

Pathological and Physical Analysis of Reinforced Concrete Poles of Electrical Distribution Network in Côte d'Ivoire

Mamery Adama Serifou¹, Daouda Kone², Brice-Martial Dally^{3*}, N'Da Miezan Kwamana^{2,4}, Achi Ferdinand N'Guessan⁴

¹Laboratoire de l'Eau, du Sol et des Géomatériaux, UFR des Sciences de la Terre et des Ressources Minières, Université Félix Houphouët-Boigny (UFHB), Abidjan, Côte d'Ivoire

²Laboratoire de Technologie, UFR Sciences des Structures de la Matière et Technologie (UFR SSMT), Université Félix Houphouët-Boigny (UFHB), Abidjan, Côte d'Ivoire

³Département des Sciences et Technologies, Université Alassane Ouattara, Bouaké, Côte d'Ivoire

⁴Direction Centrale Planification Ingénierie Qualité Produit, Compagnie Ivoirienne d'Électricité (CIE), Abidjan, Côte d'Ivoire

Email: *dallybricegodknow@gmail.com

How to cite this paper: Serifou, M.A., Kone, D., Dally, B.-M., Kwamana, N.M. and N'Guessan, A.F. (2025) Pathological and Physical Analysis of Reinforced Concrete Poles of Electrical Distribution Network in Côte d'Ivoire. *Open Journal of Applied Sciences*, 15, 3435-3450. <https://doi.org/10.4236/ojapps.2025.1511221>

Received: September 29, 2025

Accepted: October 28, 2025

Published: October 31, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution-NonCommercial International License (CC BY-NC 4.0). <http://creativecommons.org/licenses/by-nc/4.0/>



Open Access

Abstract

Reinforced concrete electricity poles play a crucial role in public lighting and in supporting electrical equipment. This enables the transmission of electric energy from electricity transformer substations to consumers. The poles are easy to produce and have a relatively long lifespan of around 10 years. However, in recent years, many poles have shown signs of degradation after just a few months of use, crumbling and threatening to collapse. This premature deterioration for the poles, has become a major concern for the Compagnie Ivoirienne d'Electricité (CIE). Hence, this study objective is to control the quality of the concrete used for the manufacture of reinforced poles used for the energy distribution in Côte d'Ivoire. To carry out this feasibility study, an on-site pathological investigation was conducted to identify recurring pathologies, as well as laboratory analyses of concrete samples of the electricity poles for a physical characterization. The survey results showed that the pathologies were of various types, including moulds, pyrites and crazing, as well as structural pathologies such as vertical and horizontal cracks, corrosion, fragility and spalling. Laboratory characterization revealed that 60% of concrete samples exhibited water absorption above the 6% standard limit, a consequence of high porosity that directly contributes to premature degradation. This high porosity is responsible for the high and persistent humidity (due to water infiltration and capillary rise or water vapour condensation within the material), which leads to the proliferation of mould, fungi, bacteria and many

other microorganisms. In addition, variations in outside temperatures cause the reinforced concrete to expand and contract to a greater or lesser extent, creating internal stresses that lead to the spread of cracks within the material. These cracks extend to the metal reinforcements, allowing oxidising substances to pass through and corrode them more easily. This leads to the poles deteriorating faster.

Keywords

Concrete Pole, Energy Distribution Network, Pathology, Pathological Investigation, Physical Characterization, Côte d'Ivoire

