

Assessment of Remaining Service Life Prediction and Bridge Rehabilitation Recommendations Using Bridge Management System and Phenolphthalein (C₂₀H₁₄O₄) (A Case Study: Cimanuk Maktal Bridge, Garut, West Java)

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Abstract

Bridge infrastructure in every region faces the risk of sudden collapse, which may result in casualties as well as reduced productivity and economic growth if not accompanied by proper maintenance management and systematic service life handling. This study aims to predict the remaining service life and comprehensively evaluate the structural condition of bridges. The prediction of the remaining service life was carried out through carbonation testing using phenolphthalein (C₂₀H₁₄O₄) as an indicator, while damage mapping was conducted using Infrared Thermographic (IRT) inspection within the Bridge Management System (BMS). The carbonation test was employed to identify the potential for early corrosion and material degradation by spraying phenolphthalein solution on core-drilled concrete samples to measure carbonation depth and pH values. IRT inspection was applied as a non-destructive method to detect internal damage that is not visible to the naked eye. The study was conducted on two lanes of the Cimanuk Maktal Bridge in Garut Regency, with testing points at A1, A2, AB1, AB2, PL1, and P1. The results indicate that points A1 (23.04 mm), A2 (33.39 mm), AB1 (1.347 mm), and PL1 (0.672 mm) have pH \geq 10, showing alkaline conditions with normal carbonation. However, points P1 (26.58 mm) and AB2 (1.656 mm) recorded pH values of 6.8 and 7.5, indicating accelerated carbonation and increased risk of reinforcement corrosion. The BMS analysis shows that Bridge I has a Condition Rating (CR) of 3 with a remaining service life of 8 years and 8 months, and is therefore recommended for rehabilitation, while Bridge II has a CR of 2 with a remaining service life of 18 years and 9 months, requiring routine maintenance. This approach demonstrates significant potential to be widely adopted in bridge infrastructure asset management across Indonesia.

Keywords: Bridge Management System, Nilai Kondisi, Phenolphthalein, Infrared Thermographic

1. INTRODUCTION

The service life of a bridge is not solely influenced by the length of time since it was constructed and subjected to service loads, but also depends on its existing condition, including visually observed damages. Such damages generally result from the deterioration of material quality due to environmental factors, loads exceeding the design capacity, or impact loading such as collisions with the bridge structure [1]. Over time, the performance of many bridges tends to decline, which in turn increases the need for maintenance, rehabilitation, and replacement. Therefore, proper management efforts in the form of accurate and effective bridge condition inspections are required [2]. Bridge inspection activities are carried out to ensure that the bridge remains safe for road users, while also safeguarding the asset value of the bridge itself. These inspections involve collecting physical and structural condition data, which serve as the basis for determining the appropriate actions maintenance, repair, strengthening, or replacement through the application of the Bridge Management System (BMS) [3]. Challenges such as corrosion and other forms of deterioration can significantly affect performance

and disrupt the functionality of bridges. To address these challenges, a bridge management system is required to ensure the implementation of optimal actions and strategies. Comparisons are often made to evaluate the advantages and disadvantages of different approaches. The BMS methodology adopts a hierarchical system, taking into account the level of damage to each element and applying condition ratings to determine the final score, including the weighting of element importance. Weighting element importance is valuable for determining the overall condition rating, as it prioritizes damage in critical elements during analysis. However, damages occurring in secondary or supporting elements must also be considered, since neglecting them may eventually lead to more severe structural problems if left unaddressed [4].

2. THEORETICAL BACKGROUND

2.1 Bridge Management System (BMS)

The Bridge Management System (BMS) is a bridge management framework implemented by the Directorate General of Highways (Direktorat Jenderal Bina Marga). The primary functions of BMS are to plan implementation activities and to monitor the condition of bridges. The process of bridge inventory using BMS can be organized systematically through periodic investigations and the analysis of data using computerized information systems. In the inspection and assessment of bridge elements under BMS, three levels of evaluation are applied to determine whether a bridge requires routine/periodic maintenance, rehabilitation, or replacement. These categories are based on the coding and evaluation of element damages. The assessment considers the degree of structural deterioration, the extent of damage, functionality, and its overall impact on the bridge [5].

