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Evaluation Of The Condition Of Engineering Structures On The Bafoussam–Makenene Section Of National Road N°4 In Cameroon Using Non-Destructive Techniques

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Abstract
The objective of this study is to evaluate the condition of engineering structures throughout their service life, in order to establish a necessary diagnosis for decision-making and to determine appropriate maintenance strategies. The methodology employed involves structural auscultation using non-destructive tests, which provide insight into the key physical degradation phenomena and the current behavior of the structure. Results indicate that the concrete remains in good condition despite exposure to various weather conditions. It was concluded that as compressive strength increases, carbonation depth decreases. The correlations are linear and range between 0.7332 < R^2 < 0.9663. Additionally, a review of structural condition assessment methods for various types of degradation was carried out. Given that the concept of a perfectly durable structure is unrealistic due to insufficient maintenance and accelerated degradation processes caused by numerous uncontrollable factors, our structures suffer from deteriorations that compromise their safety and lifespan. To extend or even maintain the service life of engineering structures, repair and maintenance interventions are inevitable.
Keywords: *Condition; Engineering Structure; Auscultation; Non-Destructive*

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I. Introduction

The first reinforced concrete bridge constructions date back to the late 19th century. However, the technique of reinforced concrete shows limitations when it comes to constructing structures with long spans. To address this, Eugene Freyssinet introduced prestressed concrete in 1907. Despite this innovative technique, structures still suffer from degradation, the severity of which remains difficult to quantify. Ensuring the safe use of engineering structures requires determining the condition of the structure and predicting its evolution. In terms of real-time monitoring, structure managers often have limited tools at their disposal (Sétra, 2006). Controlling the degradation of concrete engineering structures presents both an economic and technological challenge. Indeed, inspection operations require complex technical means and highly qualified personnel to analyze the resulting reports. Auscultation is defined as the set of specific examinations and measurements, often using advanced techniques, aimed at gaining deeper knowledge of the actual condition of a structure. It complements detailed visual inspections and helps assess the quality of materials in place, as well as the current mechanical behavior of the structure. Auscultation techniques vary depending on the nature of observed defects, and choices are guided by assumptions about probable causes (Sétra, 2010). The tools used to assess structural behavior are also diverse. The general objective of auscultation is twofold: material auscultation (identification, degradation state, material properties) and structural auscultation (mechanical condition, load response, global and local behavior).

II. Literature Review

Ngoc Tan Nguyen (2014) studied the non-destructive evaluation of reinforced concrete structures based on spatial variability and the combination of techniques. A scientific approach was therefore considered to reduce these budgets by setting up tools aimed at optimizing and improving the reliability of the structural diagnosis of structures. Non-destructive testing (NDT) methods are one of the suitable avenues. For Ngoc Tan Nguyen (2014), these techniques rely on well-known physical principles, and service companies now commonly offer their use, but many obstacles remain. The aim of Ngoc Tan Nguyen's (2014) work was to analyze the variability resulting from NDT in order to then trace back to the spatial variability of concrete in real conditions; to study the sensitivity of NDT techniques in evaluating these two durability indicators as well as their impact on the variability of NDT measurements; and to determine the minimum number of measurements necessary for a desired confidence level. In this context, Ngoc Tan Nguyen (2014) addressed the current state of knowledge and needs in terms of NDT development and in-situ diagnosis methodologies. He conducted an experimental study of concrete variability (description of the NDT techniques used, the test site and studied concretes, the measurement protocol, procedures for analyzing local and spatial variability, as well as different approaches for combining NDT techniques). He also studied the experimental effect of carbonation and humidity gradients on NDT measurements. Ngoc Tan Nguyen's (2014) research was carried out within the framework of the EvaDéOS project. From his work, it emerges that, in the case of tests on the test site, the SonReb method allows a global mean estimation with good precision. However, it is impossible to assess another property such as moisture without integrating an electrical or electromagnetic NDT technique. The test from the first measurement campaign showed that it is possible to take it as a reference (e.g., the 28-day measurement). This allows for an initial calibration to be used in a new measurement campaign for regular monitoring of the structure. Combining with the multiple regression method with non-linear forms showed good efficiency in estimating the mechanical strength and water content of the studied concretes. Ngoc Tan Nguyen (2014) states that, in the case of the Marly bridge piles, without any model calibration, the root mean square error can vary from 2.3 to 21 MPa for mechanical strength. For the author, it is therefore necessary to carry out model calibration based on a minimum number of samples. During the calibration of these models, the effect of the number of samples used was analyzed. According to Ngoc Tan Nguyen (2014), a calibration based on three specimens presenting extreme measured values (maximum, minimum, intermediate) of concrete compressive strength seems to be an interesting option for model calibration. The root mean square error of strength can decrease by about 4 MPa when using three specimens instead of one. At present, model calibration aims to obtain the best estimation of the average value of the properties of interest (e.g., compressive strength, water content). Moreover, for the author, the spatial variability of properties has not yet been integrated as a cost function in the calibration process. The comparative study between different combination approaches shows that the SonReb method alone only allows for evaluation of the average mechanical strength. Finally, Ngoc Tan Nguyen (2014) shows that taking uncertainties into account in the inversion process using Monte Carlo simulation and the Bayesian combination operator allows, in addition to evaluating the mean, the variability, and accounting for uncertainty related to local variability.