1. Introduction

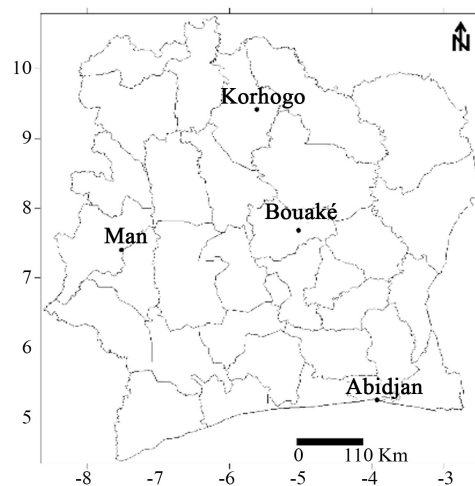
Reinforced concrete poles play an essential role of supporting lines and other electrical equipment that transport electric energy from power plants to consumers. In Côte d'Ivoire, there are three types of poles, including wooden, metal and concrete poles. Wooden poles have a relatively short lifespan because they are made of an organic material that decomposes and can be damaged by water, fungal spores and insects [1]. This leads to the weakening of the pole structure. Metal poles are prone to corrosion and rust over time when exposed to extreme meteorological conditions or corrosive substances [1]. Concrete poles have several advantages over the above-mentioned elements. They are highly resistant and can withstand severe meteorological conditions of high intensity and impact, thus ensuring long-term reliability in electricity distribution [2]. They are guaranteed against all manufacturing defects or material defects for a period of 10 years [3] [4]. Concrete supports sometimes become weakened due to problems that occur during their lifespan, mainly because the realities of their environment are not considered. Concrete is a building material composed mainly of aggregates (such as sand and gravel), water, eventual adjuvant and a binding agent (cement). It is a homogeneous mixture that hardens gradually to form a solid resistant substance. If the type of binding element used is not cement, then depending on the mixture used, it is referred to as concrete of grapes, concrete of hydrocarbon elements, or concrete of clay [5]. The pathologies that affect concrete, especially those classified as dangerous, can cause a collapse if they are ignored, hence the observations in recent years of rapid degradation of concrete poles. Indeed, the presence of ions chloride, the carbonation of concrete or the penetration of acidic gas in concrete due to open porosity are other causes of corrosion of concrete poles. Besides, other factors related to the quality of concrete, such as the water/cement ratio, cement content, the presence of impurities within the concrete components, the presence of superficial cracks, etc., and others linked to the external environment, such as rate of moisture content, of oxygen, temperature variations, bacterial attacks, etc., influences the corrosion of the poles [6]. This deterioration compromises structure's stability increases the risk of collapse and endangers lives and property. This situation is a major concern for both the local population

and the Compagnie Ivoirienne d'Electricité (CIE) employees. Therefore, resolving such a problem requires an in-depth understanding of the causes and factors that can degrade and deteriorate the material and reinforced concrete structure. The main objective of this work is to highlight the recurring pathologies that affect the durability of concrete poles of the energy distribution network. To achieve this general objective, a pathological survey to enlist the most recurrent disorders and determine the reasons for the premature degradation of the poles. Therefore, concrete samples were taken from the defective poles for characterization in order to identify the raw material responsible for the appearance of pathologies in order to propose a viable method for the correction of the identified pathologies.

2. Equipment and Methods

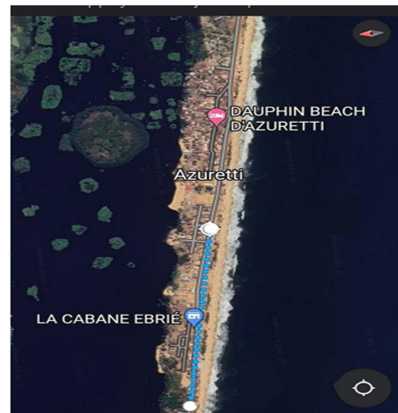
2.1. Description of the Zone of Study

The study was conducted in southern Côte d'Ivoire, at the Grand-Bassam site, specifically in the village of Azuretti. Due to its geographic location at the coast of the sea, the electricity poles are affected by sea salt. Grand Bassam is a coastal town in Côte d'Ivoire, located 43 kilometers east of Abidjan. The city has a tropical climate characterized by high temperatures of (21 °C to 35 °C) and dense humidity particularly during the rainy season [7]. Azuretti, a small village nestled between the lagoon and the ocean, is now lined with concrete electricity poles. In fact, many of these poles are less than ten years old, which corresponds to the warranty period for concrete poles against manufacturing defects according to standard NF C 67-200 and its equivalents. Two categories of poles are available in this zone, namely low-voltage (LV) public lighting poles up to 10 m high and medium-voltage electricity distribution poles reaching 14 m high with a voltage of 15 kV. **Figures 1-3** show, respectively, the location of the study area in Côte d'Ivoire, a satellite image of the study zone, and a photograph of the beach under study, illustrating the electricity poles along the coast.



Source: Bureau National d'Etudes Techniques et de Développement (BNETD).

Figure 1. Map of Côte d'Ivoire.



Source: topographic-map.com.

Figure 2. Satellite image of the study zone.



Figure 3. Study zone photography.

