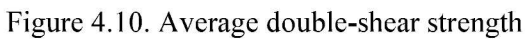


Figure 4.9. Double-strength test

Table 4.4. Experiment results of Double shear strength

Type Specimen	Load		Double shear strength
	kgf	N	MPa
PMC	16480	161504	8.1
	18800	184240	9.2
	14400	141120	7.1
	17280	169344	8.7
OPCM	17160	168168	8.4
	19400	190120	9.5
OPCM + Epoxy	8850	86730	4.3
	10160	99568	5.0
	11600	113680	5.7

The samples were calculated using Eq. (4), which showed that the average result of the double shear of the substrate concrete bond between the substrate concrete and the OPCM was the



In this study, the mechanical properties of the bonding interfaces between repair materials consisting of OPCM, PMC mortar, ER bonding, and a concrete substrate were investigated. The experiments involved compressive strength, double shear, and slant shear tests. Several significant influencing factors were compared, as showing figure 4.11. The findings and conclusions are summarized as follows.

1. Incorporating epoxy resin bonding to repair materials and concrete substrates results in a lower strength compared to other options due to the degree and time of applying the ER.
2. The use of OPCM for repair is considered sustainable because the experiment showed satisfactory results when applying OPCM compared to the other types of materials and combinations.

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V. Comparative Study on Flexural Behavior of RC Members Repaired with Various Cementitious Mortars.

5.1. Outline

In this study, composite materials including polymer-modified cement mortar (PMCM), ordinary Portland cement mortar (OPCM), and a polypropylene fiber-reinforced mortar (PFRM) mixture were used to repair five-year-old reinforced concrete (RC) specimens with exposed steel reinforcement. The study employed an integrated experimental and numerical approach to assess the structural performance of repaired, aging RC members. Five-year-old RC specimens with exposed steel were repaired using three composite mixtures: PMCM, OPCM, and PFRM. Following formulation and preliminary mechanical testing, the materials were applied, and the specimens were cured under natural conditions for three months. A subsequent four-point bending test was performed to determine the load-bearing capacity and load-strain behavior of the repaired beams [1]. These physical findings were then validated and deepened through Finite Element (FE) method analysis [2]. This chapter validates the efficacy of conventional-strength mortar, thereby establishing a framework for sustainable infrastructure maintenance in developing regions. The findings demonstrate that OPCM is a viable alternative when specialized commercial products are inaccessible, preserving structural integrity despite resource constraints

5.2. Materials and Methods

5.2.1. Repair materials, RC specimens, and validation

The repair materials were prepared using a standardized mix design involving fine aggregate (FA) and ordinary Portland cement (OPC). To enhance mechanical performance, 0.05% polypropylene fibers by weight were incorporated, resulting in the PFRM mixture used in a prior study [3]. The polypropylene fibers had a length of 12 mm, a modulus of elasticity of 5000 MPa, and a tensile strength of 390 MPa. A commercially available PMCM was applied as an adhesive layer, selected for its superior bonding characteristics [4].

The RC specimens used for this study were initially prepared by previous researchers for structural strengthening purposes [5]. These specimens were cast to three-fourths of their full thickness (100 mm), with longitudinal reinforcement positioned at the top and stirrups exposed to a height of 30 mm. Each specimen measured 1850 mm in length and 250 mm in width. The concrete mix was designed to achieve a compressive strength of 32.1 MPa and a Young's modulus of 33.5 GPa. Reinforcement was provided using SD 345 grade steel. Since the specimens' prior exposure, a

non-destructive test (NDT) was performed to confirm that the concrete remained in a structurally sound condition.

To further validate the experimental findings, 3D finite element models of the repaired RC specimens were developed using ANSYS Mechanical software for nonlinear analysis. These simulations were designed to replicate the conditions of the physical experiments, enabling a comparative assessment of experimental and numerical data and offering deeper insights into the interaction between the repair materials and the substrate concrete [6, 7].

5.2.2. Mix design, mechanical properties, and epoxy resin bonding

The mixed proportions of the repair materials are detailed in Table 5.1 and were optimized for flow and workability, with flow values ranging between 119.5 and 155 mm [8]. The repair mortar mixing procedure is illustrated in Figure 5.1, while the particle size distribution of the fine aggregate is presented in Figure 5.2. Notably, PFRM mixtures with water-to-cement (W/C) ratios of 0.3 and 0.4 did not meet the required flow criteria. For mechanical testing, cylindrical molds (50 mm diameter, 100 mm height) were used to assess compressive strength, and prismatic beam molds (40 mm × 40 mm × 120 mm) were used for flexural strength testing.

After 28 days of water curing at a controlled temperature, the mortar samples were subjected to mechanical evaluation. Compressive strength testing of the cylindrical specimens yielded average values of 37.8 MPa for PMCM, 58.1 MPa for OPCM, and 52.5 MPa for PFRM. In terms of flexural strength, PFRM demonstrated the highest value at 7.7 MPa, followed by PMCM at 6.5 MPa, and OPCM at 5.3 MPa. To further interpret these results, stress–strain curves derived from the compressive strength tests are presented in the corresponding figure. These curves reveal that PMCM and OPCM exhibit brittle behavior, whereas PFRM displays more plastic Behaviour, demonstrating ductile characteristics.

Epoxy resin XL-800 (Epo-therm), manufactured by Mitsubishi Chemical Infratech Co., Ltd., was employed as a bonding agent between the substrate concrete and the repair materials. The resin was mixed with a hardener in a 4:1 weight ratio, with a resulting density of 1.10–1.30 g/cm³ [9]. Previous studies have evaluated the bonding performance of this material through slant and shear tests [10]. In this study, the epoxy resin was combined with PFRM to investigate its influence on the repair performance of RC members.

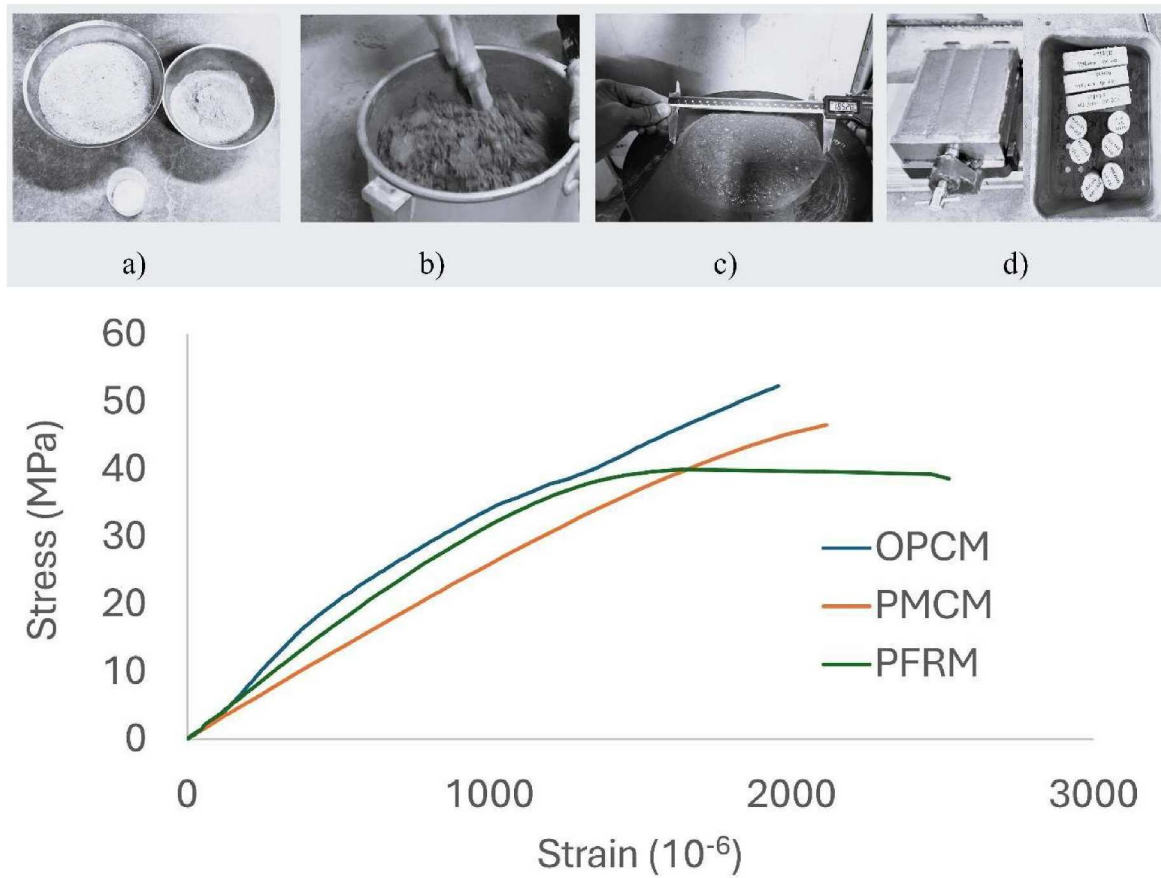


Figure 5.1. Preparation of repair mortars trials (a) fine aggregate and cementitious material, (b) fresh mortar flow measuring, (c) sampling, (d) samples for curing, and (e) Stress-strain relationship curve of repair mortars.

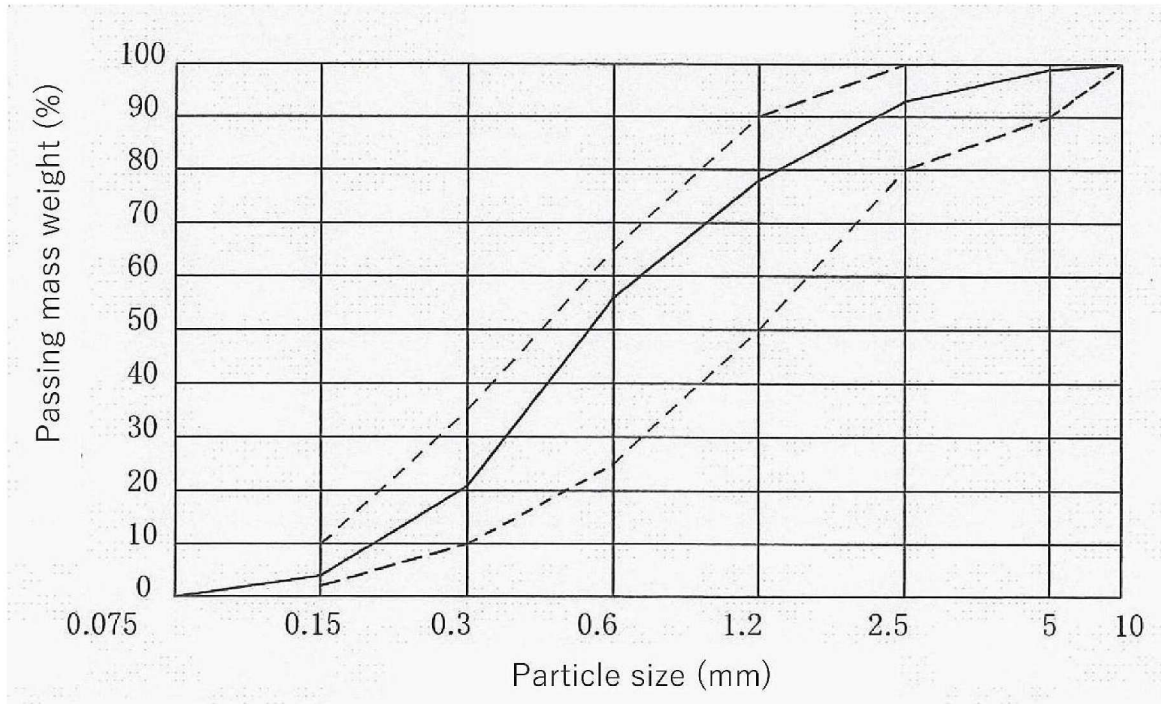


Figure 5.2. Particle distribution of fine aggregate

Table 5.1. Mix proportions of repair mortars

ID	W/C ratio	Water (kg/m ³)	Cement (kg/m ³)	Fine aggregates (kg/m ³)	Water-reducing agent (kg/m ³)	Polypropylene fiber (kg/m ³)
PMCM	-	252	1850	-	-	-
OPCM	0.3	315	1050	1984	10.5	-
PFRM	0.3	330.8	1102.5	2083.2	11	1
	0.35	330.8	945	2214.8	9.45	1
	0.4	330.8	826.9	2313	8.3	1.1

5.2.3. Repair of RC specimens

The RC specimens used in this study were originally cast five years prior (Figure 5.3(a)), and surface roughness was prepared by previous researchers. Figure 5.3 (b) presents the measured concrete surface profile (CSP). Three types of repair mortars were applied: PMCM to specimen RC-A, OPCM to RC-B, and PFRM bonded with epoxy resin at the interface to RC-C. Before

application, the concrete substrates were inspected, revealing slightly corroded reinforcement bars and dusty surfaces. Surface preparation included rust removal using a wire brush and cleaning with a water jet [8]. To prevent recontamination by dust, the cleaned surfaces were covered with plastic sheeting.

Mortar overlays were applied to cover the exposed reinforcement of the RC specimens (Figure 5.3(c)). The overlay thickness was set at 60 mm, ensuring a concrete cover of 30 mm over the reinforcement bars (Figure 5.3(d)). Formwork was installed, and the repair mortars were prepared in accordance with the mix proportions listed in Table 1 and applied as outlined in Figure 5.3 (e). During the casting of overlay mortars, ambient temperatures were approximately 30 °C for RC-A, 18 °C for RC-B, and 17 °C for RC-C. The average indoor relative humidity during casting was recorded at 50%. The repair process was conducted in a controlled laboratory environment, with the specimens cured by water spraying for seven days. Subsequently, the specimens were relocated outdoors, where their surfaces were covered to retain moisture and prevent drying.

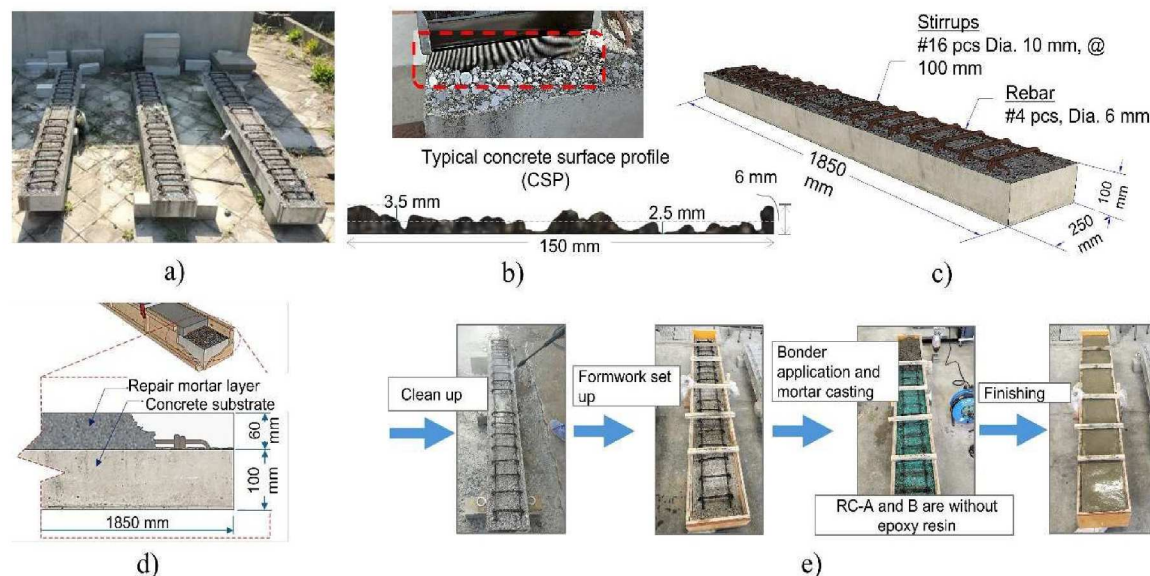


Figure 5.3. RC member repair scheme: (a) five-year-old RC specimens, (b) concrete surface profile, (c) details of specimens, (d) repairing details, and (e) process of repairs

5.2.4. Four-point bending test

To evaluate the structural behavior of the repaired RC specimens, four-point bending tests were conducted, focusing on load-bearing capacity and strain response. A hand-operated air-loading system with a maximum capacity of 500 kN was employed, applying load via a rigid steel beam with a 300 mm spacing between the loading points. Vertical loads were recorded using a data logger to ensure precise measurement.

Linear variable displacement transducers (LVDTs) were installed at both the midspan and span-end of each specimen to capture vertical displacements. Additional LVDTs were placed at the support points to detect potential interfacial debonding between the repair mortar and the concrete substrate. Six strain gauges were installed along both longitudinal sides of each specimen, aligned with the central axis of the concrete substrate and overlay mortar, positioned at the midspan and within the shear regions. Additional strain gauges were mounted on the top and bottom surfaces of the beams to measure compressive and tensile strain distributions (Figure 5. 4(a)).

To capture the tensile strain of the reinforcement, four strain gauges were installed at the critical section of the tension bars. Cross-sectional details of the RC specimens, including the 30 mm concrete cover and reinforcement bar diameters, are provided in Figure 5.4(b). These experimental methods have been validated in prior studies for assessing flexural behaviour in RC structural elements, offering detailed insights into strain distribution and failure modes [11, 12, 13].