2.2 of Bridge Remaining Service Life Using the Bridge Management System (BMS)

The remaining service life of a bridge is influenced by its condition, while the condition itself is determined by the extent of structural damage. Bridge performance gradually declines over time as it continues to carry traffic loads, which means that as the bridge ages, the demand for proper intervention increases. Therefore, it is essential to conduct an analysis of the bridge's age and remaining service life by referring to the Guidelines for Bridge Preservation Management issued by the Directorate General of Highways (Dirjen Bina Marga), using the following equation [6]:

$$NK = 5 \left\{ \frac{100 - \frac{Y}{N\%}}{a} \right\}^{\frac{1}{b}}$$

Dimana:

NK = Condition

Rating Y = Bridge Age

N = Design Service Life

a = Coefficient (4,66)

b = Coefficient (1,9051)

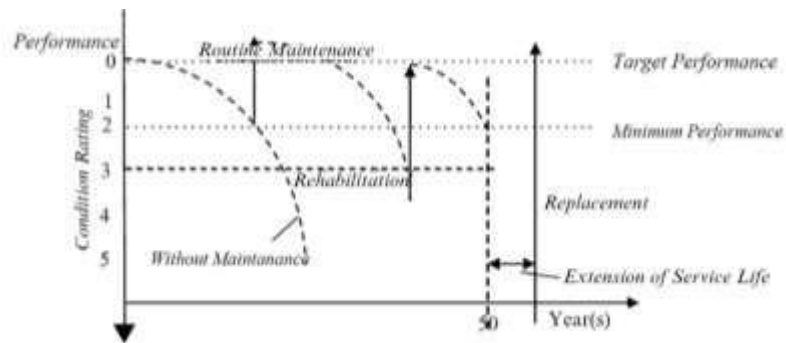


Figure 1. Bridge Remaining Service Life Diagram

Bridge Preservation Management Guidelines, Directorate General of Highways: ISBN 978-602-97229-3-2

3. RESEARCH METODOLOGY

The research methodology applied in this study consists of several stages. The first stage was the collection of samples at the study site, followed by testing the concrete condition of the bridge and capturing infrared thermographic images. The final stage of the research involved BMS analysis to evaluate the prediction of the bridge's remaining service life [7]. In summary, the research methodology employed is illustrated in Figure 2.



Figure 2. Research Methodology

3.1 Research Location

The study was conducted at the Cimanuk Maktal Bridge, Garut Regency, West Java Province. The observation



Figure 3. Research Location

3.2 Research Object

Table 1. Specifications and Dimensions of the Maktal Bridge, Garut Regency

No	Specifications and Dimensions (Maktal Bridge)	Bridge I (Asphalt Pavement)	Bridge II (Rigid Pavement)
1	Bridge Length	36,80 m	40,80 m
2	Bridge Width	11,00 m	9,00 m
3	Year of Construction	1825	2016
4	Service Life	50 Years	50 Years
5	Traffic Lane Width	8,00 m (2 x 4,00) m	7,00 m (2 x 3,50) m
6	Sidewalk Width	2 x 1,5 m	2 x 1,0 m
7	Girder Type	Precast Prestressed Concrete – Type I 40, Segmental	Precast Prestressed Concrete – Type I 40, Segmental
8	Pavement Type	AC-WC	Beton $f_c' 35 MPa$
9	Traffic Signs Availability	Tidak	Ya
10	Crossing Type	Sungai	Sungai

Sumber : Bidang Bina Marga PUPR Kabupaten Garut

4. RESULTS AND DISCUSSION

4.1 Concrete Carbonation Test Using Phenolphthalein Solution (C₂₀H₁₄O₄)

In principle, concrete in construction possesses a strong structural capacity. However, this does not guarantee that concrete cannot deteriorate. In general, concrete damage caused by acidic chemical attacks may occur due to several factors such as carbonation, decalcification, and the influence of water quality. Carbonation reduces the alkalinity of concrete; when carbonation penetrates beyond the concrete cover, the protective effect of the concrete on the embedded reinforcing steel is lost, and the steel bars begin to corrode when exposed to water and air. Therefore, carbonation poses a risk of shortening the service life of concrete structures with respect to the remaining service life of the bridge [10]. The duration of the carbonation process until it reaches the steel reinforcement can be calculated using the following equation:

$$t = \left(\frac{d}{k}\right)^2$$

t = time of the carbonation process until it reaches the reinforcing steel

d = concrete cover thickness

k = permeability

Table 2. Correlation Between Concrete Strength and Permeability

Concrete Strength (MPa)	Permeability
15	17
20	10
25	6
30	5
35	4
40	3,5

Source: *Guidebook on non-destructive testing of concrete structures, International Atomic Energy*

The purpose of the carbonation test is to determine whether the concrete cover still protects the reinforcing steel embedded within. The carbonation process neutralizes the alkaline condition of concrete. If the entire concrete cover becomes carbonated down to the reinforcing steel, the steel reinforcement will begin to corrode as soon as moisture and oxygen reach the bars.

Equipment and materials used for the carbonation test are very simple, namely:

- Concrete obtained from core drilling.
- 1% phenolphthalein solution prepared by mixing phenolphthalein with 90 cc ethanol and then adding deionized/clean water to reach a total volume of 100 cc.

Calculation of carbonation depth:

$$C = \frac{y^{\frac{1}{2}}R(4.6x - 1.76)}{\sqrt{7.2}}$$

Calculation of bridge remaining service life :

$$y = \frac{7.2}{R^2(4.6x - 1.76)^2} C^2$$

x = water–cement ratio (W/C)

C = carbonation depth

R = constant depending on a (a constant related to the concrete's exposure environment) and b (finishing/coating of the concrete)

a = 1.7 for indoor concrete, and 1.0 for outdoor concrete, values taken from Table 3.

Table 3. Correlation Between Concrete Surface Finishing Condition and Permeability

Finished Condition	Indoor	Outdoor
No Layer	1.7	1.0
Plaster	0.79	-
Mortar + Plaster	0.41	-
Mortar	0.29	0.28
Mortar + Paint	0.15	-
Tiles	0.21	0.07
Paint	0.57	0.8

Source : The Japanese Ministry Construction Publications “Engineering for improving the durability of reinforced concrete structure)

4.2 Results of Concrete Carbonation Test Using Phenolphthalein (C₂₀H₁₄O₄)

4.3 In the carbonation test of concrete, areas that remain in good condition (still alkaline) will turn pink/purple, whereas areas that have undergone carbonation, with a pH lower than 8 (acidic), will show no color change



Figure 4. Sampel 1 - A1
(Cimanuk Maktal Bridge I)

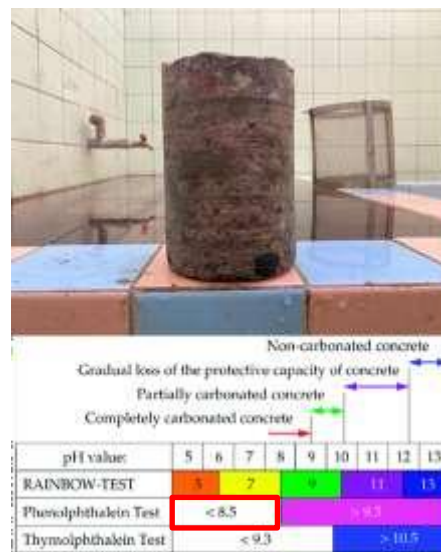


Figure 5. Sampel 2 - P1
(Cimanuk Maktal Bridge I)



Figure 6. Sampel 3 – A2
(Cimanuk Maktal Bridge I)

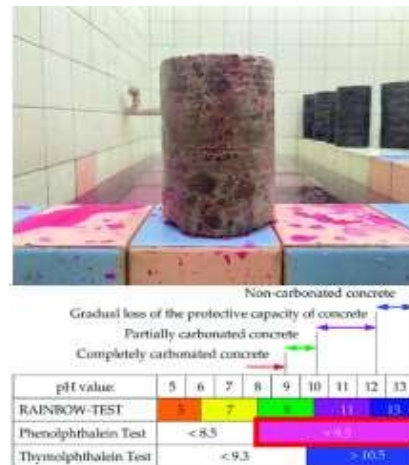


Figure 7. Sampel 4 – AB1
(Cimanuk Maktal Bridge II)