ITMAIZEH Ehab (2016) focused his work on the pathology of reinforced concrete structures. Reinforced concrete structures are often weakened by the pathologies that affect them during their lifetime. The reason is that the environment is generally not taken into consideration. The pathology that affects concrete, especially those classified as dangerous, is the cause of its collapse if ignored. To avoid reaching this stage, its progression must be slowed down or neutralized as quickly as possible by taking the necessary measures. The work carried out by ITMAIZEH Ehab (2016) deals with diagnosis, which is the essential step in the maintenance process of reinforced concrete structures. This is why great importance was given to this phase. A good diagnosis leads to the right decision so that, if a pathology exists, it can be treated and prevented from spreading to the element and the structure. Diagnosis takes several forms and goes through essential and well-known stages. It has been shown that among the most used diagnostics, non-destructive testing (NDT) is the most recommended for the advantages it offers. It is simple and causes no damage to the element or the structure. In this context, he used, on one hand, destructive methods for structures that could be locally degraded, and on the other hand, non-destructive methods for structures that needed to be preserved, such as buildings classified as historical monuments. ITMAIZEH Ehab (2016) shows that the reinforced concrete structure is not only threatened by the loads applied to it but also by the environment in which it is built. He established a summary table in which he listed the dangerous and less dangerous pathologies. At the same time, he specified for each the diagnostic method and the decision to be taken.

The author highlights the importance of diagnosis in the rehabilitation operation of a structure as well as the different means available to carry it out. It is the key step that determines the types of pathologies affecting the structure and their extent. It also allows forecasts of the evolution of these disorders. But above all, it is the step that will make it possible to implement the most appropriate repair method. For ITMAIZEH Ehab (2016), it is necessary to work on the root cause of the problem to prevent the rapid appearance of similar pathologies.

Table 1 : Summary of Structural Pathologies and Corresponding Diagnosis Methods **Adapted from ITMAIZEH Ehab (2016)**

Pathologies	Causes of pathologies	Analyses		Decision
		Destructives	Non - Destructives	
Carbonation	Reaction of carbon dioxide with cement components influenced by moisture and temperature	Carbonation test (phenolphthalein),	Radar,	Upon seeing these pathologies, immediate intervention and repair are required
Corrosion	Carbonation in concrete and presence of chlorides		Radar,	
Cracks	Causes due to material properties, direct external causes, corrosion of reinforcement		Radar, Schmidt hammer, sonic auscultation, visual inspection	
Large fissures			Visual inspection	
Shrinkage	Evaporation	Core sampling	Visual inspection	
Crazing	Moisture		Visual inspection	Repair of these pathologies can be avoided for now but must be monitored over time and not neglected
Spalling	Grain migration due to poor compaction		Visual inspection	
Lichen growth	Moisture		Visual inspection	
Bleeding	Excess water during concrete mixing		Visual inspection	

III. Materials Et Methodes

To successfully carry out our study, we used the following equipment and tools: a Garmin GPS for taking coordinates and a camera for photography.
Identification forms for different engineering structures.
Inspection forms for different engineering structures.

We also used devices and a solution to conduct non-destructive testing. These different devices and solutions are listed in table 2.

Table 2 : Summary of the main measuring instruments used on engineering structures

Disorders	**Instruments/Solutions**	**Photos Illustrations**	**Characteristics**
Concrete deterioration	Schmidt Hammer		Standard model N Strength [10-70] MPa, dimensions : 330 x 80 x 80 mm, weight 1,5Kg, C0380
	Phenolphthalein		1% Solution
	Digital caliper		

Study Site Location

The study was conducted in the West Region of Cameroon. The project area is defined by the following coordinates:
Latitude : 5° 30' 0 N
Longitude : 10° 40' 0 E

The road segment includes three sections, shown in Table 3:

Table 3 : Sections of the Study Route

Region	Code routes	Type of route	Route	Sections	Length (Km)
OUE	CAMN000406	N4	Makenene - Bafoussam	Pont sur le Ndé – Bangangté	37,50
	CAMN000407			Bangangté – Bandjoun	33,35
	CAMN000408			Bandjoun – Bafoussam	14,05
TOTAL					**84.90**