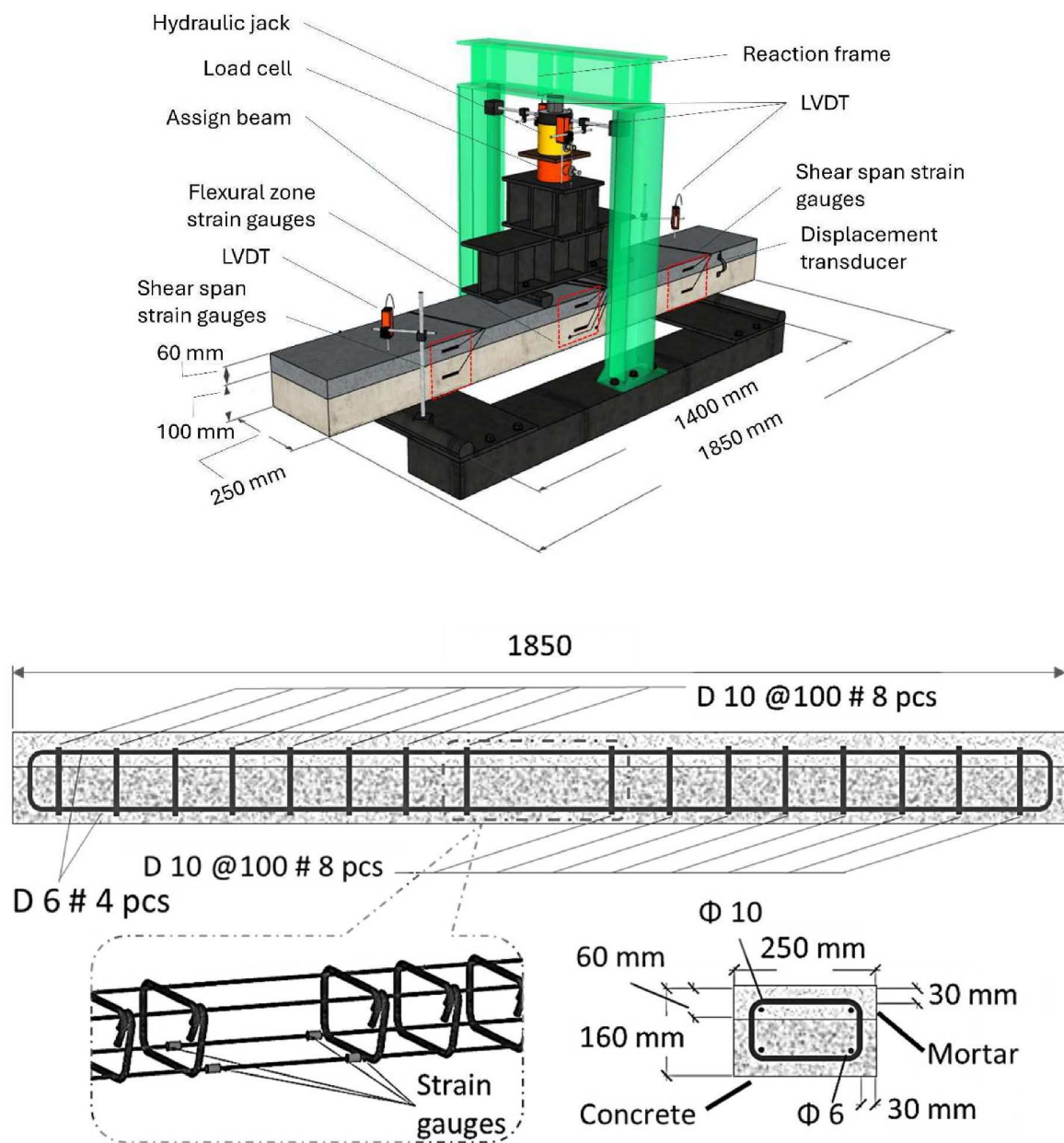


Figure 5.4. Schematic test and cross-section of specimen. a) Four-point bending test set up, b) Longitudinal, transversal cross-section or repaired RC member, and tension longitudinal rebar strain gauge set up.

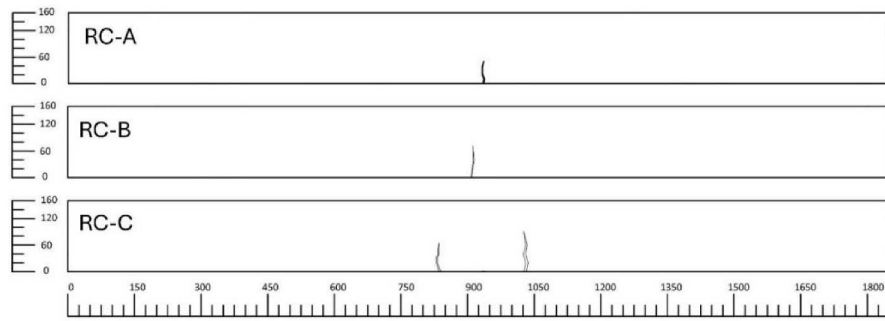
5.3. Results and discussion

5.3.1. Cracks and damage patterns

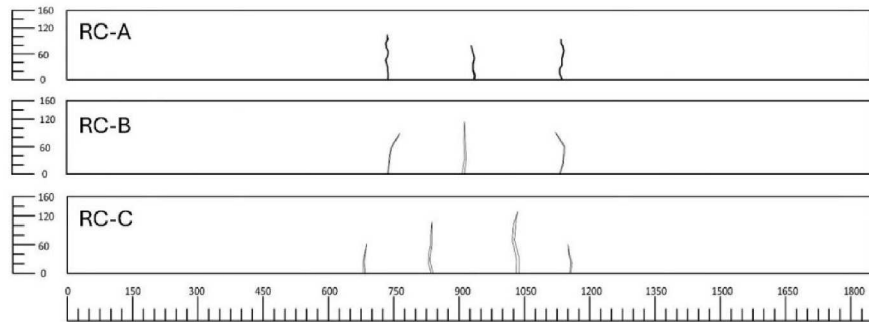
The cracking behavior of RC composite beams using polypropylene fiber reinforcement has been previously investigated [14]. In this study, cracking in specimen RC-A was first observed when the applied load reached approximately half of its ultimate capacity, specifically at 11.67 kN. An initial crack formed within the loading zone (Figure 5.5(a)), extending almost through the entire depth of the concrete substrate. The methodology for monitoring crack propagation in RC beam structures has been explored in previous studies using piezoelectric lead zirconate titanate (PZT) transducers [15]. As the load increased to 15 kN, corresponding to the yield stage (Figure 5.5(b)), additional cracks developed along the shear span. During this phase, the initial crack propagated further and eventually evolved into a critical crack that severely compromised the structural integrity of the specimen. In its final damaged state, the critical crack width measured 20 mm, with two additional cracks spaced approximately 200 mm apart.

Specimen RC-B exhibited a similar cracking pattern and progression to that of RC-A. To avoid redundancy, the analysis emphasizes the distinct behaviors observed in each specimen. Crack patterns for all repaired RC specimens at various loading stages are depicted in the corresponding figures.

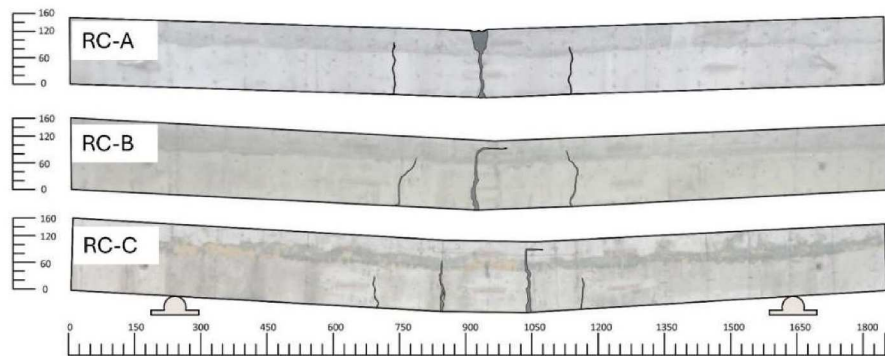
In contrast, RC-C demonstrated a unique cracking behaviour at the final loading stage, with four distinct cracks, compared to two in RC-A and RC-B (Figure 5.5(c)). Critical cracking in RC-C was observed at an applied load of 13 kN, with cracks extending further from the flexural centerline. This behavior suggests that the inclusion of polypropylene fibers in the mortar contributed to a more distributed tensile stress field at midspan. The spacing between secondary cracks along the shear span ranged from 100 mm to 150 mm. The critical crack in RC-C reached a width of 17 mm, while secondary cracks showed widths of approximately 6 mm. Notably, no interfacial debonding or fractures were observed along the repair interface in any of the repaired specimens.



a) initial crack distribution under elastic conditions



b) cracks distribution at yielding



c) crack distribution at the ultimate damage condition.

Figure 5.5. Repaired RC specimen crack and damage patterns. a) initial crack distribution under elastic condition, b) crack distribution at yielding, c) crack distribution at ultimate damage condition.

5.3.2. Deflection curves

The load–deflection behavior of the repaired RC specimens is illustrated in Figure 5.6, depicting structural responses comparable to those observed in the control specimen. All specimens exhibited similar phase transitions leading to failure, characterized by three distinct stages: elastic, yielding, and failure. Deflection was measured at the midspan using LVDTs, a critical metric for evaluating structural condition and failure mechanisms. Alternative deflection measurement techniques, such as long-gauge optical sensors, have also been investigated in prior studies [16]. For specimen RC-A, the load–deflection curve initially followed a linear elastic path up to a load of 11.67 kN, corresponding to a deflection of 1.81 mm. A sharp transition occurred at this point due to the initiation of tensile cracking in the concrete. The curve plateaued as the crack propagated toward the neutral axis, leaving only a thin layer of concrete before engaging the repair overlay. The specimen reached its peak load capacity at 19.34 kN and subsequently failed, evidenced by a 2.0 kN load drop at a deflection of 19.46 mm. The use of PMCM as an overlay has been extensively studied, particularly regarding its bonding strength and durability under adverse conditions when applied to conventional concrete substrates [17, 18].

Specimen RC-B exhibited a slightly prolonged elastic phase. Following a minor load drop of approximately 1 kN, the specimen regained strength and ultimately achieved a maximum load-bearing capacity of 22.01 kN. It failed at a load of 19.51 kN with a maximum deflection of 29.7 mm. Specimen RC-C, repaired using PFRM, demonstrated a significantly extended yielding phase beginning at 7.84 kN and reaching a peak load of 21.51 kN. This specimen maintained a relatively stable load before failure and exhibited the highest ductility among all tested specimens, with a maximum deflection of 37.15 mm. Previous studies have extensively explored the incorporation of reinforcement fibers in concretes such as ultra-high-performance and polyethylene fibers to meet the performance demands of dynamic structural applications in the construction industry [19]. To facilitate a clearer interpretation of structural behavior, load versus mid-span deflection data with error bars are presented (Figure 5.7). Statistical analysis using ANOVA followed by Tukey’s post hoc test ($p < 0.05$) revealed significant differences among the specimens in terms of mechanical behavior, including load at yielding, peak load, ultimate load, and corresponding deflections. Figure 5.8 illustrates the load versus end-span deflection behavior. Specimen RC-A exhibited a maximum end-span deflection of approximately 1 mm at its ultimate load, while the other specimens showed peak load deflections below 0.5 mm. The displacement ductility factor

($\mu\Delta$), defined as the ratio of ultimate deflection (Δ_{ultimate}) to yielding deflection (Δ_{yielding}), was evaluated to assess the ductility and strength enhancement of the repaired RC members. Results are presented in Figure 5.7. RC-A demonstrated lower ductility, with a post-yield deflection approximately six times its yielding deflection. In contrast, RC-C exhibited significantly greater ductility, reaching up to nine times its yielding deflection, outperforming the other specimens.

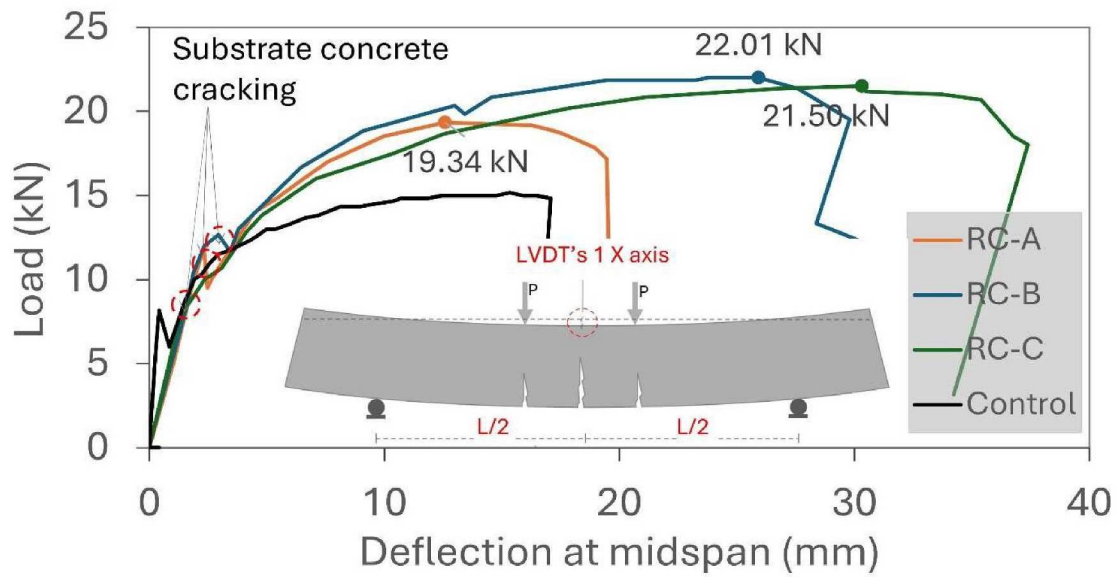


Figure 5.6. Mid-span deflection of RC specimens.

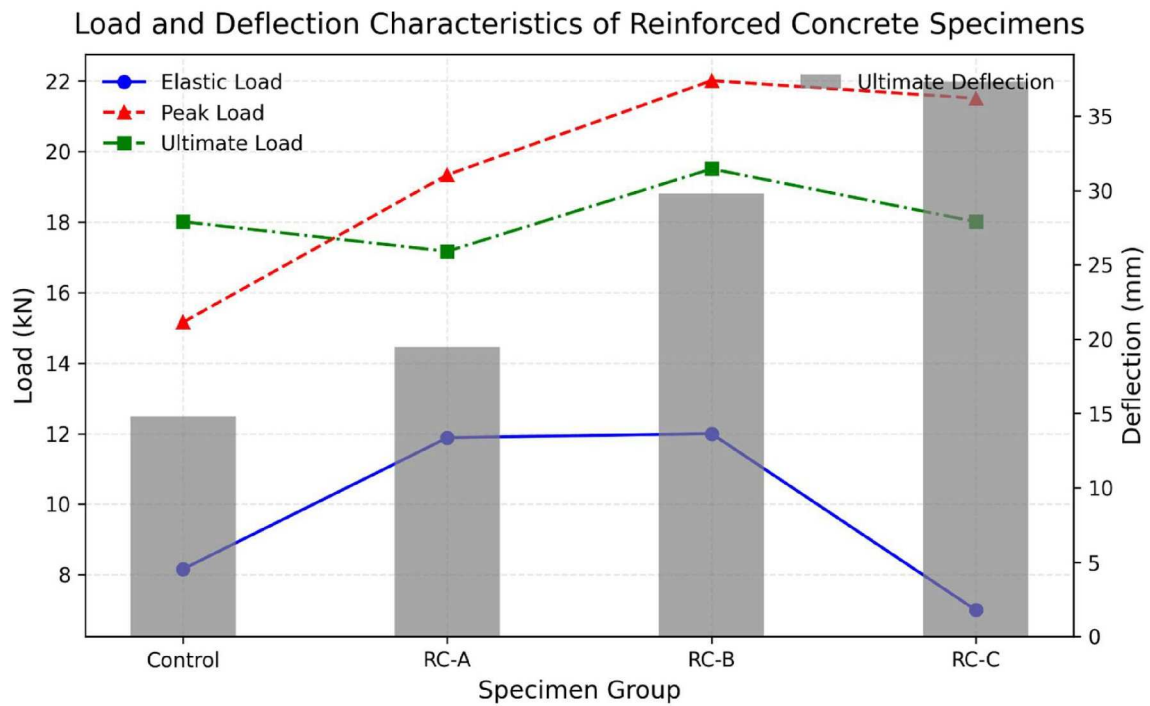


Figure 5.7. Error bars load vs mid-span deflection

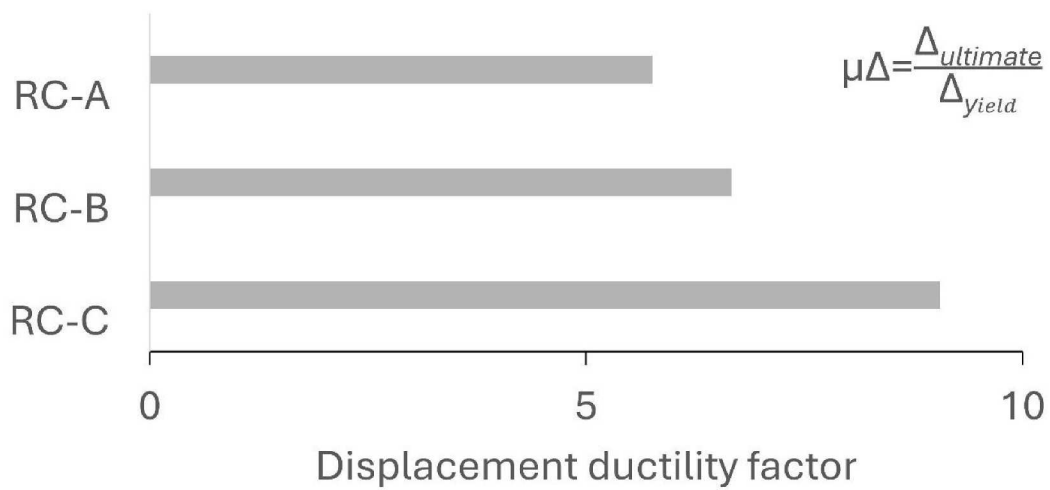


Figure 5.8. Displacement ductility factor

5.3.3. Concrete strain curves

A repair mortar overlay was applied to the compression zone of the RC specimens. The

compressive strain response, shown in Figure 5.9, highlights distinct trends among the specimens. For RC-A and RC-B, compressive strain began to yield once the applied load exceeded 10 kN, reaching peak strain values of 106×10^{-6} and 129×10^{-6} , respectively. As cracks extended into the interfacial region, the overlay mortar was subjected to high compressive forces, approaching the allowable strain limit of 3000×10^{-6} . In contrast, RC-C exhibited earlier yielding at a lower load of 7.84 kN, with a corresponding strain of 84×10^{-6} . Despite this early onset, RC-C displayed strain recovery during the plastic phase before ultimate failure, after which the specimen collapsed entirely.