2.2. Material Samples

For better readability, the listed poles have been coded and associated with their number of samples taken, as well as the height, year of manufacture, and location. The distance between two poles is approximately 50 m. The samples were taken from poles showing visible degradation. The poles in this study are located on 15 kV lines. Their height varies from 12 to 14 m. The samples taken from the concrete poles are presented in **Table 1**.

Table 1. Codification of concrete samples taken from damaged poles.

Code	Sample number	Height (m)	Year of manufacture	Location
PM2	3	13	2017	5°12'17"N 3°47'8"W
PM4	3	12	2016	5°12'15"N 3°47'12"W
PM6	3	12	2017	5°12'14"N 3°47'6"W
PM10	3	13	2017	5°12'11"N 3°46'54"W
PM11	3	12	2017	5°12'11"N 3°46'51"W

2.3. Physical Analysis of Samples

Hydrostatic weighing is a systematic process used to evaluate the physical properties of samples, including the porosity, density and water absorption of concrete. In this test, samples of poles, as shown in **Figures 4-7**, are subjected to a specific treatment. After collection, the samples are placed in an oven at 105°C for 24 hours to determine their dry mass (DM), which is measured using an electronic balance. After this, the samples are immersed in water for 24 hours to reach water saturation. The samples are then suspended in a basket that is immersed in a water tank, as shown in **Figure 7**, to measure their submerged mass (MH). After being removed from the water and lightly wiped dry, the samples are weighed suspended to determine their saturated mass (MA). This methodical process aims to evaluate various properties of the pile samples poles within the framework of the study [8].



Figure 4. Sample collection.

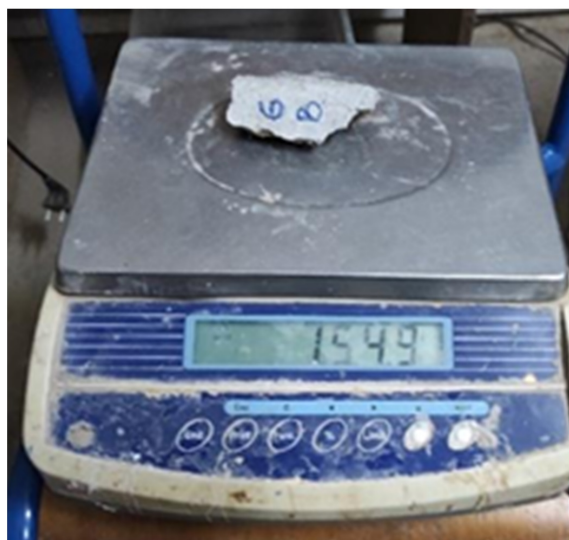


Figure 5. Sample weighing.



Figure 6. Oven.

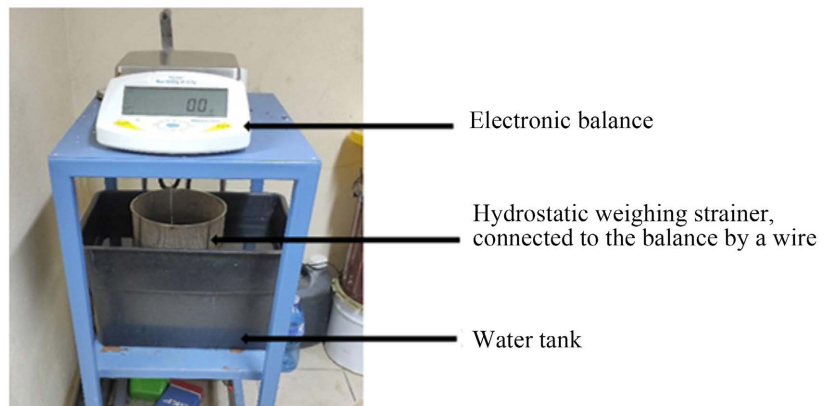


Figure 7. Hydrostatic weighing.

- **Porosity**

A concrete representing a large quantity of voids or pores may have its overall strength reduced. To quantify this porosity, we use the hydrostatic weighing method, with the following defined expression:

$$\eta = \frac{MA - MS}{MA - MH} \times 100\% \quad (1)$$

with: η : porosity in percentage (%); MA: mass of the sample in the air (g); MS: dry mass of the sample (g); MH: mass of the sample in water (g).

- **Density**

After carrying out hydrostatic weighing, the determination of density is carried out using the following formula:

$$e = \frac{MS}{MA - MH} \quad (2)$$

Note that the density; MS: the dry mass (g); MA: the mass in air (g); MH: the mass in water (g).

