Journal of the Civil Engineering Forum, September 2024, 10(3):229-238
DOI 10.22146/jcef.10433
Available Online at https://jurnal.ugm.ac.id/v3/jcef/issue/archive

An Assessment of Derelict Building Constructions Situated in Coastal Regions

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SUBMITTED 5 November 2023 **REVISED** 11 March 2024 **ACCEPTED** 17 April 2024

ABSTRACT Reinforced concrete structures constructed in coastal areas in Indonesia often suffer damage before reaching their intended service life, with steel reinforcement corrosion being a major contributing factor. This study aims to investigate the use of concrete structures produced with simple methods and inadequate supervision in coastal regions. Reinforced concrete structures near the coast are susceptible to carbonation due to marine environmental factors, leading to reinforcement corrosion. The study was conducted on the Dande Dandere Market building, Tanakeke Island, Takalar Regency, South Sulawesi. The research method employed quantitative techniques, including surveys and structural testing. Visual inspections were conducted to identify the types of damage present in the building and estimate their causes. Structural testing involved both destructive and non-destructive tests. Concrete compressive strength testing was also conducted to assess the concrete sample's compressive strength, along with carbonation testing to determine the acidity level of concrete due to the intrusion of salt compounds or carbonation formed within the concrete mass. The research findings indicate structural degradation in the market's construction, occurring more rapidly than the intended lifespan of the building. Signs of structural degradation in the reinforced concrete construction include spalling of concrete cover on beams, supporting columns, and cantilever slabs, as well as degraded reinforcement, with an average reduction in steel weight of 62.70% over six years, and an average weight loss of 0.103 grams per day. Therefore, efforts are needed to optimize the structural quality of the building through comprehensive repairs, starting from the foundation. However, for cost-efficient alternatives, it is recommended to use timber structural materials for new market construction. The use of timber in coastal buildings, which are vulnerable to marine influences, is more feasible as the presence of saltwater can inhibit wood decay caused by microorganisms.

KEYWORDS Reinforced concrete; Coastal; Corrosion; Structural; Timber.

1 INTRODUCTION

The safety and durability of buildings are influenced by their environment. Coastal locations significantly contribute to serious damage prevalence in buildings within such environments. Reinforced concrete is the most commonly used construction material today. The use of reinforced concrete protects embedded steel from alkali attacks and enables resistance to damage from adverse environments. However, it becomes vulnerable when exposed to marine environments (Sadati et al., 2015; James et al., 2019).

Corrosion weakens the bond between reinforcement and concrete, thereby reducing the strength of the concrete itself. High-strain steel reinforcement is more affected than low-strain reinforcement. Cracks resulting from corrosion and steel reinforcement significantly influence the dynamic and static load behavior of structures. Ultimately, corrosion damage to steel reinforcement can affect the bond strength between steel reinforcement and concrete, which, in turn, can affect the strength and stability of reinforced concrete structures (Liu et al., 2022).

Previous research found that exposure conditions influenced the rate of steel corrosion in concrete as the primary parameter. Parameters such as humid environmental conditions and direct contact with water fell into exposure condition categories, while corrosion rates under low relative humidity (RH) values could be disregarded (Tian et al., 2023).

Reinforced concrete buildings near the coast are vulnerable to environmental damage, especially chloride-induced corrosion of reinforcement. Factors such as environmental characteristics, urban parameters, and building construction systems contribute to the deterioration of reinforced concrete structures significantly. The physical condition of the structure affects its service life (Moreno et al., 2018).

The hazardous nature of the marine environment is closely associated with other factors that can exacerbate chemical exposure with increased structural exposure to marine aerosols (Sangiorgio et al., 2019). According to previous studies, weather conditions (including wind), location, moisture in concrete pores, and planning considerations (such as distance from the sea) all play crucial roles (Medeiros et al., 2013; Moreno et al., 2015; Adam et al., 2016). Efforts are needed to optimize the quality of structures through careful selection of concrete quality, protecting concrete reinforcement, thoughtful design, regular maintenance, and periodic repair.