The behavior of the concrete substrate primarily governed the tensile region of the repaired RC specimens. As shown in Figure 5.10, all specimens followed a similar tensile strain trajectory, with yielding occurring at approximately 13 kN. This was followed by a softening phase under continued loading until failure. The maximum tensile strain recorded in the concrete was 85.5×10^{-6} for RC-A at 12.67 kN, 103×10^{-6} for RC-B at 12 kN, and 60×10^{-6} for RC-C.

Overall, the findings indicate that while the mortar and concrete played distinct mechanical roles, the elastic response of all repaired RC specimens was largely consistent. Each specimen ultimately failed due to flexural stresses, with no evidence of failure originating in the shear zones, as confirmed by strain gauge and displacement transducer measurements. Furthermore, all repaired specimens demonstrated higher load-bearing capacities compared to the control specimens.

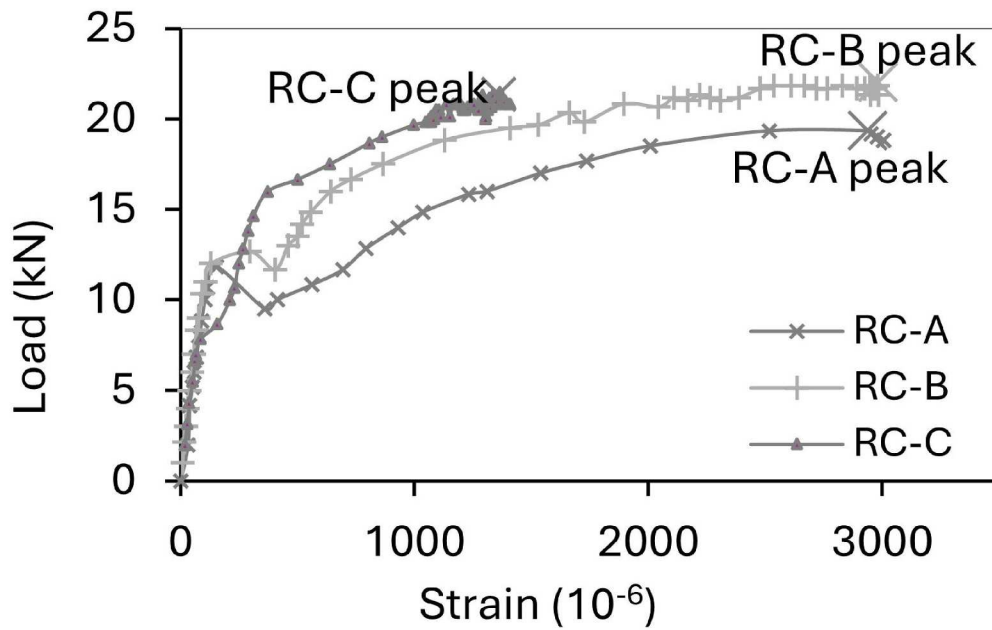


Figure 5.9. Compressive strain of mortar

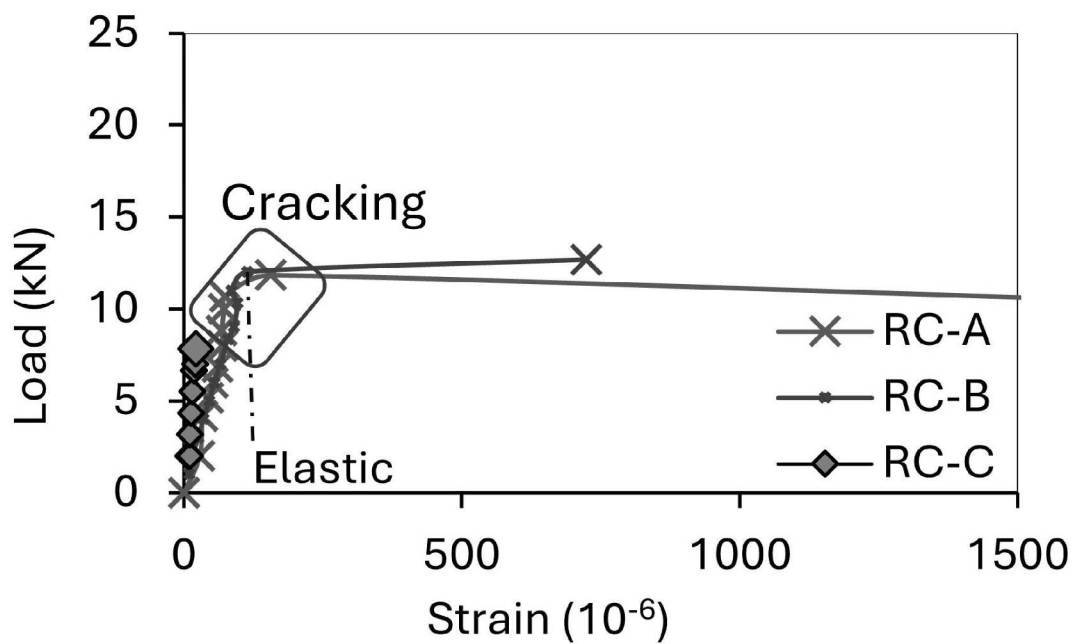


Figure 5.10. Concrete tensile strain

5.3.4. Rebar strain curves

Prolonged exposure to ambient conditions resulted in the failure of strain gauges installed on

specimens RC-A and RC-C, which prevented the acquisition of longitudinal rebar tensile strain data for these specimens. However, the remaining strain gauges functioned reliably, and the recorded data are presented in Figure 5.11. The longitudinal reinforcement in all specimens exhibited similar elastic strain behaviour. In RC-A, the tensile strain in the longitudinal rebar entered the softening phase when the applied load reached 11.84 kN.

In RC-B, all four strain gauges on the tension reinforcement remained operational, capturing the end of the elastic phase at a load of 12 kN, corresponding to a yielding strain of 394×10^{-6} . For RC-C, the recorded data indicated the onset of yielding at a load of 7 kN, with a tensile strain of approximately 101×10^{-6} , after which the rebar transitioned into the plastic deformation phase.

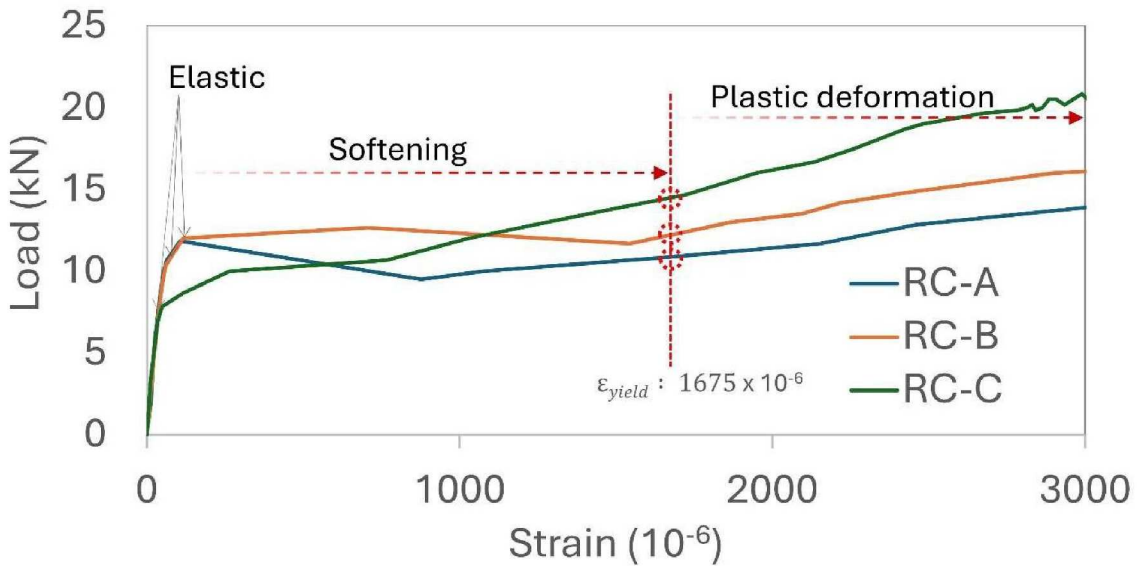


Figure 5.11. Tension reinforcement bar strain curve.

5.3.5. Load bearing capacity

As shown in Table 2, when compared with the control specimen, RC-A exhibited a significant enhancement in load-bearing capacity, achieving an increase of approximately 20%. Furthermore, this specimen exhibited superior elastic performance, reaching 11.84 kN. RC-B showed an even more pronounced improvement, reaching a maximum load-bearing capacity of 22.01 kN, a 36% increase over the control specimen, and yielding at 12.67 kN, with a corresponding deformation of 29.7 mm.

In contrast, RC-C presented lower elastic strength, with yielding occurring at a load of 6 kN. However, it displayed exceptional ductility, as evidenced by a maximum deflection of 37.15 mm. The setup for the loading test, along with the arrangement of the measurement instruments and strain gauges, is shown in Figure 5.12(a). This ductile behaviour is likely attributable to the distribution of flexural cracks illustrated in Figure 5.12(b) and the specific properties of the repair material used.

Table 5.2. Maximum load, yielding load, deflection, and maximum longitudinal rebar strain of investigated repaired RC specimens

Specimen I.D.	Maximum load (kN)	Yielding load (kN)	Deflection (mm)	Max. tensile reinforcing bars strain (10^{-6}) at peak load
Control	15.99	7.21	20.05	1042
RC-A	19.34	11.84	19.65	1485
RC-B	22.01	12.67	29.7	1228
RC-C	21.51	7.81	37.15	1497

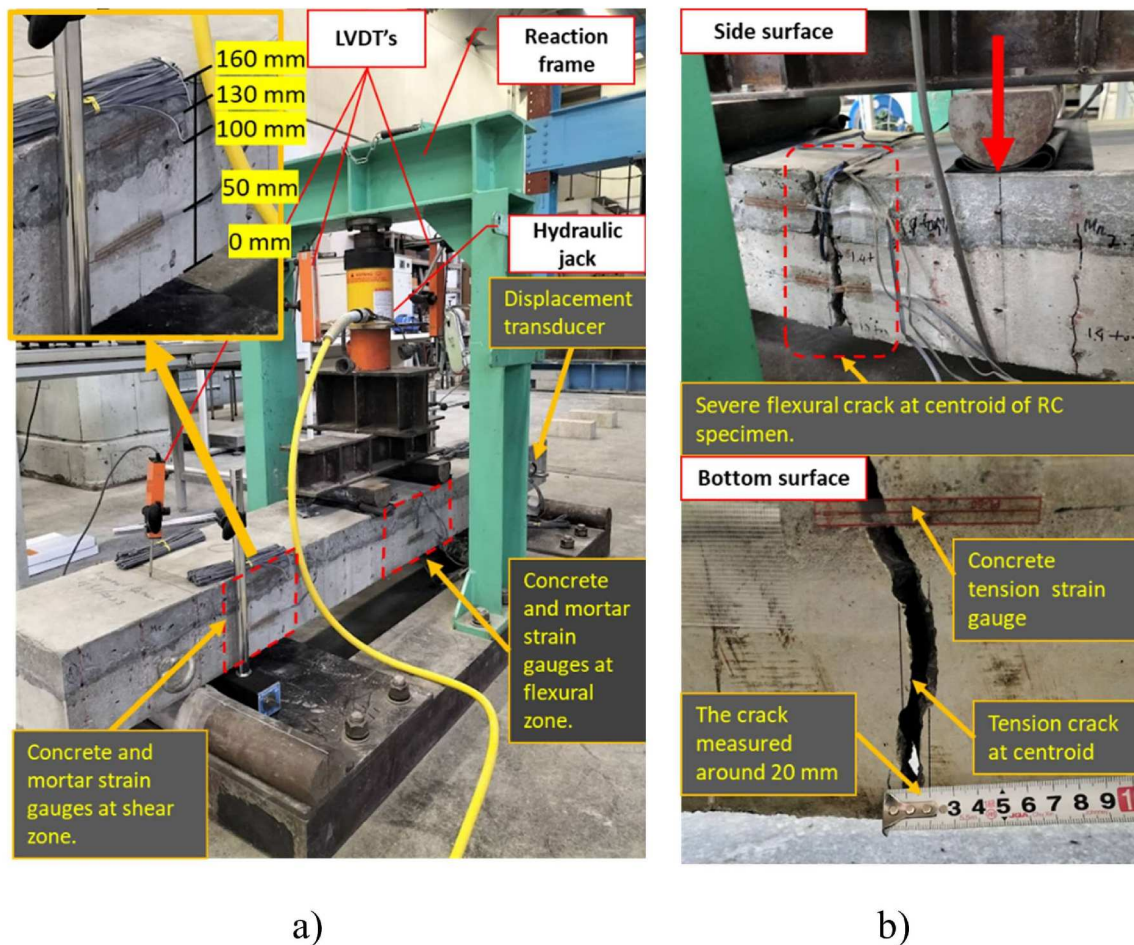


Figure 5.12. Specimen set up and failure of RC specimen, a) four-point bending load test set up and b) ultimate failure

5.4. Finite Element Method

5.4.1. Objectives

The finite element (FE) method was utilized to model and simulate the structural behaviour of the repaired RC specimens. This computational approach enabled the detailed reanalysis and comparison of experimental results with numerical simulations, allowing the behaviour of multiple specimens to be effectively represented through a single validated model. The incorporation of material properties derived from experimental data was essential to ensure the accuracy and realism of the simulation.

The experimental tests were conducted with high precision to ensure the reliability of the input

data, providing a solid foundation for finite element analysis. Simulations were carried out using ANSYS Mechanical, a widely utilized software in academic and engineering research for its ability to model complex material interactions and structural responses in reinforced concrete systems.

5.4.2. Modelling

A 3D model was developed to simulate the mechanical behaviour of the repaired RC specimens. The geometry of the model was replicated to match the experimental setup, and material properties were assigned according to the data summarized in Table 5.3. The simulation was conducted under static structural conditions.

As shown in Figure 5.13, the solid model includes both the RC substrate and the mortar overlay. Reinforcement was modeled using link elements: D10 steel bars for stirrups and D6 bars for longitudinal reinforcement. The figure also presents the geometric dimensions and element details used in the simulation. ANSYS Mechanical was used to capture nonlinear material behaviour under static loading, incorporating differences between tensile and compressive responses. The RC-B specimen, which used OPCM as the repair material, was selected as the basis for assigning material properties in the model. A uniform mesh size of 25 mm was applied.

Table 5.3. Menetrey-William based material properties for the FE model

Property	Unit	Concrete	OPCM
		Value	Value
Young's Modulus	MPa	33500	35170
Poisson's ratio	-	0.2	0.2
Uniaxial compressive strength	MPa	32.12	71
Uniaxial tensile strength	MPa	3.51	5.22
Biaxial compressive strength	MPa	36.93	81.65
Dilatancy angle	degree	16	16.5
Active table (softening)	-	Linear	Linear
Plastic Strain at Uniaxial Compressive Strength	-	0.000518	0.000839
Ultimate Effective Plastic Strain in Compression	-	0.01477	0.020925
Relative Stress at Start of Nonlinear Hardening	-	0.617	0.92317
Residual compressive relative stress	-	1	1
Plastic Strain Limit in Tension	-	0.0029	0.0005
Residual tensile relative stress	-	0.32	0.45

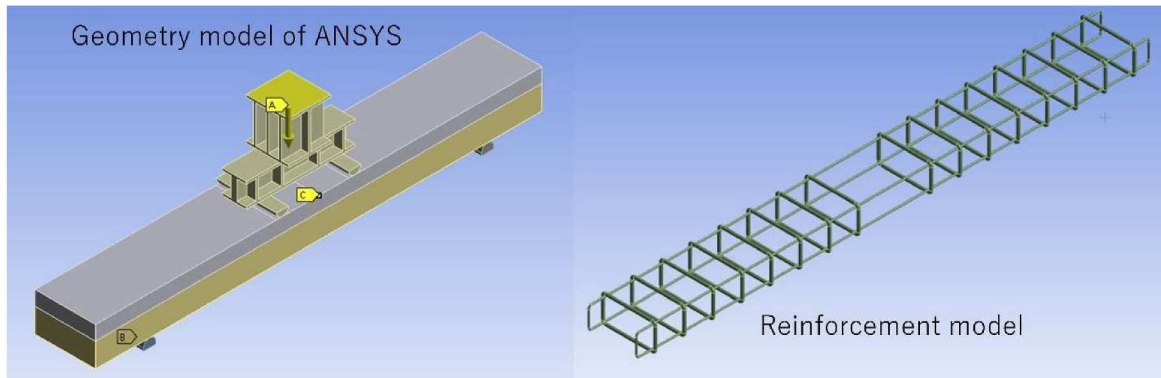


Figure 5.13. FE model and boundary condition

5.4.3. Simulations

The validity of the FE method was verified by comparing it with the experimental load–deflection curve for RC-B. The percentage of errors at the beam elasticity is 22% and the maximum load is 7%. The results indicate a significant correlation between the simulation and experimental outcomes (Fig. 5.14). This validation supports the use of FE method for further simulations of stress and strain responses under flexural loading.

In the simulation, cracking was associated with tensile failure as concrete started to crack at an applied load of approximately 13 kN. Failure of the top compression zone occurred when the stress exceeded the material's capacity, consistent with experimental observations. The stress-strain relationship obtained from the simulation, shown in Figure 5.15, reveals that OPCM resisted increasing tensile stress until progressive damage led to failure. The flexural cracking observed in the physical tests corresponds closely to the simulation results, as illustrated in Figure 16, which shows significant stress concentration and structural compromise in the flexural zone.