- **Water absorption**

Also called water absorption by immersion is used as an indicator of concrete quality. It is expressed in percentage of the dry mass and is calculated by the following relationship:

$$W = \frac{MA - MS}{MS} \times 100\% \quad (3)$$

with, W: percent absorption (%); MA: mass of sample after immersion in water until saturation (g); MS: dry mass of sample (g).

3. Results and Discussion

3.1. Identification of Pathologies in Reinforced Concrete Poles

Figures 8-13 show forms of pathologies in reinforced concrete poles observed along the Ivorian coastline. The pathologies are:

- **Moulds**

They appeared in the form of microscopic fungal colonies that developed on the surface of the structure. They generally manifest as spots of colours green, black, white or sometimes reddish and can take various forms, namely diffuse stains, streaks or localized points. Mould develops in conditions of high humidity. The effects of humidity, temperature and wind generally contribute to the development of microorganisms [9].

- **Mineral Stains (stains from mineral)**

These stains can be identified by reddish-brown marks (rust), which are caused by the oxidation of pyrite or the presence of other metallic compounds in the stone (**Figure 8**).

- **Segregation**

The common signs of segregation are visible in **Figure 9**. Manifestations of concrete segregation include the formation of layers of aggregate and a fine particle of cement on the surface of the concrete, in other words nested stone. It is an aesthetic problem, which creates an opening for aggressive chemical agents. This is caused by an unsuitable concrete mixture and improper application, resulting in poor distribution of its constituents [10]. In addition, segregation is caused by insufficient vibration of the concrete during the pouring of the element, which results in reduced physical and mechanical characteristics of the concrete (high porosity, lower cohesion and strength of the concrete, etc.) [5].

- **Spalling**

Visible cracks are often the first sign of spalling or bursting (see **Figure 10**). They can be fine or wide, depending on the severity of the problem. They can also be recognized by pieces of concrete that have been detached from the main substrate. This pathology is caused by poor concrete quality, insufficient coating for this type of environment, and the corrosive effect of the sea breeze.

- **Corrosion of Steel Frames**

The steel frames have a reddish-brown color on their surface, as shown in **Fig-**

ure 11. This is the result of an electrochemical process that causes iron to transform into iron oxides. This reaction leads to a loss of steel cross-section, as well as volumetric expansion around the reinforcement bars. This results in the disappearance of the ribbing effect and the appearance of rust stains or discoloration on the concrete surface, as well as cracking of the concrete cover. Corrosion degrades the steel/concrete interface, reducing adhesion between the two materials [11]. Two main phenomena responsible for the corrosion of steel reinforcement are, notably the carbonation of the surrounding concrete through the adsorption of carbon dioxide from the atmosphere and the penetration of ion chloride to the level of the steel frames.

- **Crazing**

This pathology of the concrete pole shown in **Figure 12** is characterized by fine cracks in the form of spider webs or geometric patterns that generally affect only the top layer of the material without seriously compromising its structural integrity.

- **Cracks**

Figure 13 shows vertical and horizontal cracks, which are linear openings with a regular pattern and a width of between 0.2 and 2 mm. A crack is a split between two parts of the material that are no longer bound together and are separated. Several types of cracks have been identified, namely vertical and horizontal cracks. These types of cleavage may have diverse causes [1], namely the permanent presence of water, which creates micro-cracks that develop into continuous or discontinuous fissures over time. Cleavage due to swelling is caused by corrosion of the steel frames, while moisture also causes microcracks and manufacturing defects in the concrete (shrinkage, bleeding, etc.).



Figure 8. Rust stain.



Figure 9. Segregation.



Figure 10. Concrete spalling.



Figure 11. Corrosion.



Figure 12. Crazing.



Figure 13. Vertical and horizontal cracks.

3.2. Frequency of Pathologies

The results of this study are presented in **Figure 14**. The most common pathologies are mould (65%), vertical and horizontal cracks (40% and 50% respectively) and spalling (30%). The presence of moulds can indeed be explained by the humid environment and the proximity of the study site to the sea and lagoon. Furthermore, although pathologies such as corrosion and segregation are less common, they can have a detrimental impact on the structure of the building and lead to its collapse. However, pyrite and crazing pathologies are rare.