Corrosion can lead to a reduction in the diameter of steel reinforcement and result in a larger volume of corrosion reaction compounds compared to the volume of reacting steel, exerting pressure on the surrounding concrete. Consequently, concrete covers may crack or spall due to the expansion resulting from corrosion reaction. Ultimately, this diminishes the performance of concrete buildings and, if left unchecked over time, renders them unusable. Therefore, corrosion of reinforced steel serves as a basis for predicting the service life of concrete buildings, especially those near the sea (Sudjono, 2005).

The utilization of land and geographical location in South Sulawesi Island continues to evolve without being tailored to the coastal environment conditions that require special treatment. Most developments adhere to the same rules and behaviors without considering location-specific approaches for areas near the coast. Additionally, there is still a lack of investigation and research on buildings along the coast of Indonesia. Therefore, this study not only assesses the safety and durability of coastal buildings, such as the market building that has been unused for seven years post-construction without maintenance, but also explores the structural viability based on its findings. Furthermore, it provides insights into managing similar cases in different locations, considering the local context where the market's lack of use is attributed to low demand from the predominantly fishing community, which prefers to trade on neighboring islands.

2 METHODS

2.1 Research Location

The study was conducted on the Dande Dandere Market building, located on Tanakeke Island, Takalar Regency, South Sulawesi, to examine its structure. The market was constructed as a simple reinforced concrete structure with a lightweight steel frame roof covered with span-deck steel. The market comprised three buildings: Building A, Building B, and Toilet Building, situated along the coast as depicted in Figure 1.

2.2 Preliminary Survey

Data collection was conducted to gather the necessary aspects for detailed surveys. The data included various documents such as Contract Drawings, Shop Drawings, As-Built Drawings, and technical specifications.

2.3 Visual Inspection

Observations of the building structure and its environmental conditions were conducted to obtain an overview of the types of damages present and to estimate their causes. Building damage was categorized into three types: minor non-structural damage, minor structural damage, and moderate structural damage. Minor non-structural damage generally occurs in parts of the building that are not the main structural components, such as non-load-bearing walls, floor coverings, and ceilings. On the other hand, minor structural damage occurs in parts of the building's structure but is still at a minor level and does not pose a threat to the overall safety of the building, such as cracks in beams or columns, slight shifts or displacements in foundations, or minor deformations in other structural elements. Moreover, moderate structural damage is more serious than minor damage. It can pose a threat to the safety of the building if not addressed properly such as large cracks or fractures affecting structural integrity, significant shifts or changes in shape in foundations or other main structures, and loss of load-bearing capacity in some structural elements.

2.4 Concrete Testing

In the analysis method of structural feasibility, especially reinforced concrete in buildings, there are generally two types of testing. Non-destructive testing involves inspecting structures without damaging the building or structure being tested, while destructive testing involves taking samples that damage the building. Evaluation of concrete quality using Core Drill Tests based on SNI 2847-2019 was conducted for the laboratory building's column structure.

2.4.1 Carbonation Testing

Concrete chip carbonation testing was conducted to determine the acidity level of concrete resulting from the intrusion of salt compounds or carbonation within the concrete mass. This test involved spraying a 1% phenolphthalein solution (1 gram phenolphthalein mixed with 90 cm^3 ethanol and added with distilled water to reach 100 cm^3). Concrete portions still in good condition (alkaline) would turn pink or purple, while carbonated portions, with a pH of 7 (neutral) or even less than 7 (acidic), would not change color (Agency, 2002).