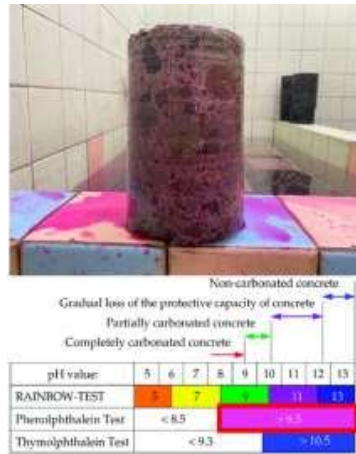


Figure 8. Sampel 5 – PL1
(Cimanuk Maktal Bridge II)

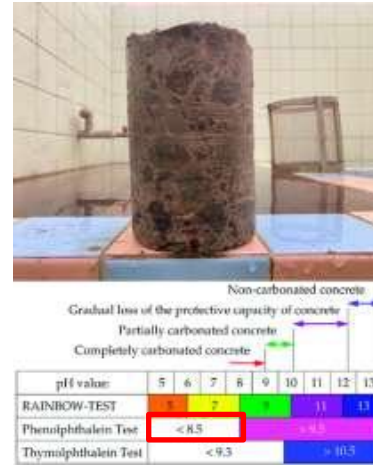


Figure 9. Sampel 5 – AB2
(Cimanuk Maktal Bridge II)

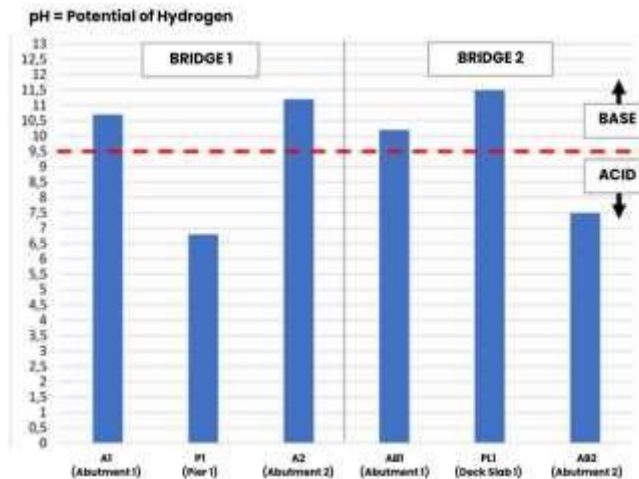


Figure 10. Diagram of Carbonation Test Results Using Phenolphthalein (C₂₀H₁₄O₄)

Based on Figure 10, the results of the carbonation test using Phenolphthalein (C₂₀H₁₄O₄) on the Cimanuk Maktal I Bridge, Garut Regency, show that section A1 (Abutment) has a pH value of 10.7 – Alkaline, P1 (Pier) has a pH value of 6.8 – Acidic, and A2 (Abutment) has a pH value of 11.2 – Alkaline. For the Cimanuk Maktal II Bridge, Garut Regency, section AB1 (Abutment) has a pH value of 10.2 – Alkaline, PL1 (Deck Slab) has a pH value of 11.5 – Alkaline, and AB2 (Abutment) has a pH value of 7.5 – Acidic. It can be concluded that section P1 (Pier) with a pH value of 6.8 on the Cimanuk Maktal I Bridge and section AB2 (Abutment) with a pH value of 7.5 on the Cimanuk Maktal II Bridge have concrete that is contaminated by an acidic environment

Table 4. Calculation of Carbonation Duration Using Phenolphthalein (C₂₀H₁₄O₄)

No	Location	Structure Elements	Carbonation Value	Bridge Age	Remaining Service Life
1	Cimanuk Maktal Garut, West Java	Bridge I Abutment (A1)	23,04 mm	+/- 200 years	
		Pilar (P1)	26,58 mm	+/- 200 years	8 years 8 months
		Abutment (A2)	33,39 mm	+/- 200 years	
2	Cimanuk Maktal Garut, West Java	Bridge II Abutment (AB1)	1,347 mm	+/- 9 years	
		Deck Slab (PL1)	0,672 mm	+/- 9 years	18 years 10 months
		Abutment (AB2)	1,656 mm	+/- 9 years	