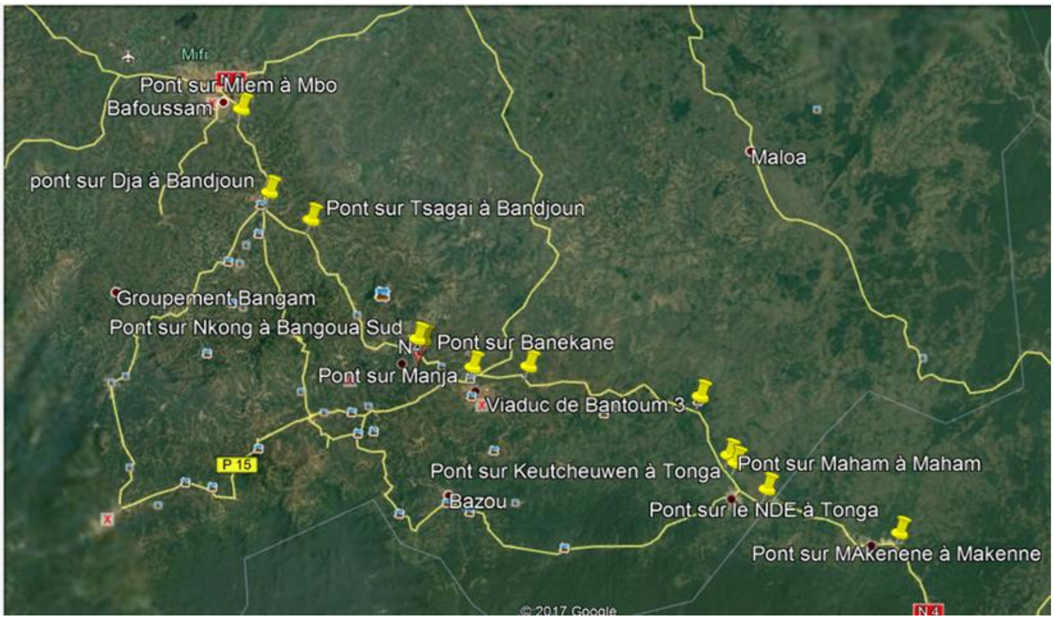


Figure 1 : Location of the different Engineering Structures along the study route

Route Selection

Over forty (40) years old, the crossing structures located along the National Road RN4 were built in the 1980s. This road was initially subject to development works intended to bring it up to standard for a structural road. Since then, aside from rare routine maintenance operations, these structures have not undergone any further development works. Engineering structures such as bridges are designed for a service life approaching one hundred years. During this period, to ensure their functionality, they must be maintained at a consistently acceptable level of service through various maintenance interventions. However, exposed to the combined effects of climate variations, traffic (growth and overloaded axles), and of course, time, these structures exhibit signs of fatigue, cracks, and deformations that worsen due to the lack of specific interventions. This results in damage that could lead to their failure. To prevent such potentially catastrophic failure, this study focuses on the engineering structures located along the Bafoussam–Makenene section (RN4) in Cameroon.

Methods

The first step in effectively analyzing a structure is to determine the causes of the existing damage. This step is often the most important in the repair or maintenance process. It involves gathering all available project-related data. Thus, we designed identification and inspection sheets to collect information on the structures. These sheets highlight information on typology, geometry, characteristics, pavement and structure conditions, deterioration of various structural components, and other potential pathologies affecting engineering structures. The design of these sheets is based on the IQOA procedure developed in the 1990s. It categorizes types of damage to facilitate identification and assessment based on visual inspection, hence the concept of "Engineering Structure Quality Image." Each category addresses the main types of deterioration that may affect specific structural elements such as decks, piers, abutments, equipment, signage, structure heads, and others depending on the structure type.

IV. Results

At the end of this study, the proposed approach ultimately helped us better understand the issue of condition assessment of engineering structures, especially bridges, from the perspective of infrastructure managers.

Table 4 : Measurement of carbonation depth in the structure

Structural element	carbonation Depth H (mm)	Compressive strength R_C (MPa)
Abutment (A2)	15	34
Beam N°3	10	44
H average	**12.5**	**39**
H max	**15**	**44**