In general, concrete damage due to chemical attacks can be caused by various factors such as carbonation,

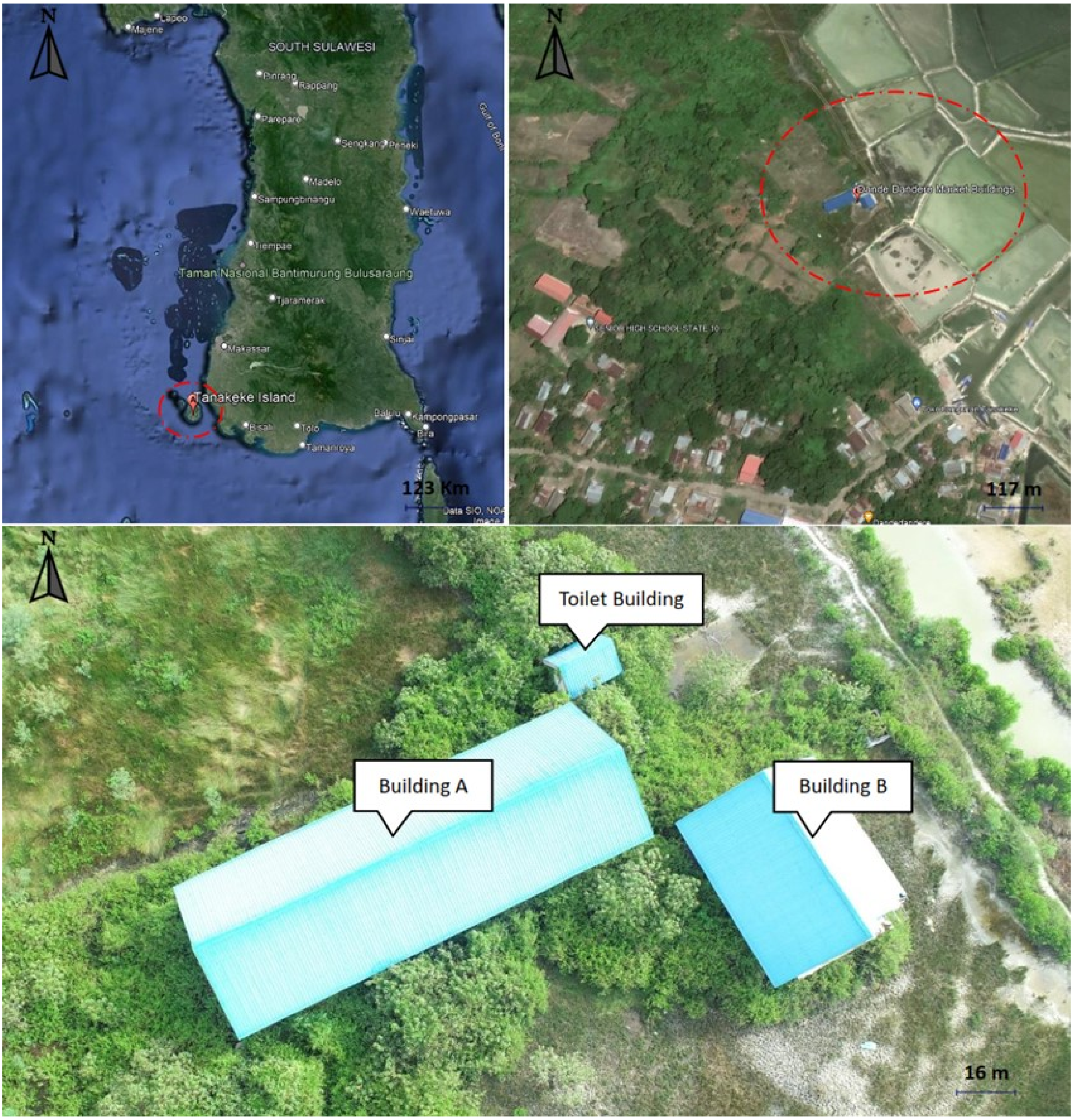

Figure 1 Research location map

chloride, sulfate, decalcification, and water quality. Concrete carbonation occurs when carbon dioxide in the atmosphere reacts with hydrated cement minerals, producing carbonate. Concrete carbonation manifests in two types: early-age carbonation and weathering carbonation. Early-age carbonation occurs when carbonation coincides with the hydration reaction of fresh concrete exposed to aggressive environments, leading to rapid carbonation and contributing to slow concrete strength development.