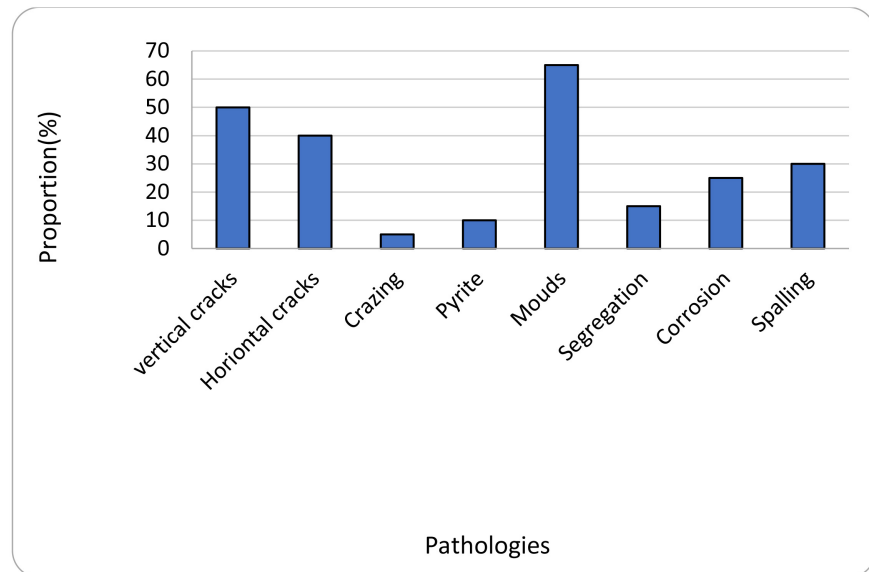


Figure 14. Repair of pathologies of reinforced concrete poles.

3.3. Physical Characterization of Concrete

To facilitate the reading of samples taken from concrete poles, we coded them by referring to their poles.

3.3.1. Porosity

Porosity is the natural consequence of the amount of water added more than that required for hydration and any voids present in the aggregates. **Figure 15** shows the porosity results for the different poles. The concrete resulting from the degraded poles has a porosity ranging from 12.11% to 21.35%. This can be explained by the presence of air bubbles when the concrete is poured and by the rapid evaporation of some of the mixing water, which hinders the crystallization of the cement in the concrete. In porous reinforced concrete, the pores act as pathways through which water or other chemical agents can infiltrate until they reach the reinforcement bars. Contact with these agents leads to the reinforcement bars degrading through oxidation. This causes the bars to swell, resulting in cracking the concrete. Cement-based materials with a porosity greater than 16% have a durability of less than 30 years [12]. Indeed, durability problems are mostly caused by the penetration of aggressive external chemical agents, in solid, liquid or gaseous form, through the pores of the concrete distributed randomly in the hardened cement paste [13]. This implies that pole PM10, which has a porosity of 21.35%, has poor durability of less than 30 years. The structure of pores influences all aspects of durability associated with the transport of active chemical agents and reaction mechanisms. In this context, the density of the microstructure, the quantity of capillary pores, the interconnection and permeability of the pore system, as well as micro-cracks, are among the factors to consider. In cementitious materials, pores form an open and interconnected system [14]. The drawback of this porosity affects both the mechanical strength and durability of reinforced concrete

poles.

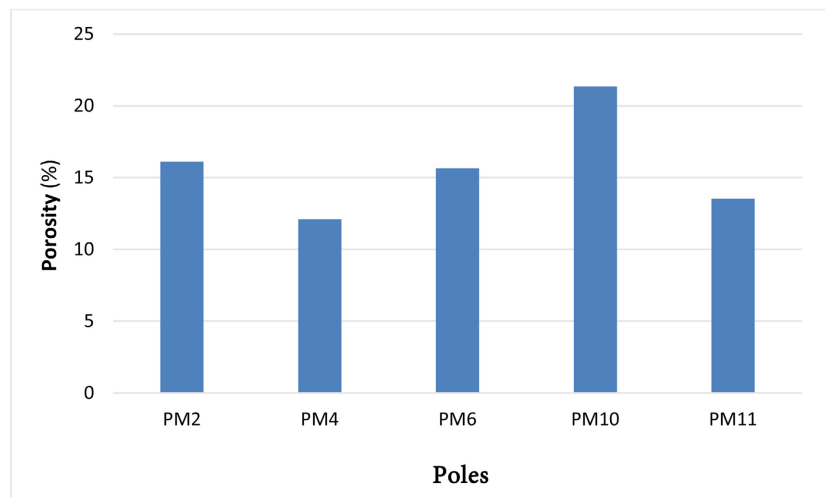


Figure 15. Porosity of concrete samples.