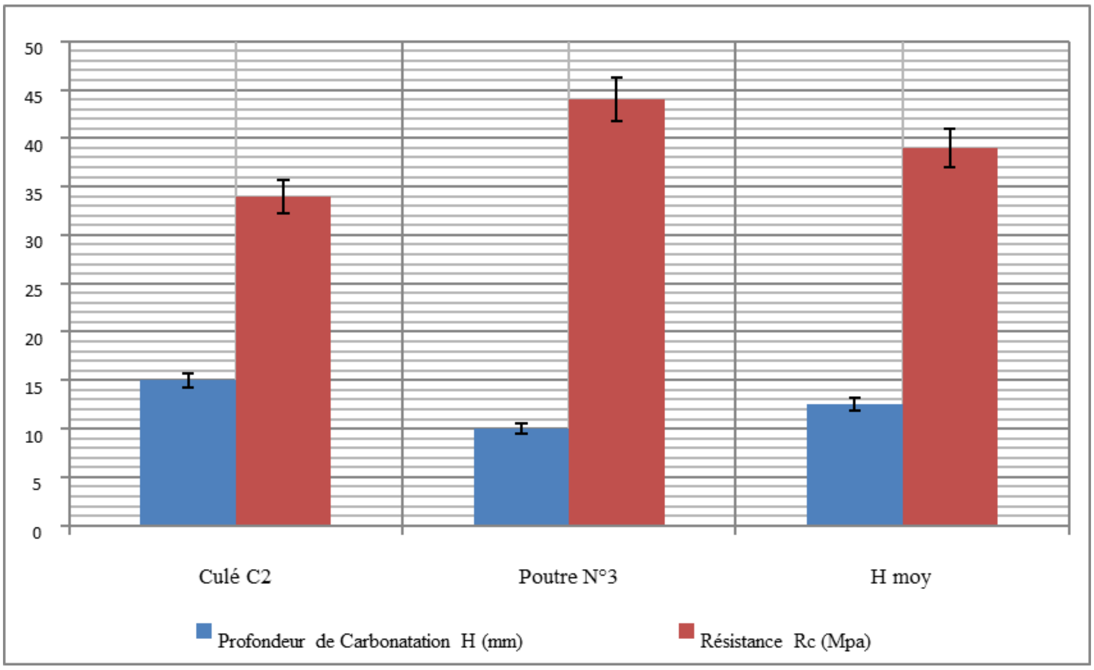


Figure 2 : Histogram of carbonation depths and sclerometric resistances

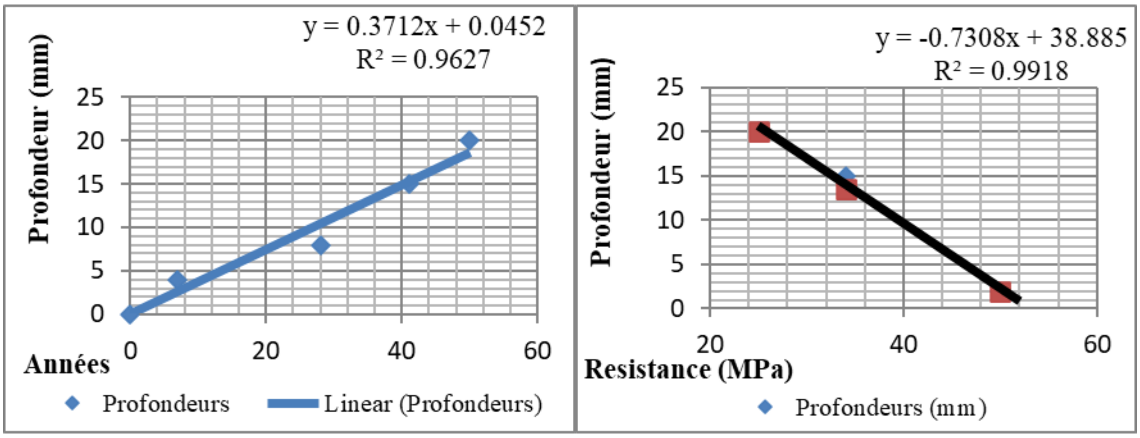


Figure 3 : Regression line of the carbonation depths of abutment C2

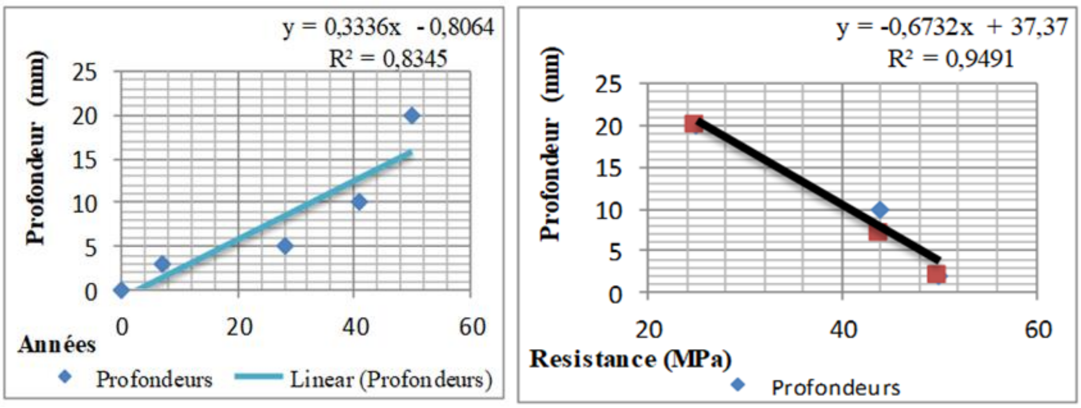


Figure 4 : Regression line of the carbonation depths of beam No. 3

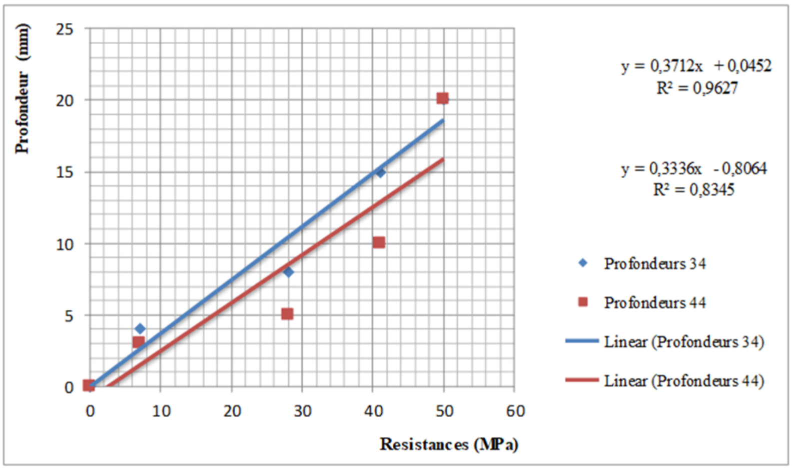


Figure 5 : Correlation between various depths and resistances

Table 5 : Measurement of carbonation depth in the structure

Structural element	Carbonation Depth H(mm)	Compressive strength R_C (MPa)
Abutment (A1)	15	44
Pier N° 2	14	38
Beam N°4	10	43
H average	**13**	**41.66**
H max	**15**	**44**