2.4.2 Strength Testing

Concrete compressive strength and Paving Block testing were conducted to determine the compressive strength of concrete samples (f_{ck} in kg cm^2). The compressive strength was obtained by dividing the compressive force (P, in kgf) from the compression testing machine by the surface area (A, in cm^2) measured previously, or by the following formula :

$$f_{ck} = \frac{P}{A} \tag{1}$$

Concrete testing was limited to chip samples from the Lods table and Paving Blocks installed on-site.

2.4.3 Density Testing

Relative dry concrete density (G, in grams cm^{-3}) testing was performed to control the strength against concrete mass density. This testing involved weighing each concrete compression test sample (W_c, in grams) before compression in a dry oven and dividing the result by the corresponding sample volume (V_c, in cm^3) to obtain the density of each test specimen :

$$G = \frac{W_c}{V_c} \tag{2}$$

2.4.4 Degradation Testing

Corrosion-induced reinforcement degradation testing was conducted to determine the rate of weight loss of reinforcement due to corrosion over six years. This testing involved preparing iron specimen pieces with known lengths, diameters, and weights before degradation by corrosion (W_{s1}, in grams). After rust removal from the specimens, they were weighed (W_{s2}, in kg). The difference between W_{s1} and W_{s2} represented the weight loss of iron due to corrosion (W_c, in grams) :

$$W_c = W_{s1} - W_{s2} \tag{3}$$

If the weight W_c is divided by a specific period (t in days), the weight loss per that period (L_o, in grams day^{-1}) can be predicted using the following equation :

$$L_D = \frac{W_c}{t} \tag{4}$$

From this principle, the average reduction in the diameter of the iron after rust removal can also be estimated. In corrosion-induced reinforcement degradation testing in the laboratory, weight or diameter differences of intact 12 mm plain reinforcement compared to their original condition after rust removal were used. These differences were divided by the number of days over six years to obtain the average weight reduction or diameter reduction per day.

3 RESULTS

3.1 Visual Inspection

The condition of the market building and its surroundings during the field visit, as depicted in Figure 2, revealed rampant wild vegetation with strong roots encroaching the area surrounding the market building, making it challenging for the team to identify Paving Block works around the building. Eventually, after a thorough exploration of these wild plants, the Paving Blocks were discovered.

Visual identification revealed structural degradation in the market's construction, occurring at a faster rate than the expected lifespan of the building. Signs of structural degradation in the reinforced concrete construction include the peeling of concrete coverings (spalling) on beam and column components, as well as on cantilever slab plates.

While observing the deteriorated upper building conditions, it was also presumed that the foundation of this market building had undergone similar, more severe conditions due to the accumulation of salt aggression and sulfuric acid from the surface soil. Based on visual identification, the soil was identified as expansive organic silty clay sand, characterized by black color. Another type of non-structural degradation involved the detachment of ceramic tiles from walls or floors and the collapse of lod's sales tables. During the team's inspection, a lods table collapsed even with only one person

Figure 2 Condition of the market building and surroundings

Figure 3 Identification of component damage in the building

attempting to step on it.

On the other hand, the lightweight steel frame and roof covering were still more robust than its supporting structure, although they showed significant signs of deterioration, indicated visually by the detachment of roof coverings and list planks. It can be directly identified that the cause of the roof component detachment was rusty nails or screws coming loose. However, despite the apparent lack of severe damage to the roof structure, it remained highly hazardous as potential debris, given that the reinforced concrete columns and beams supporting its main structure have undergone severe deterioration in bearing the construction load above.