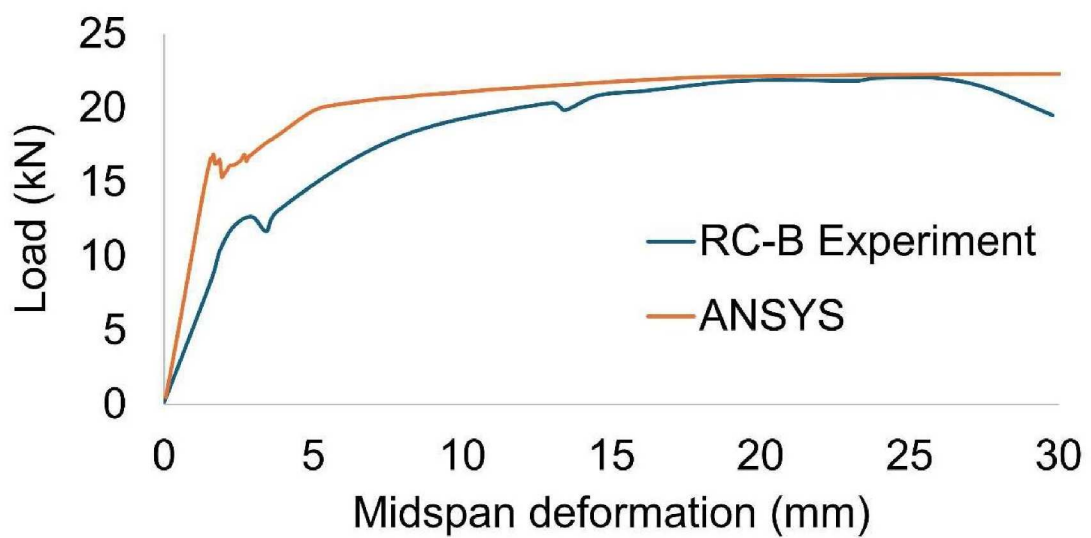
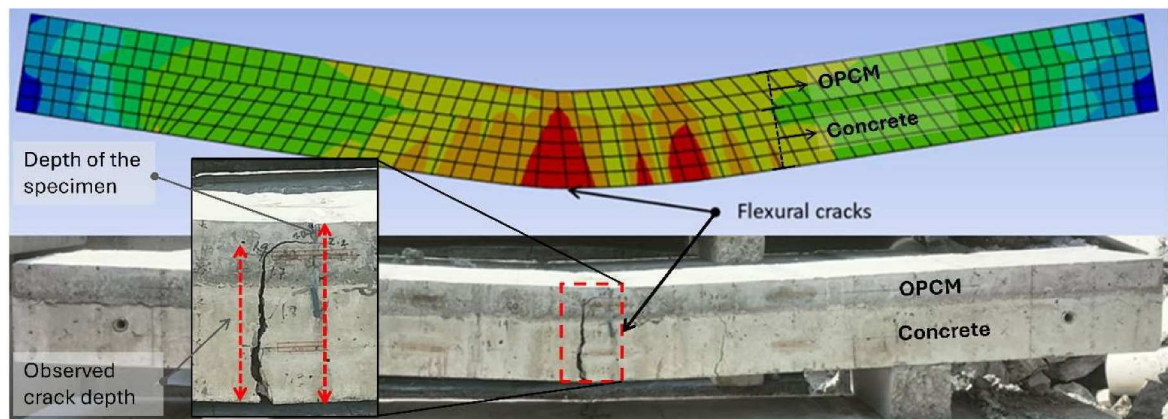


Figure 5.14. Comparisons of ANSYS simulation results of RC-B, load vs midspan deflection

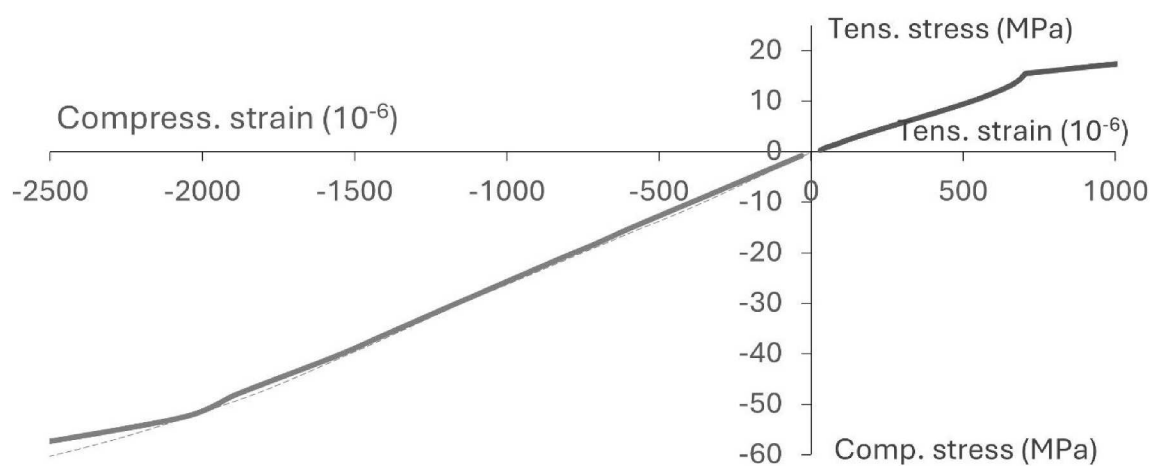


Figure 5.15. Stress and strain response of concrete ANSYS

5.5.Summary.

This study investigated the load-bearing performance of five-year-old RC specimens rehabilitated using three different mortar types: PMCM, OPCM, and PFRM. These materials were applied as overlay systems to repair surface damage and exposed reinforcing steel. The structural performance of the repaired specimens was evaluated through four-point bending tests, with each specimen simulating upper-surface deterioration repaired using one of the three mortar types. The following conclusions were drawn:

- RC-A and RC-B exhibited balanced failure mechanisms, with the tensile reinforcement exceeding the yield strain ($\epsilon_y=f_y/E_s$) and compressive strain reaching the ultimate threshold ($\epsilon_c'=3000\times 10^{-6}$) at failure. In contrast, RC-C experienced only tensile failure, with less brittle behavior influenced by PFRM plasticity.
- The RC specimen repaired with PMCM failed due to highly localized compressive stress in the flexural zone, occurring after full cracking of the concrete substrate. Notably, the bond between the repair overlay and the substrate remained intact throughout the failure process, indicating excellent adhesion.
- The ductility of the RC specimen repaired with OPC mixed with polypropylene fibers was superior to that of the other specimens. However, this increased ductility was accompanied by reduced elasticity and an increased number of cracks.
- No visible shear cracking or interfacial debonding was observed in any of the repaired specimens. All failures occurred in the flexural zone, with one or two critical cracks serving as the primary failure mechanism.

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VI. Flexural Performance of RC Beams Repaired with Conventional Cementitious Mortar.

6.1. Outline

At present, a growing number of studies have been conducted on the repair of damaged RC beams using specific cementitious materials, including fiber-reinforced cement and concrete (FRC) [1, 2], polymer cement (PC) [3], ultra-high-performance concrete (UHPC) [4, 5, 6, 7, 8], and nanomaterials [9, 10, 11, 12]. However, in underdeveloped and developing countries, OPC continues to serve as a cost-effective and versatile option for construction materials, aligning with existing fiscal constraints and long-term infrastructure development goals. The reliability of OPC mortar in maintaining a bond with the underlying concrete substrate is frequently evaluated based on its performance under loads [13, 14]. Therefore, optimizing bond strength and restoring flexural capacity in cementitious repairs are key considerations in developing effective repair strategies.

This study investigates the use of OPC as the primary repair material for RC beams, enhanced with polypropylene fiber (PF) and epoxy resin (ER), and compares its performance with PMC. The research aims to identify material combinations that optimize strength, flexural performance, and crack resistance. Specifically, the study addresses the following objectives: evaluating the flexural performance of repaired RC beams using OPC, OPC modified with PF and ER, and PMC; second, assessing the compatibility, workability, and strength of the repair materials under varying load conditions; third, analyzing crack propagation and failure mechanisms in the repaired specimens. A final step involves the validation of the experimental findings using finite element (FE) modeling. The selection of an appropriate repair material is influenced by factors such as structural damage, environmental conditions, and specific performance criteria [15]. Although alternative materials and modified cement formulations may offer improved performance, ordinary Portland cement (OPC) remains the preferred choice under typical conditions, owing to its affordability and widespread availability. In numerous developing regions, limited financial resources and high demand for repair materials make OPC a practical option despite the superior performance and lower environmental impact of certain alternatives [16, 17]. Promising results indicate that the link between the OPC mortar and concrete substrate can be effectively restored and enhanced [14, 18]. The evaluation of OPC in comparison with alternative cement-based repair materials is an integral

aspect of this research. The objective of this research is to identify effective conventional cement-based repair materials to advance and optimize strategies for enhancing flexural performance. The anticipated outcome is to demonstrate the viability of OPC, particularly when combined with PF and ER, as a suitable repair material for RC structures. This viability stems from its inherent strength, capacity for effective bonding, control of crack propagation, and contribution to enhanced flexural performance. While the advantages of OPC mortar are well-documented, the long-term durability of its bond with existing concrete, especially in harsh environments, warrants further investigation.

6.2. Methodology and Experimental Program

The proposed repair strategy is formulated based on the structure's in-situ condition and is subsequently validated through flexural analysis, as illustrated in Figure 6.1. To systematically evaluate the effectiveness of this strategy, the research framework is organized into two primary stages: specimen preparation followed by comprehensive testing and analysis, as detailed in Figure 6.2. The process begins with the design of a concrete mix, specifically for RC repair. The specimens were cast with a notched surface beneath the rebar with a rough texture and cured for 7 days before repairing mortar casting. The post-repair specimens were wrapped and stored under natural conditions for 28 days to ensure maximum strength. The repaired RC specimens were subjected to a four-point bending load test to assess their strength responses. In addition, FE analysis was conducted to validate the experimental results, offering computational support for the observed performance.

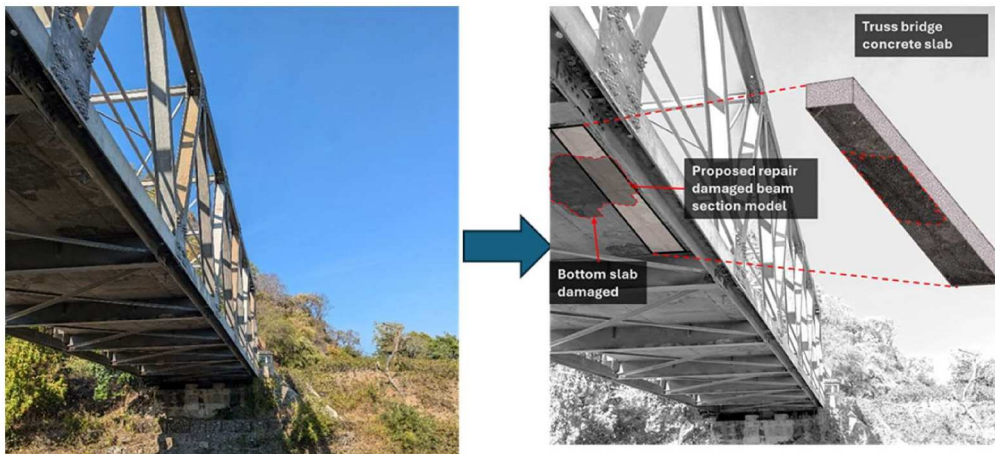


Figure 6.1.. The repair plan is based on the actual condition of the structure and validated through flexural analysis.

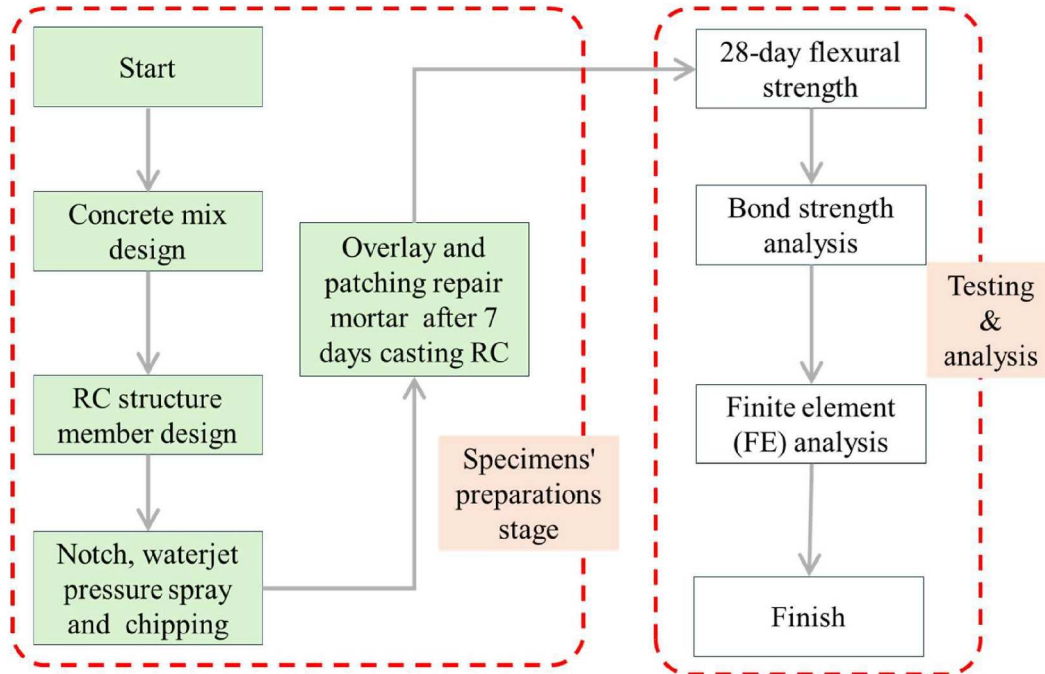


Figure 6.2. The experiment framework

6.2.1. Material experiment.

A. Concrete for RC beam

The RC beam structure was constructed utilizing OPC with a density of 3.16 g/cm^3 . The fine aggregate comprised commercially available sea sand—free from salt, silt, and organic impurities—exhibiting a density of 2.59 g/cm^3 and grain size distribution of 2.44. Coarse aggregates comprised crushed gravel with a particle size range of 5–20 mm and density of 2.71 g/cm^3 . All materials conformed to the Japanese Industrial Standards (JIS) specification [19]. The concrete mix incorporated water and a water-reducing agent (WRA) with densities of 1 g/cm^3 and 1.02 g/cm^3 , respectively. The mix proportions, detailed in Table 1, were determined based on standard guidelines using a trial mix methodology to achieve the required compressive strength and slump. The fundamental mixture proportions were designed as a water-to-cementitious material ratio (w/cm) of 0.5 and a sand-to-aggregate volume ratio (s/a) of 0.48, targeting a 28-day compressive strength of 30 MPa.

Table 6.1. Concrete mix design proportion for RC beams

Mix	w/c (%)	s/a (%)	Water (kg/m ³)	OPC (kg/m ³)	Fine aggregates (kg/m ³)	Coarse aggregates (kg/m ³)	Admixture (WR) (kg/m ³)	Air content (%)	Slump (cm)
CS	50	48	175	350	853	975	2.3	4.5±1.5	10±2

B. Repair cementitious mortar

The repair mortar utilizes OPC, fine aggregates, and water with the same densities mentioned in concrete material, and high-range water reducer (HWR) admixture (density 1.02 g/cm³) for the cement mortar mixtures. The cement mortar was designed with a w/c ratio of 0.3, mixing ratio of 1:2.2 by volume, and combined with PF for the mix design, utilizing 0.08% and 0.1% of the total mass of cement. The mix proportions are listed in Table 6.2, indicating the proportion of ordinary Portland cement mortar (OPCM) and OPCM-F for the combination with PF.

The incorporation of PF is anticipated to enhance the mechanical properties of the mortar matrix. Specifically, PF is expected to improve mortar aggregate bonding, reduce porosity, and increase the ductility of the resulting composite material [20]. PF, supplied by a commercial company, exhibits approximate properties: a density of 0.91 g/cm³, a length of 12 mm, a diameter of 42.6 µm, and a tensile strength of 390 N/mm².

Table 6.2. Mix proportion design of cementitious material for the repair of concrete

Type of mortar	W/C (%)	Water (kg/m ³)	OPC (kg/m ³)	PMC (kg/m ³)	Sand (kg/m ³)	PF (kg/m ³)	Admixtures (kg/m ³)
OPCM	30	230	767	-	1272	-	6.13
PCM	14	258	-	1850	-	-	-
OPCM-F 0.08	30	230	767	-	1226	0.62	7.7
OPCM-F 0.1	30	230	767	-	1225	0.77	7.7

C. Polymer-modified cement (PMC)

PMC functions to improve adhesion, reduce permeability and increase flexural and tensile strength by reducing shrinkage and cracking [21]. The PMC employed in this research was a commercial repair polymer cement (RepairmixJ1, produced by Tokuyama Company, Japan), a repair material for concrete structures. This PMC is composed of material consisting of Portland cement (which

contains crystalline silica), silica sand (which contains silica, aluminum oxide, and iron oxide), admixtures (which contain calcium oxide), and fibers. The PMC mortar mix proportions were based on manufacturing guidelines.

D. Epoxy resin (ER)

This research incorporated ER into the specimens as a precoating layer to facilitate bonding between the substrate concrete and repair materials [22]. Prior to their application, ERs are typically synthesized using a combination of two primary substances: a main agent and hardener. The ER XL-800 (Epotharm®) was employed, wherein the main agent and hardener of XL800 were mixed in a weight ratio of 4:1, which resulted in a density of 1.10–1.30 g/cm³. Mitsubishi Chemical Institute Co., Ltd. manufactured a laminating epoxy (XL800) with the properties listed in Table 6.3.