3.3.2. Density

Figure 16 presents the density results based on the different concrete samples of the poles. According to **Figure 16**, pole PM4 has the highest density followed by pole PM11. However, pole PM10 has the lowest density. The values of the density of the concrete samples show that all the concrete falls within the range from 2.05 to 2.29. According to standard NF EN 206/CN, concrete with a density between 2 and 2.6 belongs to the normal concrete category. Therefore, the various types of concrete used in electricity poles are normal concrete. The density of reinforced concrete affects its durability. Its chemical composition and internal chemical reactions also contribute to its disintegration. Indeed, its density affects porosity and thus the ability of the concrete to resist the intrusion of corrosive chemical substances impacts the degradation of reinforced concrete. High density results in compactness and therefore low porosity.

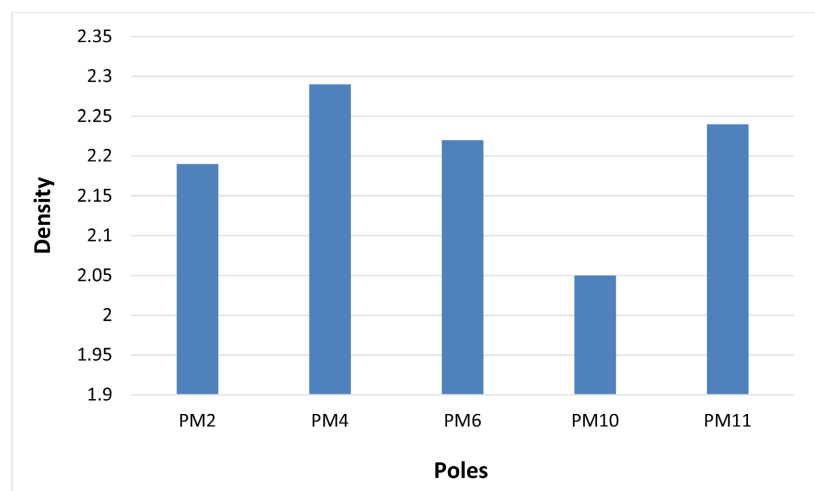


Figure 16. Density of concrete samples.

3.3.3. Absorption

Water absorption is the result of capillary movements in the pores of concrete opening to the exterior environment. The absorption results are shown in **Figure 17**. This figure shows the absorption values obtained on the poles studied, which vary from 5.92% to 10.43%. As shown in **Figure 17**, absorption evolves in a similar way to porosity, as the absorbed water is retained in the pores of the concrete. However, the water absorption coefficient defined by standard NF C 67-250 must not exceed 6%. This indicates that poles PM2, PM6 and PM10 are not certified this standard. Poles PM10 exhibit high absorption.

Furthermore, after prolonged exposure to the elements without protection, pathologies such as corrosion of the reinforcement, initiated by both carbonation and chloride ion attack appear on the concrete substrates. Thus, steel can only be corroded if it is simultaneously exposed to both water and oxygen. The definite failure of these structures is due to the unsuitable quality of certain components and/or an improper mixture of cement ratio and water proportion. This is highlighted in the literature, which emphasizes that the high quantity of water added to concrete increases porosity and absorption [15]. These parameters influence both the mechanical properties and the durability of concrete with respect to physicochemical aggressiveness. This is what explains in other words, pathologies such as cracks, spalling and on the other hand, non-compliance to fundamental quality standards, confirming the defects observed. Intense constituents act as a barrier against flowing water. And flowing water aggregate would increase, thereby creating a discontinuity of capillary pores in the concrete, instead of passing through it [16]. As an indicator of porosity, water absorption is used as a criterion for concrete quality.