In Figure 3, severe damage or significant degradation was evident in the structural elements of the slab, column, and beam throughout almost all parts of the construction in Main Buildings A and B. This type of structural damage included cracked and expanded concrete with wide openings (more than 1.0 mm), spalling of concrete covers and corrosion, as well as severe expansion of reinforcements (rebar fracture and easy tearing). The damage depicted in the figure was attributed to the very low quality of concrete during the initial implementation, making it vulnerable to the aggressive influence of the coastal environment. Similarly, the damage has also occurred to architectural components, such as floor damage caused by soil conditions, roof and listplank detachment due to wind influence, and corrosion on nails/screws from the surrounding environment.

3.2 Concrete Testing

Figure 4 shows white-colored debris samples with adhering reinforcements in concrete or mortar. The white

Figure 4 Samples of concrete debris from the site

Figure 5 Rebar samples and the condition of corroded rebars that can be fractured

Figure 6 Results of carbonation testing on concrete debris and structural elements

color of this debris provided an initial indication that the concrete had detached due to carbonation. Figure 5 illustrates the visual condition of reinforcement elements that have undergone severe corrosion, characterized by brittle fractured reinforcement metal and easy tearing, resulting in a reduction in the cross-sectional area of the reinforcement steel. The reduced diameter of the reinforcement due to continuous corrosion will reduce the bearing capacity of reinforced concrete elements such as beams, columns, and slabs in the market, both under tensile and compressive stresses.

3.2.1 Carbonation Testing

The carbonation occurring is diffusion carbonation, where CO_2 from the air penetrates the pores of the concrete and reacts with the calcium hydroxide present in it. This reaction occurs uniformly throughout the concrete structure, leading to a decrease in the pH of the concrete around the carbonation zone. Consequently, the concrete loses its alkaline properties and becomes more acidic, thereby increasing the risk of corrosion to the steel reinforcement.

The results of carbonation testing on concrete samples are depicted in Figure 6. The figure illustrates a noticeable difference in the surface color of two types of samples from different sources. Concrete chip samples from the location of Dande Dandere Market, Tanakeke Islands, exhibited no color change after being sprayed with phenolphthalein solution. This result suggesteds an increase in calcium carbonate content on the surface of these concrete chips, shifting the pH of the reinforced concrete from alkaline to acidic conditions. In contrast, the reference sample used in this test, a laboratory core drill specimen with concrete, remained alkaline. Upon spraying with phenolphthalein solution, it immediately changed color to pink or purple. Similarly, direct spraying of the same solution on the surface of a peeled column structural element showed no color change, indicating that the reinforced concrete had undergone carbonation.

Further testing was also conducted on concrete powder samples using XRF (X-Ray Fluorescence) equipment in the UNHAS Faculty of Mathematics and Natural Sciences Laboratory, which can analyze the composition of elements and oxide compounds. The test results indicated that the average Calcium Oxide (CaO) content formed from the two samples was 42.80%, classified as very high as it exceeded the Silica Oxide (SiO_2) content of 37.32%, which was a determinant of concrete strength.

3.2.2 Strength Testing

In the case of the low strength of concrete on the low lods table samples, issues arose during the preparation of the compression test specimen. Chunks of debris from the reinforced concrete low lods table samples were formed into 5×5×5 cm^3 cubes using a concrete cutter. However, precise shapes and sizes were not obtained as expected due to damage occurring to the sides or edges of the cubes during the cutting process, as shown in Figure 4. During compressive strength testing with a Compression Testing Machine performed on one of the test specimens that managed to be formed into a cube, no compressive strength results were obtained. The sample immediately cracked soon after the test started. This result indicated that the compressive strength of the concrete in the market was already very low compared to the planned concrete quality of 24.90 MPa.