Table 6.3. Properties of ER [20]

Properties	Physical properties (MPa)
Tensile strength	≥ 30
Flexural strength	≥ 40
Lap shear strength	≥ 10
Bond strength to concrete	≥ 1.5

6.2.2. Specimens of RC

Nine rectangular-section RC beam structures were designed for this research. The cross-sectional dimensions were 160 mm × 250 mm, and the structural member length was 1200 mm (calculated for the four-point bending test as 900 mm). The concrete strength was approximately ±30 MPa, and the concrete cover had a thickness of approximately 40 mm. Three of the 13 mm diameter reinforcing bars were placed in the tensile and compressive zones of the test beam. Their physical properties, based on JIS G 3112 [19], are listed in Table 6.4. The stirrups were constructed with a 6 mm diameter reinforcement, with a spacing of 200 mm between each component. The detailed design dimensions and reinforcement arrangements of the specimens are illustrated in the Figure. 6.3.

The RC beam specimen design followed the ACI 318 standard [23]. Figure 6.4 shows the repaired area and load position of the RC beam specimen in detail. The cross-sections illustrate the longitudinal reinforcement, dimensions, reinforcement ratios, and stirrup spacing. Section A-A

shows the cross-sectional area of the RC beam specimen in the reinforced concrete region and illustrates the boundaries between the compression and tensile zones. The variations observed in the bottom layer indicate the repair materials or treatments employed in sections B-B and C-C. Repairs were performed in the tensile zone and at the bottom. The specimens were designed to investigate the repair techniques and performance of the repair materials.

Table 6.4. The properties of steel bar SD 345 (JIS G 3112)

Diameter	Yielding stress (MPa)	Ultimate stress (MPa)
13 mm (longitudinal bars)	345	490
6 mm (stirrups)	285	380

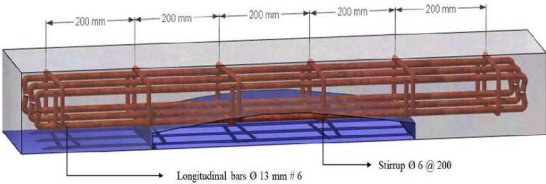


Figure 6.3. Detail of reinforcement arrangement

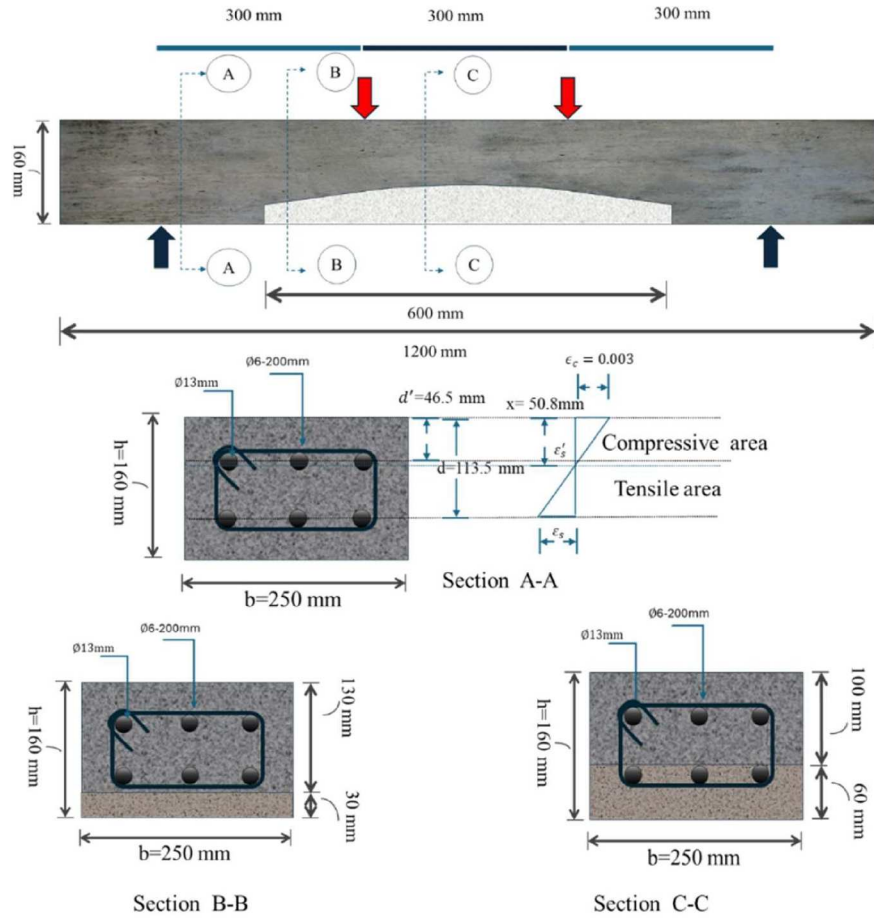


Figure 6.4. Cross-section and repair position of RC structure

6.2.3. Methodology and experiment of RC beams

A. Methodology of mixing concrete and repairing mortar

The mixing temperatures for concrete and cementitious repair materials ranged from 22 °C to 30 °C, focusing on assessing the properties of fresh concrete and repair mortars in terms of workability, ease of placement, repair suitability, and surface bonding. The methodology for mixing fresh concrete is presented in Table 6.5. This approach was applied consistently across all RC beam specimens, and the results were comparable. All the samples were cured and tested after 28 days.

However, to ensure consistency across the various repair mortar mixes, the temperatures of the repair cementitious materials were meticulously regulated throughout the evaluation process, as listed in Table 6.6. The room temperature during casting depended on the environmental conditions

of the building, which were influenced by the prevailing outdoor temperature. The temperature of the mortar was affected by the initial temperatures of the aggregates and cement, which, in turn, influenced the conditions under which it was cast and cured. The flow rate measurement of fresh repair mortar is a key indicator of its workability characteristics [24]. OPCM demonstrated the highest flow rate, suggesting superior fluidity, and PMC was approved at 146 mm, following the manufacturing guidelines. Adding PF to OPCM reduced the flow rate, and the results are acceptable for repair applications. To facilitate the testing process, cylindrical samples with a diameter of 50 mm and a height of 100 mm were prepared to investigate the physical properties of the repair mortar. Furthermore, samples for compressive strength and flexural strength were prepared following the specifications outlined in ASTM [25]. All the samples were cured and tested after 28 days.

Table 6.5. Fresh concrete mix properties

No	Type of Mix	Slump (mm)	Air content (%)	Room temperature (C°)	Concrete temperature (C°)
1	RC-Control	139	5.5	25.2	26.4
2	RC-OPCM	128	5.75	26.4	22.5
3	RC-PCM	84.5	5.2	29.5	24.4
4	RC-OPCM-F0.08	150	5.8	28.6	24.7
5	RC-OPCM-F0.1	55	5.5	33.4	28.7

Table 6.6. Fresh properties of the repair mortar

Note	OPCM	OPCM-F0.08	OPCM-F0.1	PCM
Flow rate (mm)	193	178	168	146
Room temp (°C)	25.2	28.5	29.6	28.2
Mortar temp (°C)	24	25.4	28.1	24.6
Mix temp (°C)	21.5	21.5	21.5	21.5

B. RC specimen preparation

Experimental investigations were conducted on RC beam specimens in the laboratory. A control RC specimen was prepared with fully cast concrete, designed according to the specified mix, and

subjected to a 28-day curing period to develop the standard strength. Strain gauges were attached to predetermined locations on both the concrete surface and reinforcing bars to accurately monitor the strain responses. Prior to initiating the four-point bending load test, the control specimens were positioned within the testing frame, and essential measurement devices, such as linear vertical displacement transducers, were carefully installed in critical areas. Figure 6.5 summarizes the control specimen preparation, curing, and flexural testing setups.

In contrast to the control specimen, the repair specimens were cast with a centrally located notch at the surface to simulate a repair condition. The fabrication process of the repair RC specimens mirrored that of the control specimens. As illustrated in Figure 6.6 (a), wooden plates were employed to create a notch, in the central region of the top surface, measuring 600 mm in length and 30–40 mm in depth. Figure 6.6 (b) and (c) illustrate the use of a waterjet sprayer and chipping tools to rough the surface, thereby promoting a well-bonded interface for the repair mortar overlay. Following a 7-day curing period, the prepared RC beam specimens were used to cast the repair mortar. Figure 6.6 (d) illustrates the surface treatment, with and without ER. ER was applied to the RC beam under saturated surface dry conditions to ensure proper surface attachment. Subsequently, the repair mortar was applied, as shown in Figure 6.6 (e). Figure 6.6 (f) presents the curing condition of RC beams. Strain gauges were positioned as illustrated in Figure 6.6 (g), and additional crack-measurement instruments were affixed to the concrete-mortar interface to monitor any potential cracking during loading, as depicted in Figure 6.6 (h).

The specimens are systematically named (nomenclature) to reflect their composition and treatment. The control specimen is designated as RC-control. The specimen repaired with OPCM is labeled as RC-OPCM. Specimens with PF added into the OPCM matrix are indicated as RC-OPCM-F0.08 and RC-OPCM-F0.1, where the values correspond to fiber volumes of 0.08% and 0.1%, respectively. The specimen repaired with PMC is designated as RC-PCM. An additional surface treatment of ER is denoted by the suffix “E” at the end, resulting in designations such as RC-OPCM-E, RC-OPCM-F0.08-E, RC-OPCM-F0.1-E, and RC-PCM-E.

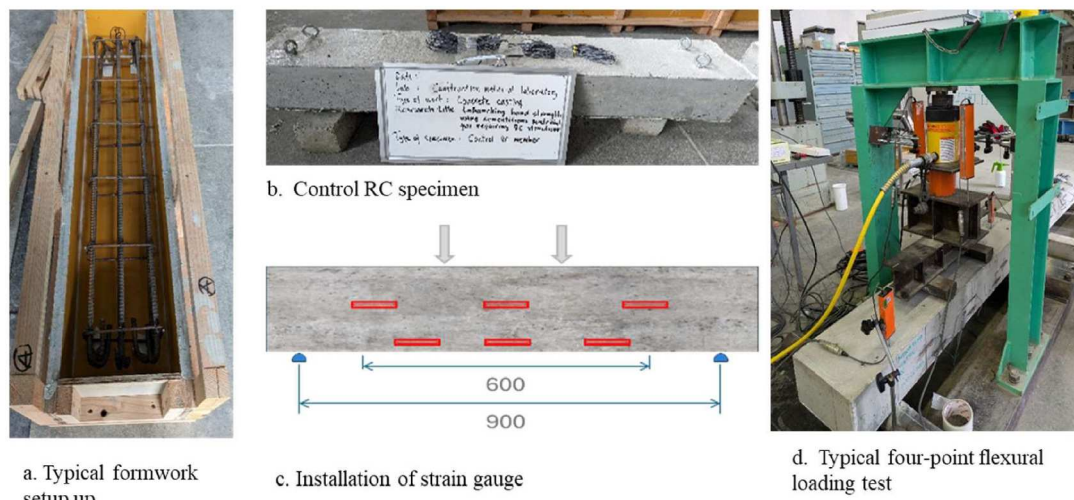


Figure 6.5. Control RC specimen preparation and testing



Figure 6.6. Typical repaired RC specimen preparation and testing

C. Four-point bending load test

Four-point flexural testing was employed to evaluate the flexural characteristics of materials, specifically to determine the performance of repair mortar in the tensile zone of RC beam specimens. Following a full 28-day curing period after repair, strain gauges were affixed to the surfaces of both the concrete and the repair mortar. Strain gauges were installed to measure the compressive-strain responses in the concrete in critical sections on the left and right sides of the specimen. Correspondingly, strain gauges were attached to the tensile regions of the repair mortar to monitor tensile strain responses. Additional gauges were positioned at the top and bottom centers of the specimens to capture both the compressive and tensile strain responses, while the shear strain was measured at the ends of the span on each side, as illustrated in the Figure. 6.7.

Six displacement transducers for measurement of crack opening were employed to monitor the bond behavior between the repair mortar and the existing concrete substrate in the RC beam specimens. To measure displacement, two displacement transducers were placed at each of the following three locations: the interface between the mortar and concrete at the beam's bottom, the center point of the predicted failure zone, and on both the left and right lateral surfaces of the beam. The displacement transducer measured the joint opening between the repair material and the substrate, providing data to assess the bond integrity.

A manual hydraulic jack with a maximum capacity of 500 kN was used to apply the load gradually and manually. This configuration facilitated the precise tracking of the cracking behavior and deflection throughout the testing period, yielding valuable insights into the structural interaction between the repair mortar and the underlying concrete substrate of the RC beam specimens.

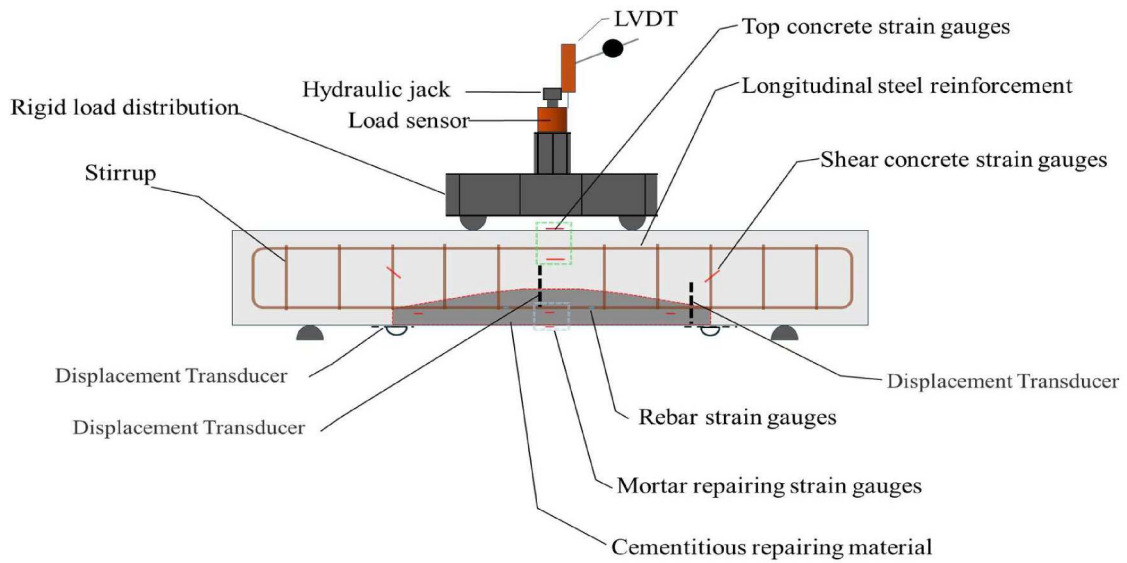


Figure 6.7. Typical four-point bending test setup

6.2.4. FE analysis

FE analysis was employed to model and simulate the structural behavior of the repaired RC beam specimens. The simulation was conducted using the ANSYS Mechanical and FE software, which are commonly used in academic research [26]. An FE simulation was conducted to evaluate the structural behavior of the repaired RC specimen and compare it with the experimental results. The primary objective of the simulation was to capture the load-strain behavior of the tensile reinforcement, as this parameter serves as a key indicator of structural performance. To ensure the reliability of the subsequent FE analysis, experimental tests were performed with precision.

A three-dimensional (3D) model was developed to simulate the mechanical behavior of the repaired RC specimens. The RC specimen model was geometrically replicated in ANSYS to correspond with the experimental specimen, and the material properties were assigned to the experimental data. The software permits the exact modeling of intricate interactions within repaired RC beams, thus enabling a comprehensive examination of their structural performance.

The repaired RC specimen, labeled RC-OPCM, was geometrically modeled in 3D using ANSYS software to replicate the experimental setup. The concrete and mortar components were represented as solid elements, with assumed perfect bonding (no slip) at the surface of connection, while the reinforcement bars, including both longitudinal and transverse reinforcements, were modeled using link elements. A uniform mesh size of 25 mm was used to ensure computational

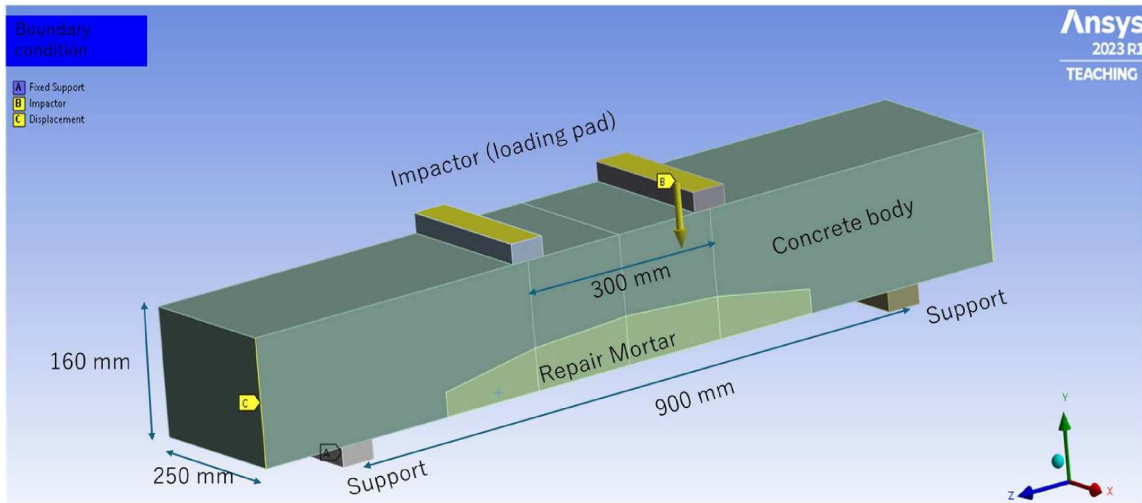


Figure 6.8. Repaired RC specimen model in ANSYS.

efficiency while maintaining the accuracy of the results. The model was designed to closely reflect the actual dimensions and material properties of the experimental specimens. Figure 6.8 shows the ANSYS model, which provides a detailed representation of the geometric configuration, boundary conditions, and loading arrangements used in the experiment.