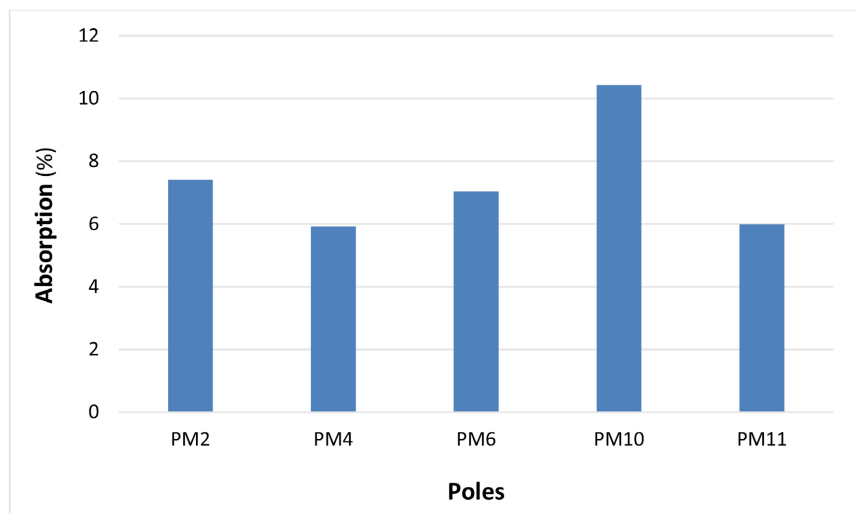


Figure 17. Absorption of concrete samples.

4. Relationship between Observed Pathologies and Test Results

The data from electricity pole PM10 (**Figures 15-17**) show the lowest density (of

2.05), which translates into the highest porosity (with 21.35%) and water absorption (with 10.43%). This contrasts with the analysis of the physical data from the samples from pole PM4, which show high density (of 2.29) with the lowest porosity (with 12.11%) and water absorption (which is 5.92). When porosity is high, the substrate has a high-water absorption capacity, resulting in low density. Thus, the water, which remains in the substrate for a long time in the presence of humic matter from aggregates (sand, gravel, etc.) or air, causes mineral and biological stains to proliferate. In general, the mechanical strength of cementitious materials depends on their porosity. The more porous they are, the less resistant they become. Also, when the structural elements are very porous, their absorption of water or chemical agents is important, which leads to the corrosion of reinforcements in concrete. This corrosion of the steel frames causes swelling followed by spalling of the parts of the concrete in contact with the corroded part. The origin of this significant porosity is linked to the discontinuity of the size of gravels of the concrete, as well as to high cement shrinkage. Similarly, failure to control the consistency of concrete leads to defects in concrete pouring, which can increase porosity. However, porous concrete has low durability. In addition to these concrete failures, one of the essential elements of concrete columns intended to ensure structural stability, namely the steel frames, is attacked by external agents. Here are the fundamental causes. Indeed, as shown, most of the poles (PM2, PM6 and PM10) have high water absorption of over 6%. This explains the recurring appearance of pathological disorders (see **Figure 13**) such as moulds, *i.e.* microorganisms or fungi, various types of cracks, corrosion and spalling, which over time spread throughout these electricity poles. In the design of electricity poles, very little iron sulphide mineral (pyrite) is present in the aggregates used. When in contact with air (oxygen) and water, pyrite oxidizes, transforms into iron sulphate and swells. The frequency of pathology shows that it is rarely responsible for material deterioration. The same applies to the cracking of reinforced concrete, which is caused by drying too quickly before the application of wet curing. These pathological disorders are very rare or even non-existent on some poles PM4 and poles PM11.

5. Conclusions

This feasibility study identified eight types of damage observed on site. Microorganisms and cracks accounted for a significant proportion of the total, ranging from 50 to 65 percent. Pathologies such as spalling, corrosion and segregation are less frequent but must not be overlooked as they largely result from the aforementioned pathologies. In other words, they strongly have significant aesthetics impact and stability of concrete structures, depending on their cause of occurrence. These are due to poor concrete quality, the unawareness of aggressive chemicals presence in the environment and non-compliance with standards for this material, of which steel frames, play a key role in mechanical stability. With regard to laboratory tests, the results of the samples analyzed showed that 60% of the con-

crete in the columns exhibited absorption levels that are detrimental to their durability, with the corrosion problem of the reinforcement steel frame. This poor performance stems from the properties of the raw materials, formulations, manufacturing processes and transport of concrete.

All of these defects result in cracking or even breaking of the concrete and corrosion of its reinforcement steel frame. This study shows that even with supposedly professional companies, without rigorous ongoing monitoring and sanctions, the expected durability of concrete structures will always be compromised and affected.