The Paving Block samples obtained from the site were first cut to form 5×5×5 cm^3 sizes to conform to the

Figure 7 Compression strength testing of paving blocks sample (left) and testing aparatus (right)

standard size for compressive strength test specimens. The testing of Paving Block samples is shown in Figure 7. The average compressive strength test result of five 5×5×5 cm^{-3} cube specimens obtained a value of 11.45 MPa, which was only about 46% of the planned strength of 24.90 MPa. Similarly, the relative density of concrete, determined by weighing the test specimens in dry conditions, was obtained at 2.29 grams cm^{-3}. This result represented a decrease of 4.6% from the weight of the paving block, which commonly exceeded 2.4 grams cm^{-1}.

3.2.3 Degradation Testing

The results obtained from testing four reinforcement bars with an initial diameter of 12 mm revealed an average weight reduction of 62.70% over six years. This result corresponded to an average weight loss of 0.103 grams per day or a reduction in the diameter of the reinforcement bars by 2.0 µm per day over the six years. Considering that the reinforcement bars served as components for both compression and tension reinforcement in reinforced concrete, such rapid dimensional reduction (from a diameter of 12 mm to approximately 7.33 mm over approximately six years), it can be inferred that the structural integrity of the market building was significantly decreased. This degradation was attributed not only to the deterioration of concrete material but also to the reduction in diameter and quality of the reinforcement bars.

4 DISCUSSION

Several factors can contribute to the low quality of structural concrete, including failure to meet the physical and chemical quality of constituent materials, inappropriate composition of all materials not in accordance with the expected quality, and methods of mixing and handling concrete during early-age maintenance that do not comply with industry standards. The main indicators of good concrete quality, reflecting planned quality, are typically observed in the compressive strength test results at a certain age (usually above 28 days) of test specimens taken during casting. When the quality of concrete reaches only 46% of the planned quality, it may be attributed to one or several factors mentioned above. Considering the location of the market, built on the beach of one of the islands in Takalar Regency obtaining materials may be challenging, leading to the potential use of local aggregate materials (sand and gravel) of poor quality. Moreover, bringing aggregate materials through boat crossings could expose them to seawater contamination during transportation. In addition to aggregate quality, low concrete quality can also result from the use of mixing water containing salt compounds which can hinder the cement hydration process. Despite using clean water with neutral pH during the construction, poor workmanship, by excessive water usage for improved workability can lead to high concrete porosity and poor water resistance, as noted in the previous study (Wibowo et al., 2020).

Previous studies (Siregar and Atur, 2006; F, 2007) indicated that in aggressive environments like coastal areas, seawater, or water vapor containing salt ions, chlorides, and sulfates can easily penetrat the pores of porous concrete layers. Subsequently, a highly complex chemical reaction occurs with calcium hydroxide ($Ca(OH)_2$) which is expansive in nature. This reaction leads to the growth of new material inside the concrete pores, known as ettringite (Calcium Aluminate Sulfate, $Ca_4Al_6O_{16}S$). Ettringite formation results in a volume expansion, exerting pressure, within the concrete. This pressure causes tension within the concrete, leading to surface cracking, followed by concrete cover cracking and spalling, ultimately initiating corrosion of the reinforcement.

In the mechanical review presented in Table 1, the very low compressive strength of concrete diminishes its

Table 1. Comparing the actual and standard conditions

Aspect	Actual Conditions	Standard Conditions
Compressive Strength of Concrete	Very low, reducing the ability to withstand pressure from its own weight or dead loads above	Sufficiently high to withstand pressure from its own weight and dead loads with an adequate safety margin (ASTM C39/C39M)
Spalling Mechanism	Occurs more rapidly on the lower side of cantilever slabs due to pressure mechanism	Should not occur if the concrete has adequate compressive strength and is properly protected (ACI 301-16)
Response to Load	The slab bends downward, experiencing tension on the upper side and compression on the lower side, leading to compression cracking or crushing and spalling	The structure should remain stable under load without significant deformation, preventing cracking or spalling (SNI 1727:2020)
Durability of Components	Upper tie beam components also experience similar degradation mechanisms	All components should maintain structural integrity over time without such degradation (SNI 2847:2019)

ability to withstand pressure from its own weight or dead loads above it. Typically, the spalling observed is influenced by the pressure mechanism acting on the cross-section side of the stressed component. In cantilever slabs, spalling tends to occur more rapidly on the lower side. This phenomenon occurs due to the weight of the slab itself, causing it to bend downward. As a result, its upper side experiences tension, while its lower side experiences compression. The compressed side of the slab may undergo compression cracking or crushing, eventually leading to spalling. This mechanism is also observed in upper tie beam components.