Table 6.7 lists the material properties assigned to the model in ANSYS Mechanical software.

Table 6.7. Material properties for the FE model (Drucker-Prager method)

Properties	Concrete	OPCM	Longitudinal bar (Ø13 mm)	Stirrup (Ø6 mm)
Element type	Solid	Solid	Link/truss	Link/truss
Unit weight (density), kg/m ³	2300	2300	7850	7850
Elastic modulus, GPa				
$(E_c = 4700\sqrt{f_c})$ Eq. 1	26	42	200	200
E_c = elastic modulus for concrete				
F_c = Compressive strength				
Compressive strength, MPa	33	80	-	-
Biaxial compressive strength, MPa	37	92	-	-
Poisson's ratio	0.18	0.18	0.3	0.3
Yield strength, MPa	-	-	345	285

Tensile strength, MPa	3.2	6.5	490	380
Flexural strength, MPa	4.7	9.1	-	-

6.3. Experimental results and discussion

6.3.1. Concrete and cementitious mortar properties.

As shown in Figure 6.9, the mean compressive and flexural strengths of all specimens, measured after 28 days [27, 28]. The compressive strength values derived from the mix design exhibited a strong correlation with experimental results for RC specimens. This close alignment underscores the reliability of the mix design in predicting the actual performance of concrete. Likewise, the flexural strength, consistent across all RC specimens. The average compressive strength was approximately 30 MPa, while the average flexural strength was around 5 MPa.

A comparative analysis of the compressive strength of the cylinder and flexural and compressive strength for cube specimens of repair cementitious material is presented in Figure 6.10. The results demonstrated that OPC-based mortars, specifically OPCM and OPCM-F, exhibited higher compressive strength compared to PMC. In terms of flexural strength, the specimens incorporating OPC-based mortar with PF (OPCM-F) demonstrated optimal performance. This highlights the positive impact of PF addition to OPCM, leading to a substantial improvement in mechanical properties. This improvement underscores the potential of OPC-based mortars with PF for repair applications that require better durability and structural integrity.

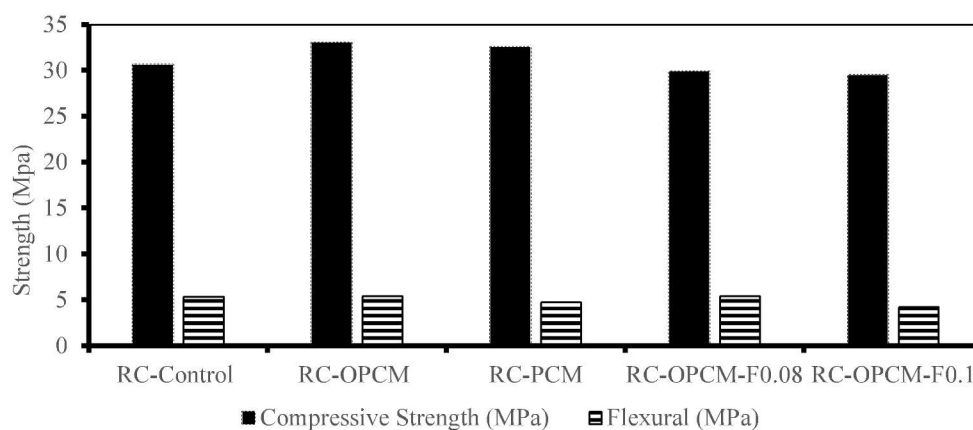


Figure 6.9. Physical properties of concrete

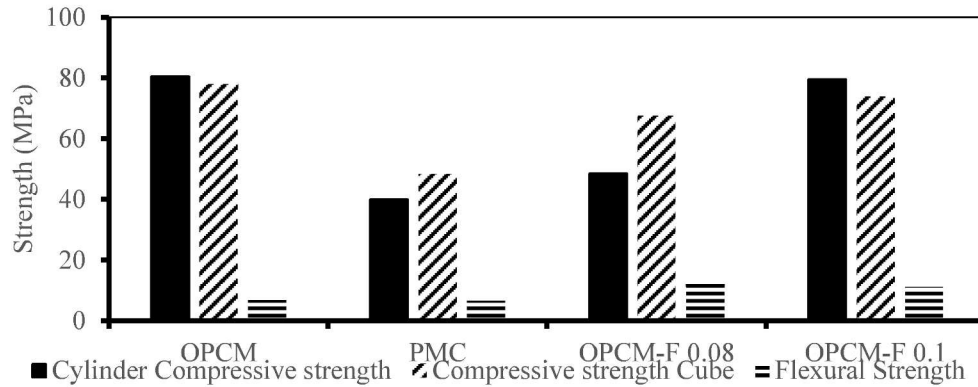


Figure 6.10. Physical properties of repair mortar

6.3.2. Flexural four-point bending experiment.

A. Failure mode and characteristic load

Figure 6.11 illustrates the crack propagation, crack spacing, and total number of cracks observed in the specimens of both the RC control and repaired beams. The RC control specimen exhibited a considerable number of cracks that displayed flexural failure and an irregular distribution of cracks. The repaired RC beam specimens were categorized into two distinct groups: one treated with ER and the other without the application of ER. The group without ER, designated RC-OPCM, exhibited a remarkably higher incidence of cracks than the specimens treated with OPCM combined with PF, including those treated with PMC. The number of cracks observed in the RC-OPCM was lower than that observed in the RC control, highlighting the effectiveness of the treatments employed in the repaired specimens. Additionally, following the initiation of flexural cracks, shear cracks were observed in all samples without ER treatment.

The group treated with ER exhibited a behavior similar to that of the RC beam specimens without ER. Although the application of the ER led to a noticeable reduction in the number of cracks, this decrease was not statistically significant. While epoxy treatment improved crack control, it did not completely prevent crack formation.

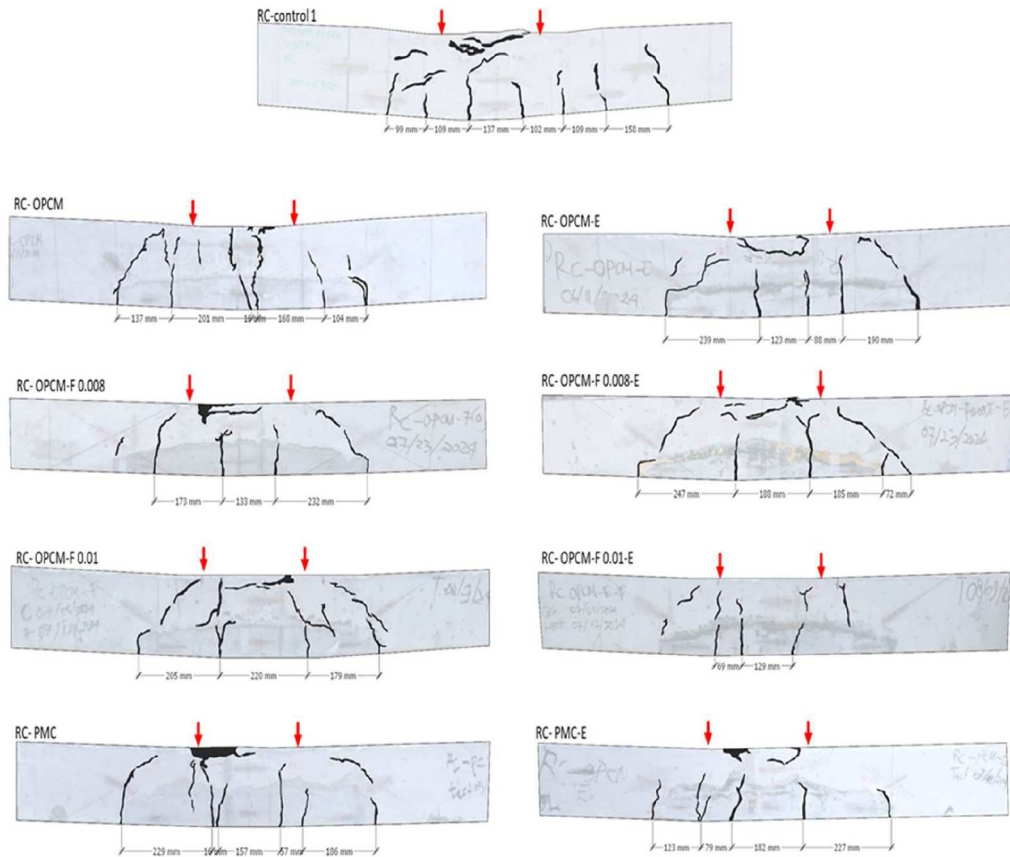


Figure 6.11. Crack distribution of RC beam specimens

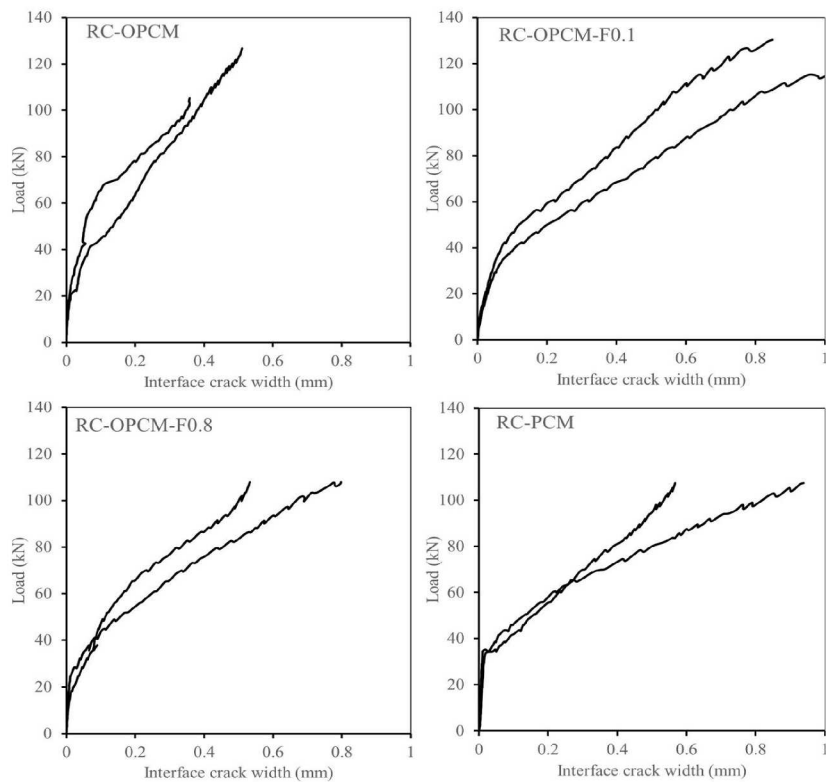
B. Load-crack width relationship

Figure 6.11 illustrates the bond opening beneath the RC beam specimens in response to an applied load. The results indicate that the RC-OPCM specimens with and without the ER treatment exhibited early crack initiation at an engagement force of approximately 20 kN (Figure 6. 12(a)). Contrastingly, the RC-OPCMs combined with PF, including those treated with ER (Figure 6. 12 (b)), demonstrated delayed crack initiation, with openings commencing at forces exceeding 20 kN. Furthermore, RC-PMCs, both untreated and treated with ER, exhibited significantly higher resistance to cracking, with crack openings observed only at forces exceeding 30 kN.

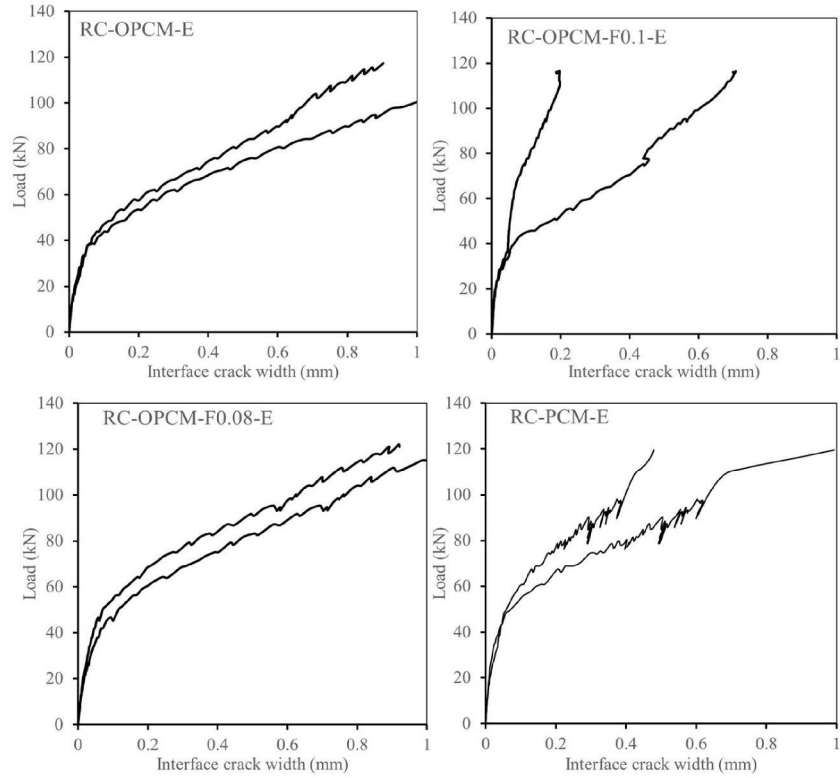
The serviceability limit state requirement for exterior applications, as established by ACI 224R-01 [28] with a maximum allowable crack width of 0.3 mm, was met by most repair specimens under service loads of 60–75 kN. These findings highlight the significant influence of material composition and treatment on crack behavior. The addition of PF to the OPCM mixture and the

application of ER effectively delayed crack initiation and limited the crack width, thereby enhancing the overall performance of the repaired RC beam specimens.

Another transducer demonstrated the same effect as previously described; however, a crack opening subsequently developed after the initial crack occurred beneath the transducer in the RC beam specimens. The extent of the opening was dependent on the position of the crack in the RC beam specimens.



(a) RC Specimens without epoxy resin (ER)



(b) RC Specimens with epoxy resin (ER)

Figure 6.12. Interface crack width distribution of RC beam specimens at the bottom

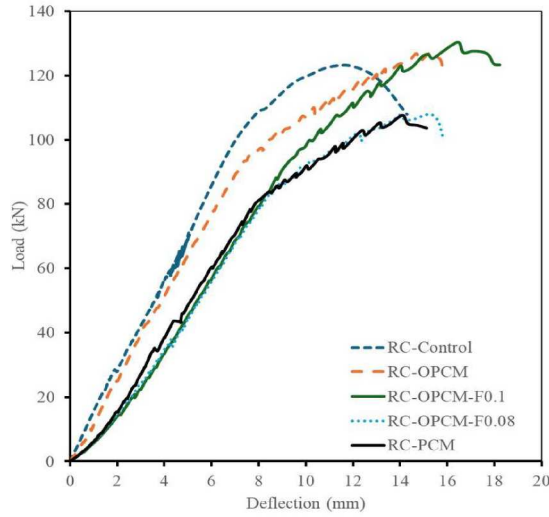
C. Load-deflection responses and ductility

The load-deflection responses of the specimens, with and without ER, are presented in Figure.6.13 and correspond to the physical properties listed in Table 6.8. The beam exhibited nearly linear elastic behavior up to initial crack load, ranging between 24 kN and 28 kN for the RC control, RC-OPCM and RC-OPCM with PF. The RC-PMC specimens exhibited a higher initial crack load. The specimens comprising the RC OPCM and combined PF exhibited superior performance in terms of deflection at the maximum load. Concerning stiffness, the specimens designated as RC control and RC-OPCM exhibited comparable performances until the load achieved the yield load. Thereafter, RC control exhibited superior stiffness, whereas the RC-OPCM specimen exhibited enhanced ductility. All specimens with ER exhibited enhanced ductility, including the RC PMC. RC-control failed in the flexural, while repaired specimens exhibited combined flexural-shear failure. The results emphasize the role of OPCM combined with PF and ER applied to the bonding surface in improving ductility while maintaining an adequate load-carrying capacity similar to that

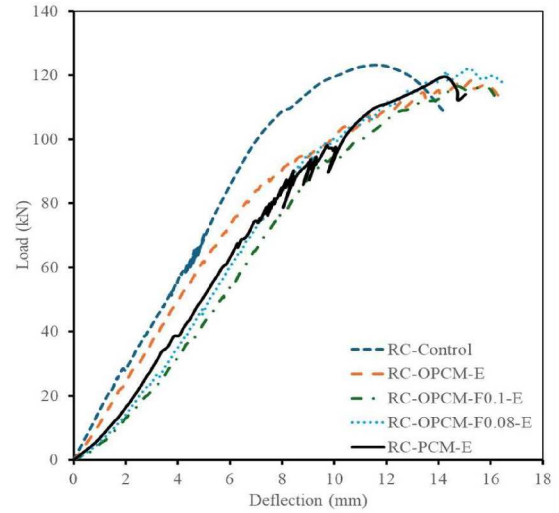
of RC control (Figure 6.13 (a), (b)). Another factor influencing this phenomenon is the compressive strength of OPCM, which reaches 80 MPa. Additionally, the contribution of external enhancements helps reduce stiffness loss and enhance the deformation capability. This behavior is particularly advantageous for structures subjected to dynamic or seismic loading, where ductility and energy absorption are critical

Table 6.8. The physical properties of RC beam specimens

Type of RC	Cracking load (kN)	Max. load (kN)	Deflection at Max. load (mm)	Failure
RC-Control	25	122.9	12	Flexural
RC-OPCM	25	126.9	14.7	Flexural and shear
RC-OPCM-E	26	118.7	15.3	Flexural and shear
RC-OPCM-F0.08	28	107.9	14	Flexural and shear
RC-OPCM-F0.08-E	26	122.2	15.2	Flexural and shear
RC-OPCM-F0.1	26	130.4	16.5	Flexural and shear
RC-OPCM-F0.1-E	24	116.5	14.8	Flexural and shear
RC-PCM	37	107.5	14.2	Flexural and shear
RC-PCM-E	35	119.5	14.3	Flexural and shear