This study will enable the Compagnie Ivoirienne d'Electricité (CIE) and local manufacturers to implement stricter quality control measures for the water-to-cement ratio of reinforced concrete used in coastal environments in Côte d'Ivoire. Standards better suited to these more aggressive environments can be developed for poles. This strict quality control will also identify design and implementation defects, reducing future repair costs and litigation. The study will encourage ensuring the safety of populations benefiting from CIE services through regular inspections (at least twice a year), which are aimed at collecting relevant data for monitoring and maintaining existing poles. Additionally, new issues can be identified, encouraging the development of rules and performance-based approaches for manufacturing electricity poles.

Acknowledgements

The authors would like to thank the Direction Centrale Planification Ingénierie Qualité Produit (DCPIQ) of the Compagnie Ivoirienne d'Electricité (CIE) for its technical support in carrying out this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Derardja, C. (2004) Types, causes et remèdes des dégradations des constructions existantes. Ph.D. Thesis, Université de Biskra.
- [2] Presticom (2023) Poteaux Électriques en Béton. https://presticom-ci.com/public/poteaux_electriques
- [3] NF C67-200: Supports pour lignes aériennes-poteau en béton armé-spécifications. <https://www.boutique.afnor.org/fr-fr/norme/nf-c67200/poteaux-en-beton-arme-specifications/fa016953/5125>
- [4] NF C67-250: Supports pour lignes aériennes-poteaux en béton précontraint spécifications. <https://www.boutique.afnor.org/fr-fr/norme/nf-c67250/poteaux-en-beton-precontraint-specifications/fa016952/5124>
- [5] Zeghad, M. (2018) Recyclage des déchets inorganiques dans les nouveaux bétons: Bétons autoplaçants (BAP), bétons fibrés ultra-hautes performances (BFUHP). Thèse de Doctorat, Université Mouloud Mammeri de Tizi Ouzou.
- [6] Ahmad, S. (2003) Reinforcement Corrosion in Concrete Structures, Its Monitoring

- and Service Life Prediction—A Review. *Cement and Concrete Composites*, **25**, 459-471. [https://doi.org/10.1016/s0958-9465\(02\)00086-0](https://doi.org/10.1016/s0958-9465(02)00086-0)
- [7] Jeremy, J. (2022) Reportage. Erosion côtière. À Azuretti, même le cimetière se meurt (2/2). Lebanco. <https://www.lebanco.net/news/45446-reportage-erosion-cotiere-a-azurettimeme-le-cimetiere-se-meurt-2-2.html>
- [8] Febelcem (2009) Durabilité des bétons par la maîtrise de l'absorption d'eau. Technologie, 16.
- [9] Tran, T.H. (2011) Influence des caractéristiques intrinsèques d'un mortier sur son encrassement biologique. Master's Thesis, École Nationale Supérieure des Mines de Saint Étienne.
- [10] Boudjedra, F., Benouis, A. and Grini, A. (2016) Effet de la composition sur la ségrégation des bétons. *Academic Journal of Civil Engineering*, **34**, 679-686. <https://doi.org/10.26168/ajce.34.1.82>
- [11] Conciatori, D. (2006) Effet du microclimat sur l'initiation de la corrosion des aciers d'armature dans les ouvrages en béton armé. Thèse de doctorat, École Polytechnique Fédérale de Lausanne.
- [12] Bakayoko, I. (2020) Incidence de la qualité des matériaux sur la stabilité des bâtiments: Cas de la ville d'Abidjan. Master's Thesis, Université Félix Houphouët-Boigny.
- [13] Chemrouk, M. (2015) The Deteriorations of Reinforced Concrete and the Option of High Performances Reinforced Concrete. *Procedia Engineering*, **125**, 713-724. <https://doi.org/10.1016/j.proeng.2015.11.112>
- [14] Breysse, D. (2010) Deterioration Processes in Reinforced Concrete: An Overview. In: Maierhofer, C., Reinhardt, H.W. and Dobmann, G., Eds., *Non-Destructive Evaluation of Reinforced Concrete Structures*, Elsevier, 28-56. <https://doi.org/10.1533/9781845699536.1.28>
- [15] Serifou, M. (2013) Béton à base de recyclats: Influence du type de recyclats et rôle de la formulation. Master's Thesis, Université Sciences et Technologies—Bordeaux I.
- [16] Liu, X., Chia, K.S. and Zhang, M. (2011) Water Absorption, Permeability, and Resistance to Chloride-Ion Penetration of Lightweight Aggregate Concrete. *Construction and Building Materials*, **25**, 335-343. <https://doi.org/10.1016/j.conbuildmat.2010.06.020>