4.4 Results of Inspection and Condition Assessment of the Bridge Using the Bridge Management System (BMS)

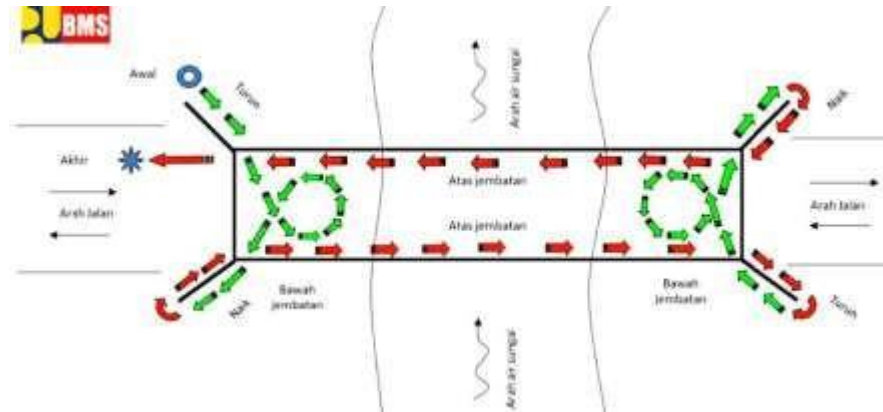


Figure 11. Typical Flow of Bridge Inspection

Source: Bridge Inspection Guidelines No. 01/P/Bm/2022, Directorate General of Highways PUPR.

Table 5. Technical Screening of Cimanuk Maktal I Bridge (Asphalt Pavement)

Nilai	Kriteria	Nilai Kondisi
Structure (S)	Hazardous	1
Damage (R)	Moderately Severe	1
Quantity (K)	Less than 50%	0
Function (F)	Element still functioning	0
Impact (P)	Affects other elements	1
Condition Value (NK)	(NK = S+R+K+F+P)	3

Table 6. Condition Assessment of Cimanuk Maktal I Bridge (Asphalt Pavement)

Nilai	Condition
0	Bridge/element in good condition and without damage
1	Bridge/element with minor damage, requiring only routine maintenance
2	Bridge/element with damage requiring monitoring and periodic maintenance
3	Bridge/element with damage that structurally requires immediate action
4	Bridge/element in critical condition
5	Bridge/element non-functional or collapsed

Table 7. Condition Rating Categories of Cimanuk Maktal I Bridge (Asphalt Pavement)

Condition Value	Category	Penanganan Indikatif
0 - 2	Good to Minor Damage	Routine / Periodic Maintenance
3	Severe Damage	Rehabilitation
4 - 5	Critical or Collapsed	Replacement

Source: Bridge Management System (BMS) No. 17/SE/Db/2017, Directorate General of Highways PUPR.

Table 8. Technical Screening of Cimanuk Maktal II Bridge (Rigid Pavement)

Nilai	Kriteria	Nilai Kondisi
Struktur (S)	Berbahaya	0
Kerusakan (R)	Cukup Parah	1
Kuantitas (K)	Kurang dari 50%	0
Fungsi (F)	Elemen masih berfungsi	0
Pengaruh (P)	Mempengaruhi elemen lain	1
Nilai Kondisi (NK)	(NK = S+R+K+F+P)	2

Table 9. Condition Assessment of Cimanuk Maktal II Bridge (Rigid Pavement)

Nilai	Condition
0	Bridge/element in good condition and without damage
1	Bridge/element with minor damage, requiring only routine maintenance
2	Bridge/element with damage requiring monitoring and periodic maintenance
3	Bridge/element with damage that structurally requires immediate action
4	Bridge/element in critical condition
5	Bridge/element non-functional or collapsed

Table 10. Condition Rating Categories of Cimanuk Maktal II Bridge (Rigid Pavement)

Nilai Kondisi	Kategori	Penanganan Indikatif
0 - 2	Good to Minor Damage	Routine / Periodic Maintenance
3	Severe Damage	Rehabilitation
4 - 5	Critical or Collapsed	Replacement

Source: Bridge Management System (BMS) No. 17/SE/Db/2017, Directorate General of Highways PUPR.