(a) RC Specimens without epoxy resin (ER)



(b) RC Specimens with epoxy resin (ER)

Figure 6.13. Load deflection relationship

D. Load and repair mortar strain responses

During the four-point bending tests, initial crack formation was consistently observed in the mid-span region of the beams, manifesting a flexural crack pattern. Upon application of the initial load, tensile strains were induced at the bottom of the RC beam specimens. Crack initiation was observed to originate from the installed strain transducers. Subsequently, a transition from tensile to compressive strain was recorded at these locations. As illustrated in Figure 6.14, this phenomenon occurred in the majority of RC Ordinary Portland Cement (OPCM) beam specimens upon reaching a load of 20 kN. In contrast, RC Polymer-Modified Concrete (PMC) specimens exhibited this transition at a load of 35 kN. Notably, this behavior was consistently observed in both Epoxy Resin (ER)-treated (Figure 6.14 (b)) and untreated (Figure 6.14 (a)) sections of the RC specimens, indicating a similar response regardless of ER application

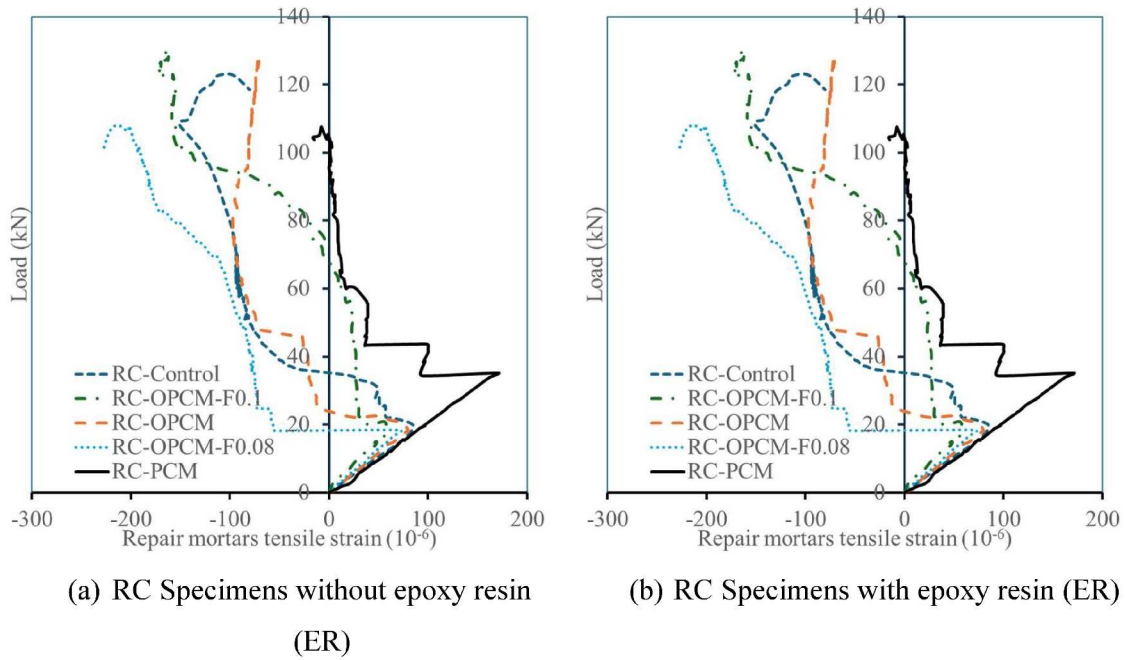
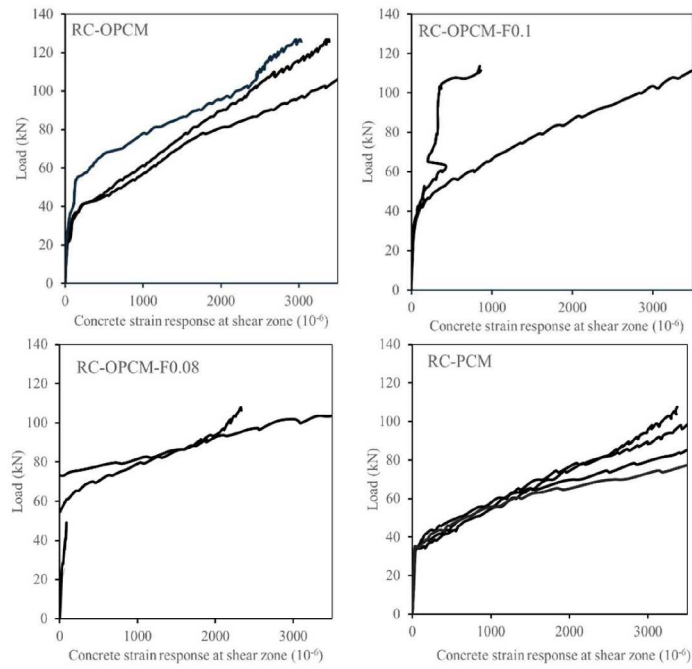


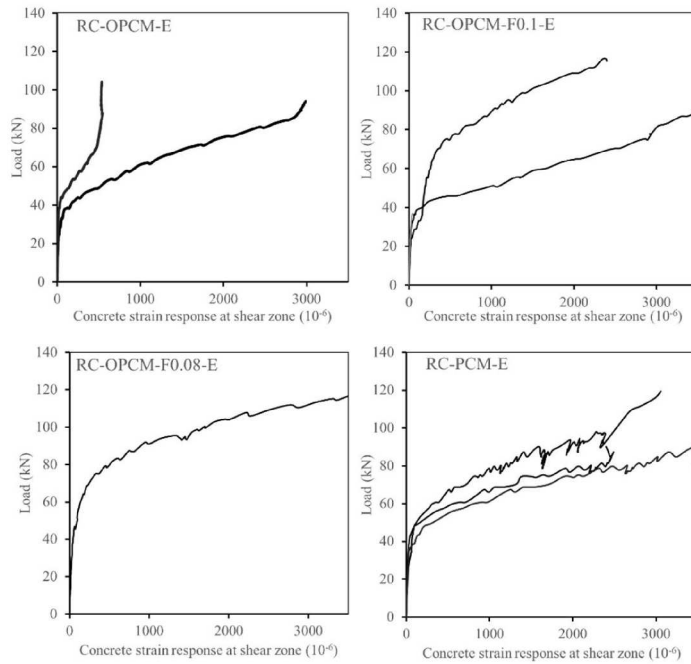
Figure 6.14. RC mortar repair cementitious strain load relationship

E. Load and shear of concrete response

Figure 6.15 illustrates the relationship between applied load and concrete strain in the shear zone of RC beams. The figures reveal that strain began to occur and increase significantly at load of approximately 35 kN, coinciding with the initiation of shear cracking following the appearance of the initial crack, which occurred in the flexural area. The RC specimen using OPCM, as the primary binder, exhibited consistent shear behavior and had a similar behavior to RC repaired with additional use of PF. When PF was incorporated into the OPCM mix, a slight increase in shear strain response was observed, indicating a marginal improvement in shear capacity within the shear cracking zone. In contrast, RC specimens made with PMC, both without and with Epoxy Resin (ER), demonstrated a notably higher capability to respond to shear strain compared to the OPCM specimens, as shown in Figure 6.15 (a) and (b), respectively. This observation suggests a quantifiable enhancement in the material's resistance to tensile stresses induced by shear cracking. Notably, while both PMC variants exhibited improved performance, the difference in shear strain capacity between the PMC specimens with and without ER was determined to be statistically insignificant.



(a) RC Specimens without epoxy resin (ER)

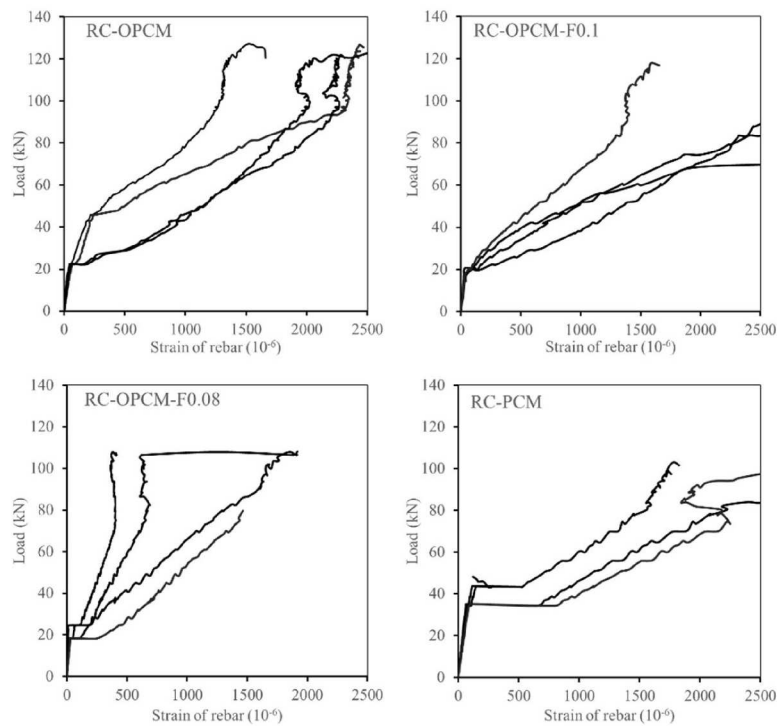


(b). RC Specimens with epoxy resin (ER)

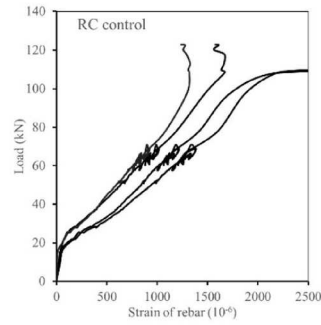
Figure 6.15. Concrete strain response at the shear zone and load relationship RC beam specimens

F. Load longitudinal rebars response

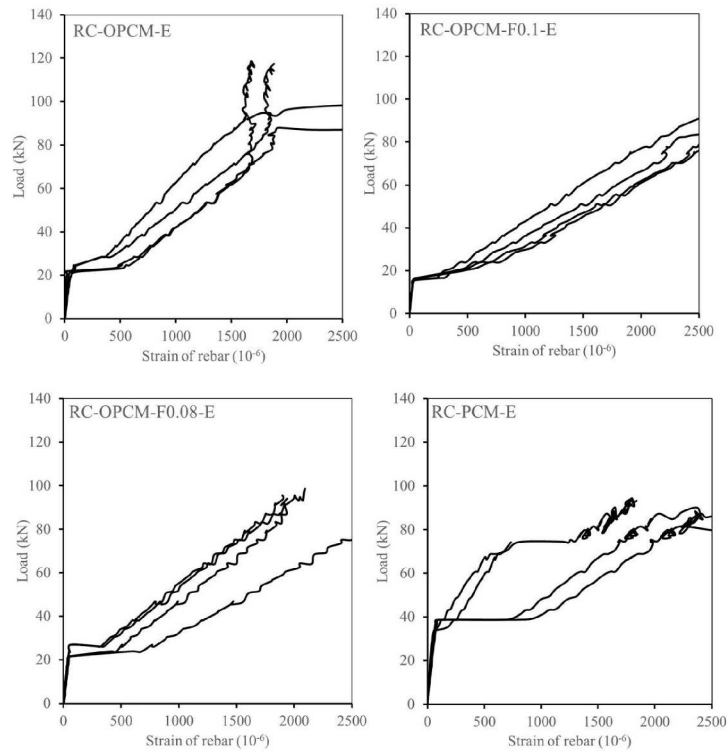
Figure 6.16. illustrates the correlation between the load applied to the RC beam specimens and the strain behavior of the longitudinal rebar situated in the tensile zone. No initial strain response was observed at the commencement of the load application. However, as the load continued to increase to 20 kN, this phenomenon commenced in the RC control specimen, and changes began to occur, manifesting as a response to the strains. Following the application of a load above 20 kN, the observed changes were identical for RC OPCM, RC OPCM combined with PF utilizing the ER, and RC OPCM combined with PF without utilizing the ER. For the samples from the RC PMC, changes were observed above 35 kN. The RC control and repaired RC beam specimens exhibited comparable conditions when the strain response reached the threshold for the steel yield stress. Subsequently, the strain response demonstrated erratic behavior, which rendered the analysis challenging.



(a) RC Specimens without epoxy resin (ER)



(b) RC control specimen



(c) RC Specimens with epoxy resin (ER)

Figure 6.16. Strain in the longitudinal tensile zone and load relationship of RC beam specimens

6.3.3. FE method

Figure 6.17 presents a comparative analysis of the strain response obtained from experimental testing and numerical simulation. The results demonstrate a strong correlation between the two approaches, particularly in the elastic range, with nearly identical behaviors.

The tensile reinforcement bars yielded at an applied load of approximately 23 kN, corresponding to a strain of 84.77×10^{-6} . Beyond this point, the strain continued to increase until the bars reached their maximum capacity, failing at a strain of 1750×10^{-6} . These findings demonstrate the ability of the numerical model to predict both the yielding and failure stages of the reinforcement, thereby instilling confidence in the accuracy of the simulation methodology.

The simulation captured the strain load behavior and provided a detailed representation of the progressive damage and stress distribution within the concrete body as the load increased. When the applied load reached 130 kN, the concrete exhibited extensive damage, with clear patterns of crack formation in the tensioned regions. Tensile damage began earlier, with cracks developing at a load of 23 kN, which was consistent with experimental observations. Figure 6.18 illustrates the damage patterns observed at the final loading stage, highlighting areas of severe tension and compression stresses corresponding to the crack locations identified in the experimental results.

Additionally, the simulation offered valuable insights into the stress response of the material in Figure 6.19. At a load of 23 kN, the tensile stress in the concrete reached a critical value of 2.92 MPa, indicating the onset of cracking. This value closely matches the tensile strength of the concrete, confirming the accuracy of the numerical model. As the load increased to 130 kN, the concrete reached its maximum compressive strength of 30 MPa, indicating the material's capacity limit under compression.

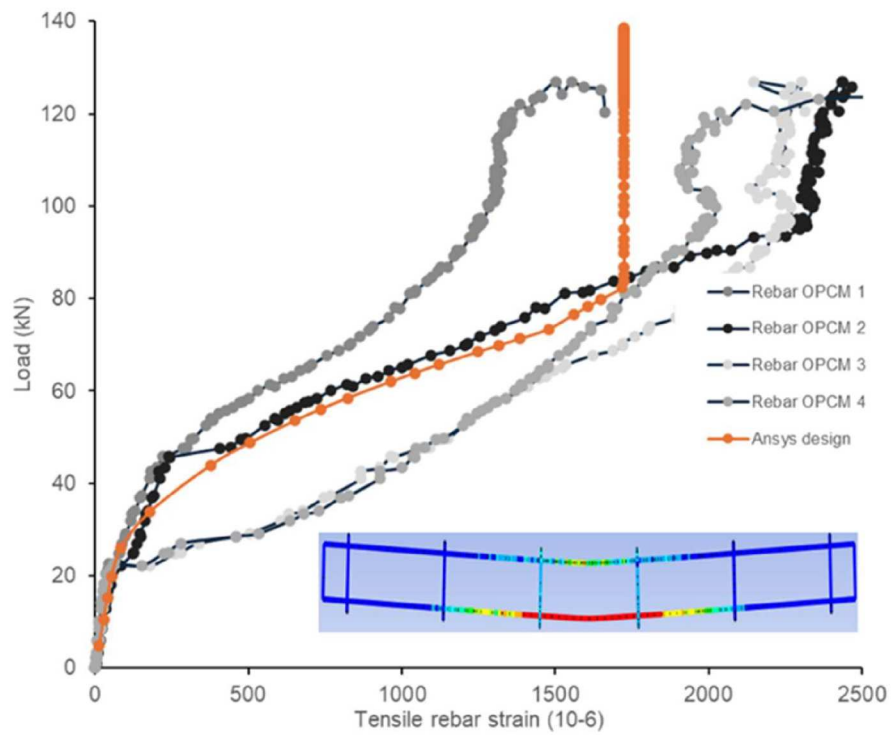


Figure 6.17. Experimental and simulation tension reinforcement bars strain responses

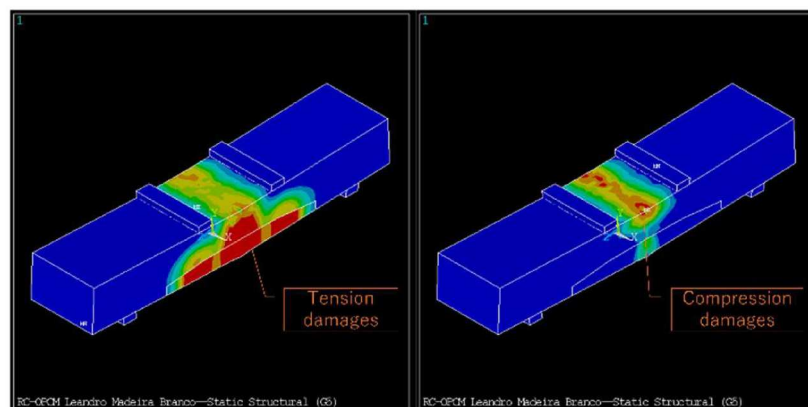


Figure 6.18. The damage exposed in the ANSYS simulation

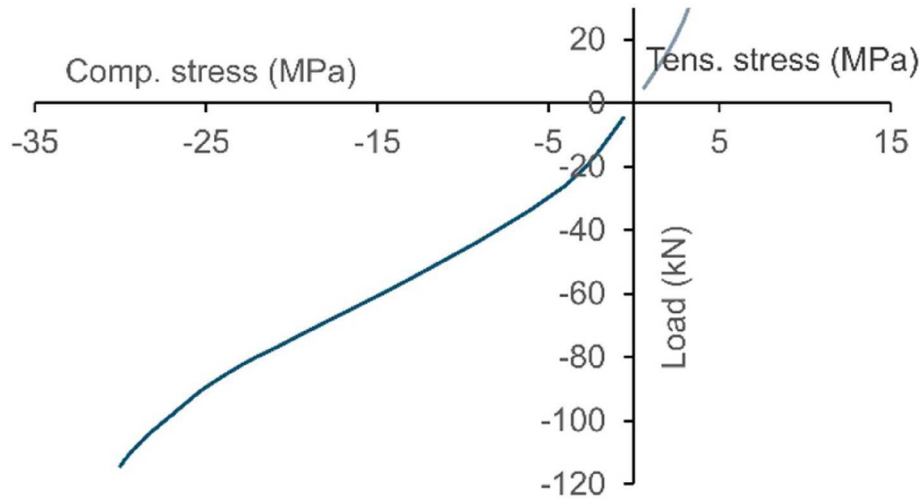


Figure 6.19. FE simulation compressive and tension stress response

6.4. Summary

This research aimed to evaluate the flexural performance of OPCM as a primary repair material for the tensile zone of RC beams and its effectiveness in restoring the flexural strength of damaged RC beams. Two types of repaired specimens were tested: beams repaired without ER and those repaired with ER. Eight beams were repaired using either the OPCM or PMC, and one beam served as a control. The experimental results revealed that the repair of the severely damaged tensile zones of RC beams with a combination of OPCM, PF, and ER significantly enhanced the original flexural performance. Based on the results and discussion, the following conclusions were drawn.