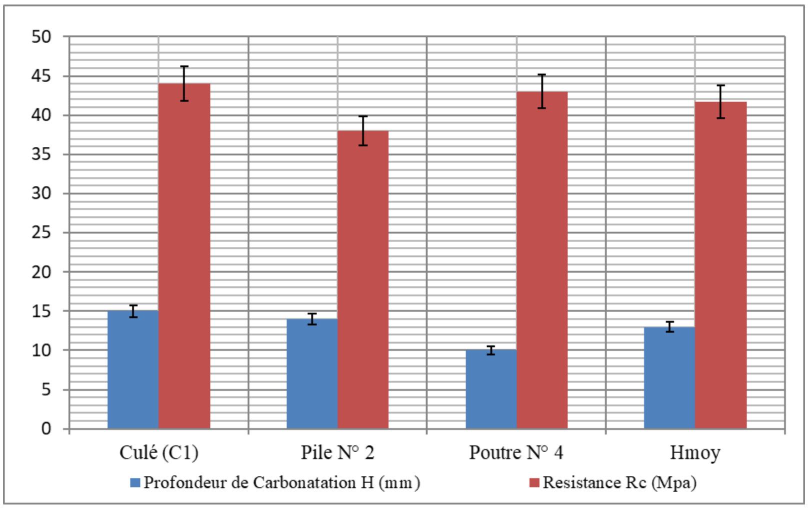


Figure 6 : Histogram of carbonation depths and sclerometric resistances

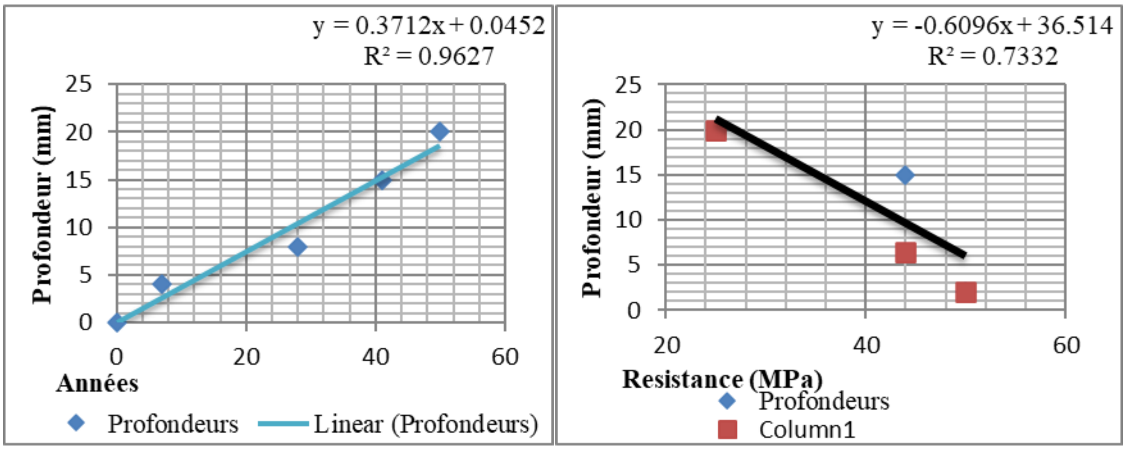


Figure 7: Regression line of the carbonation depths of abutment C1

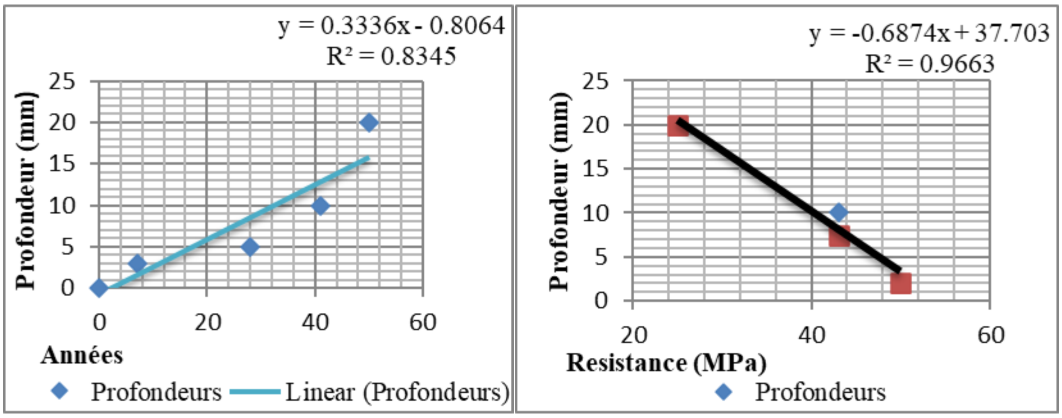


Figure 8: Regression line of the carbonation depths of pier No. 2

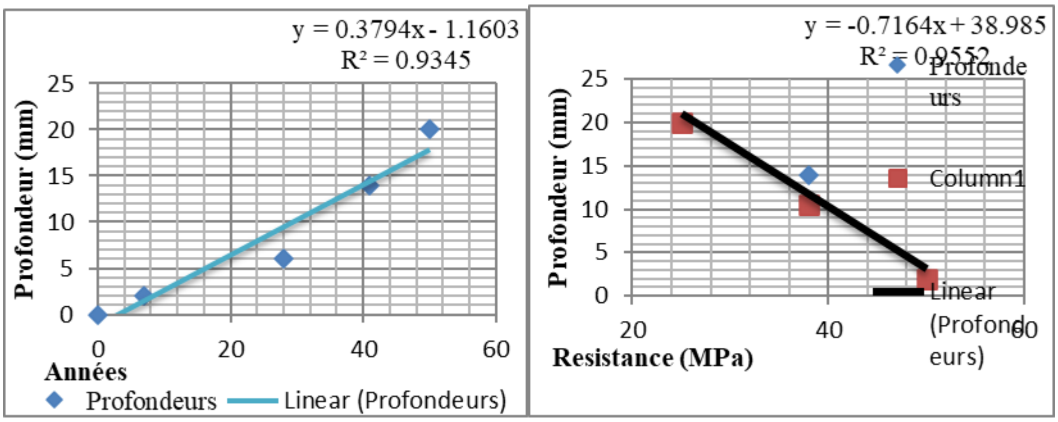


Figure 9: Regression line of the carbonation depths of beam No. 4

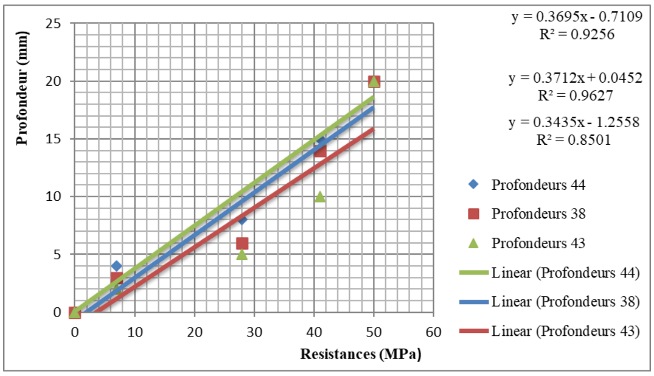