4.4 Calculation of Bridge Remaining Service Life Using the Bridge Management System (BMS)

4.4.1 Remaining Service Life of Cimanuk Maktal I Bridge (Asphalt Pavement)

$$\begin{aligned}
 NK &= 5 \left\{ \frac{100 - \frac{Y}{N\%}}{a} \right\}^{\frac{1}{b}} \\
 3 &= 5 \left\{ \frac{100 - \frac{Y}{50\%}}{4,66} \right\}^{\frac{1}{1,9051}} \\
 \left\{ \frac{100 - \frac{Y}{50\%}}{4,66} \right\}^{0,525} &= 5 - 3 \\
 \left\{ 100 - \frac{Y}{50\%} \right\}^{0,525} &= 2 \times 4,66^{0,525} \\
 \left\{ 100 - \frac{Y}{50\%} \right\} &= \sqrt[0,525]{4,4867} \\
 100 - 17,44 &= \frac{Y}{50\%} = 41,28 = 41 \text{ years } 3 \text{ months}
 \end{aligned}$$

Based on the calculation results using the Bridge Management System (BMS) method, the remaining service life of the Cimanuk Maktal I Bridge (Asphalt Pavement) with a Condition Value of 3 is obtained as follows: 50 years (design life) – 41.28 years = 8.72 years. Therefore, the remaining service life of Bridge I is 8 years and 8 months.

4.4.2 Remaining Service Life of Cimanuk Maktal II Bridge (Concrete Pavement))

$$NK = 5 \left\{ \frac{100 - \frac{Y}{N\%}}{a} \right\}^{\frac{1}{b}}$$

$$2 = 5 \left\{ \frac{100 - \frac{Y}{50\%}}{4,66} \right\}^{\frac{1}{1,9051}}$$

$$\left\{ \frac{100 - \frac{Y}{50\%}}{4,66} \right\}^{0,525} = 5 - 2$$

$$\left\{ 100 - \frac{Y}{50\%} \right\}^{0,525} = 3 \times 4,66^{0,525}$$

$$\left\{ 100 - \frac{Y}{50\%} \right\} = \sqrt[0,525]{6,7301}$$

$$100 - 37,773 = \frac{Y}{50\%} = 31,11 = 31 \text{ years } 1 \text{ months}$$

Based on the calculation results using the Bridge Management System (BMS) method, the remaining service life of the Cimanuk Maktal II Bridge (Concrete Pavement) with a Condition Value of 2 is obtained as follows: 50 years (design life) – 31.11 years = 18.89 years. Therefore, the remaining service life of Bridge II is 18 years and 10 months

4. CONCLUSION

This study demonstrates that the integration of the Bridge Management System (BMS) with carbonation testing provides a more comprehensive overview of bridge conditions. The findings reveal that:

1. The carbonation test using the phenolphthalein indicator ($C_{20}H_{14}O_4$) showed carbonation penetration of 23.04 mm (A1), 33.39 mm (A2), 1.347 mm (AB1), and 0.672 mm (PL1) in concrete with $pH \geq 10$ (alkaline), indicating normal carbonation penetration. In contrast, penetration of 26.58 mm (P1) and 1.656 mm (AB2) at pH 6.8 and pH 7.5 indicates accelerated carbonation, as the decrease in pH increases the risk of reinforcement exposure to corrosive environments.
2. Bridge I requires rehabilitation, with a remaining service life of 8 years and 8 months ($CV = 3$).
3. Bridge II requires routine maintenance, with a remaining service life of 18 years and 9 months ($CV = 2$).
4. Several structural elements experienced carbonation that reduced the pH to acidic levels, indicating a risk of steel reinforcement corrosion.
5. The novelty of this research lies in the integration of the BMS method with carbonation testing and Infrared Thermographic technology within a single bridge condition assessment system. This approach has not yet been widely applied in Indonesia and may serve as a new model for more comprehensive bridge evaluation.

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