1. Consistent compressive and flexural strength results across all concrete samples suggest material equivalence. In the context of repair mortars, while OPCM demonstrated superior strength compared to commercial PMC, it remains capable of achieving comparable repair effectiveness in reinforced concrete (RC) structures.
2. The control, epoxy-treated, and non-epoxy-treated RC beam specimens exhibited peak load capacities of 110–135 kN. However, the epoxy-treated beams exhibited enhanced pre-failure performance, crack control, and ductility.
3. The incorporation of OPCM and OPCM in conjunction with PF, including ER, markedly enhanced the load-bearing and shear strain capacities of the repaired RC beams,

particularly in configurations involving PF, which demonstrated superior performance under elevated strain conditions.

4. ER proved to be an effective method for mitigating the severity and propagation of cracks, thereby delaying their growth and ensuring the structural integrity of the material.
5. The midspan remained the most susceptible to cracking, which is consistent with the expected flexural behavior of the material.
6. The homogeneity of the concrete substrate in the RC beam specimens, along with the cemented repair material, proved effective during the repair stage. All specimens exhibited crack openings of approximately 1 mm as measured by the transducers.
7. The response of the OPCM-repaired RC beam predicted by the integrated FE model matched the experimental observations. The simulated damage patterns and concrete crushing at the loading points closely resemble the observed damage progression, confirming the accuracy of the integrated FE analysis model.

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VII. Conclusions and future research

7.1. Conclusions

This thesis presents an experimental study designed to evaluate the performance of various cementitious mortars for repairing reinforced concrete (RC) structures. The primary objective was to investigate the effectiveness of different repair materials and techniques by focusing on critical parameters, such as bond strength, load-bearing capacity, failure mechanisms, and ductility. The results of this study provide valuable insights into the behavior of repaired RC elements. The key findings and conclusions of this research are summarized below:

1. This study emphasizes the importance of bond and flexural strengths between repair mortar and existing concrete substrates for the effective repair and rehabilitation of concrete structures in the least developed countries, such as Timor-Leste.
2. Bond strength experiments demonstrated that Ordinary Portland Cement Mortar (OPCM) performed significantly better than Polymer-Modified Cement (PMC) in repair applications. Using PMC resulted in outcomes that were not significantly lower in terms of ductility compared to RC beams repaired with OPCM or a combination of both.
3. The implementation of OPCM as an overlay exhibited a satisfactory load-bearing capacity. The specimen exhibited its capacity to bear loads and maintained its elasticity before the beginning of cracking.
4. The efficacy of Epoxy Resin (ER) in mitigating crack severity and propagation was demonstrated in the experimental setting. However, the strength of the bond formed by ER with repair materials and concrete substrates exhibited variability. In certain instances, the bond strength was determined to be inferior to that of repairs conducted without ER, depending on the degree and timing of the ER application.
5. The application of the cementitious repair material to the homogeneous concrete substrate completed the initial repair stage for the RC beam specimens. The transducer measurements have been confirmed.
6. The integrated finite element (FE) model accurately predicted the behavior of the OPCM-repaired beam. The model's simulated damage and concrete crushing patterns demonstrated agreement with experimental observations, which validates its predictive utility for structures that have undergone such repairs.

The investigation confirmed that Ordinary Portland Cement (OPC) and its derivatives are effective repair media for enhancing structural strength, ensuring interfacial bond integrity, and controlling crack propagation. Significantly, these materials restore the flexural performance of the repaired beams to levels comparable to the undamaged control specimens. The findings presented herein offer critical insights that may prove instrumental in the optimization of repair methodologies and the facilitation of the development of resilient infrastructure in regions that are limited in their resources.

7.2. Future Study

The experimental study demonstrated that OPCM is an effective repair material, both on its own and when combined with other materials. This is due to its strength, strong bonding ability, ability to control crack propagation, and enhance flexural performance during the initial repair process. It can restore strength to levels comparable to those of undamaged RC structures. However, future research is needed to understand OPCM behavior better, such as follows:

1. In the least developed countries, such as Timor-Leste, it is essential to mandate a life cycle cost analysis (LCCA) that incorporates local constraints, such as limited maintenance budgets, material shortages, and logistical challenges, to develop sustainable and economically viable infrastructure. This analysis will help decision-makers find solutions that balance initial affordability with long-term durability and operational resilience.
2. Evaluate the combined effects of harsh weather conditions, thermal cycling, and environmental exposure on the degradation of bond strength in deteriorating reinforced concrete (RC) structures. This is especially important in the least developed countries, where determining the extent to which specific local climatic stressors cause loss of structural integrity is essential for prioritizing cost-effective maintenance, including ensuring public safety.
3. Developing, comprehensively characterizing, and field implementing low-carbon, high-performance repair solutions, specifically geopolymers mortars and alkali-activated binders, as well as integrating them with fiber-reinforced composites, to establish sustainable, durable, and environmentally responsible methods for infrastructure maintenance.
4. Strategies for enhancing the accuracy of modeling in finite element (FE) method simulations primarily focus on refining the constitutive material model, optimizing the

calibration and identification processes for material parameters, and integrating advanced experimental data into the simulation framework.

Appendix

Life cost analysis (LCA) of conventional cementitious materials for RC beam repairing

Outline

Infrastructure deterioration often results in the need for large volumes of urgent, high-cost repairs. Although traditional cement-based materials are standard for repairing reinforced concrete (RC) beams, they have a substantial environmental footprint [1,2]. The construction industry is responsible for approximately 40% of human-made greenhouse gas emissions globally, with cement production accounting for over 5% of annual anthropogenic CO₂ emissions, primarily due to clinker manufacturing [3, 4].

These materials have a significant impact, particularly in the context of climate change and the growing energy demands of the construction sector in developing nations. However, the long-term consequences of these materials in Least Developed Countries (LDCs), such as Timor-Leste, remain under-researched. In Timor-Leste, for example, domestic cement production is not yet operational, resulting in a high reliance on imported materials. This significantly amplifies the environmental impact and transportation costs of common cementitious repair materials.

The impact of climate change is one of the greatest environmental challenges, as energy demand is increasing significantly worldwide, particularly in the construction sector in underdeveloped countries, which serves diverse purposes (transportation, residential, commercial, offices, etc. [5]. Due to the country's infrastructure development needs and limited resources, there is an urgent need for sustainable repair techniques that balance performance, cost, and environmental responsibility. This study conducts an extensive life cycle assessment (LCA) of conventional cement-based materials used for reinforced concrete (RC) beam repair in Timor-Leste. This study evaluates the sustainability of repair practices by analyzing environmental indicators, such as global warming potential (GWP) and CO₂ emissions, as well as economic factors, including transportation, labor, and maintenance costs. The results provide essential guidelines for policymakers and stakeholders in Timor-Leste by identifying optimal procedures that balance structural integrity with environmental and economic efficiency. This work contributes to the literature on sustainable construction by addressing the lack of country-specific life cycle assessment (LCA) data for infrastructure maintenance.

Life cycle assessment (LCA)

This study evaluates the life cycle performance of conventional cementitious materials used to repair reinforced concrete (RC) structures in the tropical climate of Timor-Leste. The goal is to create a framework that comprehensively assesses the cost variations and environmental impacts of repair practices in a region with limited cement production capacity and economic constraints. The analysis considers an RC structure with an initial service life of 50 years [6] and aims to extend its service life by an additional 50 years through proper maintenance. The study examines the entire maintenance process, including material transportation, mixing, and application, for a volume of approximately 1 m³ of repair material. Importantly, the assessment considers local variables that affect the structural performance and durability of the repair, such as aggressive coastal exposure, high humidity, and the effect of unskilled labor on application quality. Accounting for these factors provides a realistic view of the sustainability of infrastructure maintenance in developing tropical nations.

The Life Cycle Assessment (LCA) framework adopted for this study is illustrated in Figure A-0.1.

The analysis follows a sequential workflow:

1. **Material Acquisition & Logistics:** The process begins by analyzing the supply chain of raw materials, specifically the arrival of imported cementitious materials at the port and their transport to warehouses, alongside the local production of aggregates.
2. **Production & Construction:** The second stage covers concrete production and the transportation of aggregates to the site for utilization during the construction phase.
3. **Economic Assessment:** The third stage evaluates the Life Cycle Cost (LCC), combining the initial project capital costs with ongoing maintenance expenditures required throughout the structure's service life.
4. **End-of-Life (EoL) & Circularity:** Finally, the framework accounts for demolition and landfilling costs. Crucially, it includes a recovery loop where demolition waste is processed into recycled aggregates for future utilization, thereby reducing the demand for natural resources.

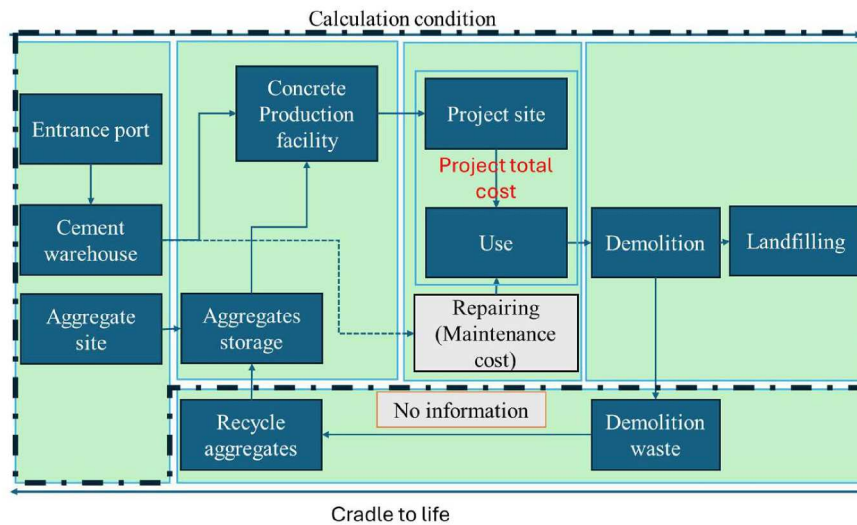


Figure A.0-1. Flowchart LCC analysis of repairment in Timor-Leste

Table A.0 9. Emission and greenhouse gas information of Timor-Leste
(<https://www.emission-index.com/countries/timor-leste>)

Country	Unit	Timor-Leste
Population	Million	1.34
Gross Domestic Product (GDP) in USD	Billion	\$1.96
Total Greenhouse Gas Emissions in 2021	Million	5.75m
Change in Emissions since 2020	Percent	0.80%
Percentage of Total Emissions (2021)	Percent	0.01%
Rank – Emitters in 2021		152
Total Greenhouse Gas Emissions since 1990	Million	127
Compound Annual Growth – Emissions since 1990	Percent	8.60
Percentage of Total Emissions (1990-2021)	Percent	0.01
GDP Per Capita (USD)		\$1.46
Emissions Per Capita	Percent	4.3

Calculate emissions and cost.

The population of Timor-Leste is 1.34 million, and its economy is relatively small, with a GDP of \$1.96 billion. The Gross Domestic Product (GDP) per capita is estimated to be approximately \$1,460. Based on data since 1990, Timor-Leste ranked 152nd globally for greenhouse gas emissions in 2021. The country's emissions totaled 5.75 million metric tons of carbon dioxide equivalent (MtCO₂e), which is a 0.8% increase from the 2020 estimate, as shown in Table A.0-1[7].

Carbon Calculation Assumptions (Timor-Leste Construction & Maintenance)

The following assumptions and parameters are used to estimate the carbon footprint (CO₂ emissions) of construction and maintenance activities in Timor-Leste.

1. Transportation & Logistics

Methodology and Variables Calculations for transport emissions are based on truck movements. The key variables in this analysis include the distance traveled (measured in kilometers or miles), payload weight (in tons), fuel type, and vehicle efficiency.

These calculations apply to specific supply chain routes. For imported materials, the distance is measured from the entrance port to the central warehouse. Distribution emissions are calculated based on the distance from the warehouse to the project site. Finally, for raw materials, the tracking covers the distance from the quarry directly to the project site.

2. Materials Selection & Sourcing

Material emissions are calculated based on the weight production per unit of CO₂ consumed (kgCO₂/kg).

Locally Sourced Materials:

Fine Aggregates

Coarse Aggregates

Supplementary materials

Water

Repair & Specialized Materials:

Polymer Modified Cement (PMC)

Polypropylene Fiber (PF)

Epoxy Resin (ER)

WRA (water reducer agents)

3. Labor & Operations

Operational emissions are estimated using time and human input variables. Labor emissions are calculated based on working hours and associated CO₂ consumption factors, including worker commutes, metabolic energy, and the use of on-site support equipment. Similarly, maintenance

emissions are determined by the duration of maintenance work relative to its carbon consumption intensity.

Determine Discount Rate

To determine the discount rate, the focus is on underdeveloped countries, such as Timor-Leste, which are characterized by weak economic growth and a reliance on a single income source. Note that Timor-Leste joined ASEAN in 2025, and comparisons are drawn with similar Asian economies, such as Cambodia and Laos, to establish financial parallels. Additionally, the analysis incorporates project-specific risks, financing structures, and national economic conditions [8,9,10].

Perform Net Present Value (NPV) analysis

Use the NPV method to evaluate life cycle costs by adding up the present values of all relevant costs, including initial project costs, operational costs throughout the project lifecycle, maintenance costs, and final disposal costs. The calculation is as follows [11,12, 13]:

$$LCC = C_{\text{initial}} + \sum_{t=1}^n \frac{C_{\text{maint},t} + C_{\text{repair},t}}{(1+r)^t} \quad \text{Equation A.0-1}$$

With

- C_{initial} : Initial material, labor, and equipment costs.
- C_{maint} : cost of maintenance, labor, and equipment costs.
- C_{repair} : Costs associated with subsequent failures (including mobilization and surface prep).
- r : Real discount rate.
- n : Year in which the expense occurs.

Summary

This information is intended to guide the planning of government infrastructure repairs in the least developed countries (LDCs), such as Timor-Leste. A summary of the findings is provided below.

- Site-Specific Variability: Calculation results may vary across projects due to the unique costs and maintenance requirements of each site.
- Future Application: Testing this method on a diverse range of repair materials would help assess and improve future repair decisions.

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Achievement

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Acknowledgements

The research presented in this dissertation, titled "Experimental study on cementitious mortars for repairing reinforced concrete members," was made possible through the dedication and support of many individuals and institutions.

First and foremost, I offer my deepest gratitude to Almighty God for His boundless grace, strength, and protection throughout my academic journey. Without His divine guidance and the gift of perseverance, this work would not have been possible.

I would like to express my profound thanks to my supervisor and chief examiner, Professor Yoshitake. Your wisdom, patience, and insightful guidance have been instrumental in the completion of this research. I am truly honored to have studied under your mentorship. My sincere appreciation also goes to the members of my examination committee: Professor Nakamura, Professor Nakashima, Dr. Watanabe, and Dr. Yamada. Your constructive feedback, technical suggestions, and intellectual expertise greatly enhanced the quality of this work.

I am deeply grateful to Mr. Makihara and Abel Fernandes for their invaluable technical assistance and support during the experimental phase of this study. To my colleagues in the Concrete Material Laboratory at Yamaguchi University, thank you for your friendship, the stimulating discussions, and for making the lab a second home during my time in Japan.

I would like to extend my heartfelt thanks to the Japan International Cooperation Agency (JICA) for providing the scholarship that made this dream a reality. I am also indebted to my home institution, Universidade Nacional Timor Lorosa'e (UNTL), for granting me the opportunity to pursue advanced studies in Japan and for their continued support of my professional development. Living far from home was made easier by my Timorese friends in Ube, Yamaguchi, Japan. Thank you for being my family away from home; your friendship and shared meals provided the emotional support I needed to stay focused.

To my beloved family, you are my greatest motivation. To my wife, Joana, thank you for your unwavering love, your sacrifices, and for being the pillar of our home while I pursued this degree. To my six wonderful children—Ernia, Malevia, Alessandro, Miles, Elvano, and Leandra—thank you for your patience and for being my daily inspiration. I also thank my brother, Gaudencio, and my niece, Nafa, for their constant encouragement.

Finally, I dedicate a special tribute to the memory of my late mother, Herminia Madeira. Although she is no longer with us, her spirit and the values she instilled in me continue to guide my path. This achievement belongs to her as much as it does to me.

Yamaguchi, Japan