Figure 10: Correlation between various concrete depths and resistances

Figures 11, 12 and 13 present the proportions of variances established between the measurements of the compressive strengths and the corresponding rebound indices. The expressions proposed for these variances are power-form relationships showing a linear regression with a coefficient of determination $R^2 = 0.957$ and a standard error S = 3.121 MPa.

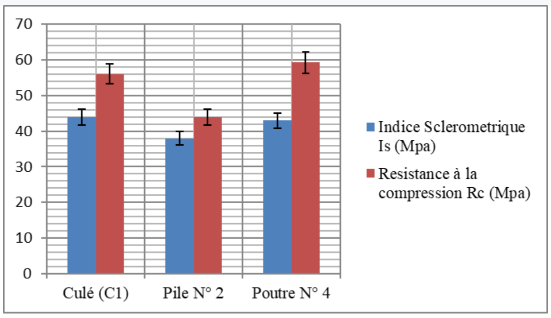
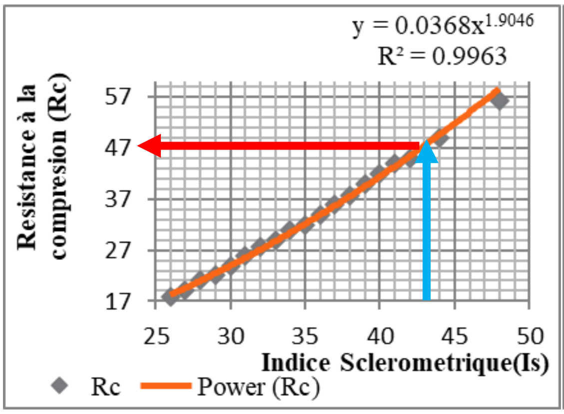