The occurrence of vertical cracks and peeling of column covers is also attributed to the pressure mechanism acting on the column. Under the compressive force from the load above it, the column tends to shorten or even bend. When the entire cross-section of the column experiences uniform compression, the concrete cover becomes the weakest part, while the core part, restrained by reinforcements, is stronger. In cases where the concrete compressive strength is low, the unrestrained concrete cover section cannot withstand significant compressive strains, resulting in cracking and expansion, ultimately leading to earlier spalling. Similarly, when the columns have undergone flexural bending, certain surface sides of the column bear greater compressive strains, characterized by crack expansion in the compressed area, eventually leading to spalling.

Based on these findings, we recommend the demolition of this building and its replacement with more efficient and effective materials suitable for coastal locations. According to Kuzman and Grošelj (2012), processed timber construction emerges as the top priority among various construction types, followed by solid timber construction, concrete construction, brick construction, and steel construction. Timber buildings offer numerous advantages, including comfort, attractiveness, versatility, affordability, ease of construction, low cost, durability, and environmental safety (Kozak and Cohen, 1999). Timber has been utilized for various constructions due to its ease of shaping, structural strength, and suitability for various applications (Joseph and Tretsiakova-McNally, 2010). Moreover, a natural understanding of timber building materials combined with traditional skills can result in a structurally robust and environmentally savvy buildings (Rifai, 2010), making it easier for coastal communities to work with and oversee structural work using wooden materials. Additionally, timber's vulnerability to the influence of coastal environments can be mitigated, as microbial decay can be inhibited by exposure to saltwater, making wood a more environmentally friendly choice for coastal buildings (Treu et al., 2019).

5 CONCLUSION

The condition of the Dande Dandere Market Building, located in Maccini Baji Village, Tanakeke Islands District, Takalar Regency, South Sulawesi, which was constructed seven years ago, is severely deteriorated. It is characterized by extensive cracks and swelling of concrete, widespread spalling of the concrete covers, corrosion, and easily fraying reinforcement bars. The structural quality of the concrete only reaches 46% of the planned quality. Detailed identification of the upper structure's reinforcement steel has revealed progressive corrosion, marked by a reduction in diameter of 2.0 μm per day over time. Given these conditions, reinforcing the structure is challenging due to the comprehensive degradation of structural elements. Repairs are necessary, from reinforcing the foundation to upper building elements. However, pursuing rehabilitation would entail costs exceeding those of new construction. Reinforcing the structure with encased foundations, columns, and beams with new concrete or with Fiber Reinforced Polymer fails to provide adequate strength recovery due to the extremely poor concrete quality and corroded reinforcement bars. These costs may even surpass the initial construction budget. If the building were to be reconstructed using reinforced concrete, waterproof and durable concrete is imperative. Alternatively, if steel is chosen, it is advisable to use steel with thicker anti-corrosion coatings. However, we strongly recommend using timber materials due to their cost-effectiveness, ease of implementation, supervision by coastal communities, and environmental friendliness, making timber structural elements more suitable for buildings in the coastal region.

DISCLAIMER

The authors declare no conflict of interest.

ACKNOWLEDGMENTS

We would like to express our sincere gratitude to Zentaro Furukawa, Associate Professor Faculty of Environmental and Life Science, Okayama University, for their invaluable guidance and support throughout this research project. Their expertise and insightful feedback greatly contributed to the quality and success of this study.

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