Figure 11: Histogram of various sclerometric resistances



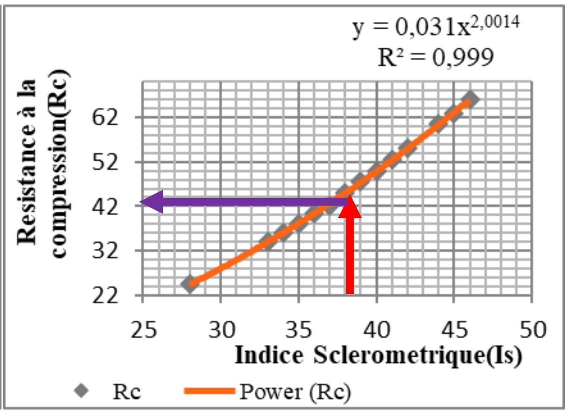


Figure 12: Trend curve of the resistances of abutment and pier

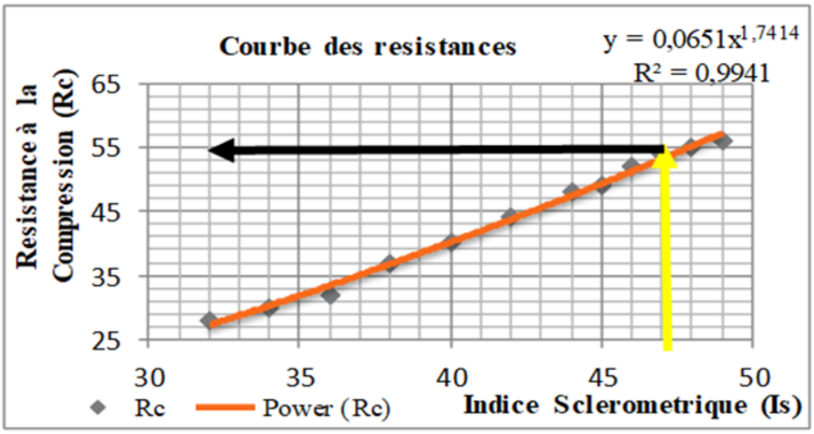


Figure 13: Trend curve of the resistances of the beam

Figures 14 and 15 present the proportions of variances of the regression model established between the measurements of the compressive strengths and the corresponding rebound indices. The expressions proposed for these variances are power-form relationships with a coefficient of determination $R^2 = 0.957$ and a standard error S = 3.121 MPa.

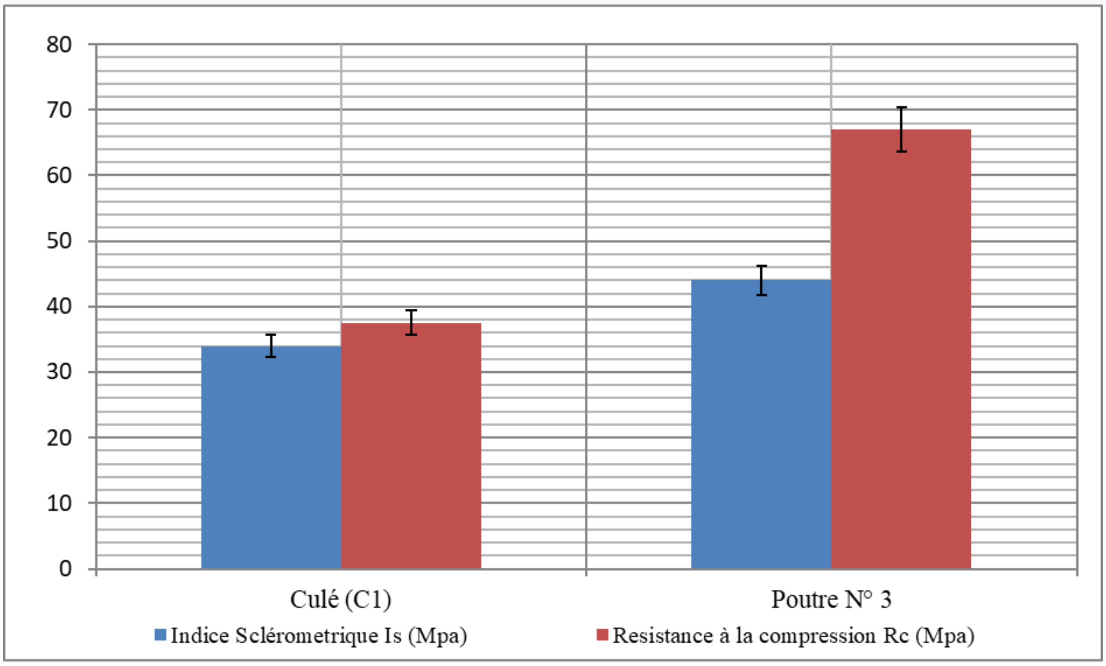


Figure 14: Histogram of the Different Schmidt Hammer Strengths

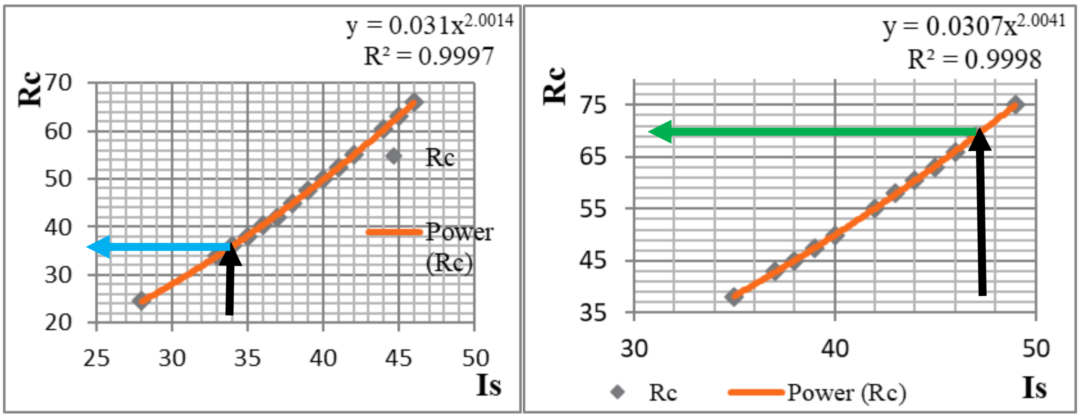


Figure 15: Trend Curve of the Abutment and Beam Strengths

Table 6 : Measurement of Compressive Strength According to the Increasing Order of Schmidt Rebound Index of the Structure

test	Increasing order of Schmidt rebound index (MPa)		
	Abutment (A1) α = 0	Pile N° 2 α = 0	Beam N°4 α = -90
1	32	28	35
2	34	33	37
3	36	33	38
4	38	34	38
5	38	34	38
6	40	34	38
7	40	34	39
8	42	35	40
9	42	35	40
10	42	36	40
11	42	36	42
12	42	37	42
13	44	38	42
14	**44**	**38**	**43**
15	44	38	43
16	44	38	44
17	44	39	44
18	44	39	44
19	45	40	45
20	45	41	45
21	46	41	46
22	46	42	46
23	46	42	46
24	47	44	46
25	47	44	46
26	48	45	47
27	49	46	49
Schmidt rebound index	**44**	**38**	**43**
Average Schmidt rebound index	**41.66**		
Compressive strength Rc (MPa)	**56**	**44**	**59.25**
Average compressive strength Rc (MPa)	**53.1**		

Table 7 : Measurement of Carbonation Depth of the Structure

Structural elements	Carbonation Depth H(mm)
abutment (A1)	15
Pile N° 2	14
Beam N°4	10
H avg	**13**
H max	**15**

Table 8 : Measurement of Compressive Strength According to the Increasing Order of Schmidt Rebound Index of the Structure

Test	increasing Order of Schmidt rebound index (MPa)	
	Abutment (C2) α = 0	Beam N°3 α = -90
1	26	40
2	27	40
3	27	41
4	28	41
5	28	42
6	29	42
7	30	42
8	30	42
9	30	42
10	31	43
11	31	44
12	32	44
13	33	44
14	**34**	**44**
15	35	45
16	35	45
17	36	45
18	37	45
19	38	45
20	38	46
21	38	46
22	39	48
23	40	49
24	41	50
25	42	50
26	44	51
27	48	55
Schmidt rebound index	**34**	**44**
Average Schmidt rebound index	**39**	
Compressive strength Rc (MPa)	**37.5**	**61**
Average compressive strength Rc (MPa)	**49.25**	

Table 9 : Measurement of Carbonation Depth of the Structure

	Carbonation Depth H (mm)
Abutment (a2)	15
Beam N°3	10
Havg	**12.5**
H max	**15**

V. Discussion

After conducting various laboratory tests, the following conclusions were drawn:

- ✓ We can conclude that the more the resistance increases, the more the carbonation depth decreases. The different figures 3 and 4 show that the proportion of the variance is between 0.8345 < R^2 < 0.9918 this refers to an excellent regression model then it tends towards 1
- ✓ The depths show a linear regression according to the proportion of the variance with the values of the compressive strength (0.8345 < R^2 < 0.9627), which confirms the trend mentioned by the studies of Searsale et al. (1970), Messad (2009) and Boucetta (2014) see Figure 5.
- ✓ We can conclude that the more the resistance increases, the more the carbonation depth decreases. The different figures 7, 8 and 9 show that the linear regression obtained by the coefficient of determination is between 0.7332 < R^2 < 0.9663
- ✓ It is also noted that for a given depth, the compressive strength values are significantly higher. This is explained by the fact that the limestone filler is an inert addition which can only have a filling effect. Figure 10 shows the correlation between the different carbonation depths and the resistances

✓ From these figures, it can be concluded that there is a good variation in the proportion of variance, the coefficient of determination ($R^2 = 0.957$) between the compressive strengths and the corresponding rebound indices for each element of the structure confirms the chosen model. To this end, it can be said that the results found by the sclerometer show that the concrete is still in good condition despite its exposure to different weather conditions. In addition, the compressive strength must always be greater than the sclerometric index.

VI. Recommendations

In order to understand the development of a structure and the appearance of disorders, it is necessary to know its condition at the time of acceptance. The project owner should ensure that a "zero point" evaluation is carried out. This will serve as a reference point for future inspections and monitoring of the structure. Likewise, it is important to create a directory for all structures in order to have all the technical design and execution plans, which will later be used to conduct relevant investigations and determine the state of the structures. For the project we worked on, after more in-depth additional studies conducted as part of the Detailed Design (APD) and considering the importance of the road axis connecting the Ndé Bridge to the Mem Bridge for Cameroon's economy in the sub-region, we recommend that the rehabilitation works of the bridges be carried out as soon as possible. A carefully planned schedule will not only ensure the safety of workers but also the smooth flow of goods and people during the execution of the works.

VII. Conclusion And Prospects

Conclusion

At the end of our study, the objective was to carry out an inventory and detailed inspection of the structures along the study route on National Road RN4 connecting the Central region to the Western region of Cameroon, in order to address this issue and identify potential improvements. This was based on diagnostic evaluation (which can be performed on a healthy structure, a potentially damaged one, or a visibly damaged one) as well as on the characterization of the various materials constituting the structure. The main challenges encountered involved the lack of certain survey and evaluation data (types of materials used in the construction, historical importance, load-bearing capacity, and repair history); the positioning and sizing of passive/active reinforcement; the concrete mix design; and the evaluation of certain mechanical and physical characteristics of materials using non-destructive tests on different structural elements.

Prospects

At the conclusion of this work, we realize that there remain many aspects worth exploring or investigating further, such as:

- Selecting specific structures to monitor the progression of deterioration phenomena and confirm or refute findings related to degradation, the reliability of methods, and repair materials under local conditions.
- Quantitative and financial estimation of projected rehabilitation work.

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