applied sciences

MDPI

Article

Developing a Fuzzy Expert System for Diagnosing Chemical Deterioration in Reinforced Concrete Structures

Atiye Farahani [1,*], Hosein Naderpour [2], Gerasimos Konstantakatos [3], Amir Tarighat [4], Reza Peymanfar [5,6,7] and Panagiotis G. Asteris [3,*]

[1] Department of Civil Engineering, Tafresh University, Tafresh P.O. Box 39518-79611, Iran
[2] Faculty of Civil Engineering, Semnan University, Semnan P.O. Box 35131-19111, Iran; naderpour@semnan.ac.ir
[3] Computational Mechanics Laboratory, School of Pedagogical and Technological Education, 14121 Heraklion, Greece; gkonstantakatos@aspete.gr
[4] Department of Civil Engineering, Shahid Rajaee Teacher Training University, Tehran P.O. Box 16788-15811, Iran; tarighat@sru.ac.ir
[5] Department of Chemical Engineering, Energy Institute of Higher Education, Saveh P.O. Box 39177-67746, Iran; reza_peymanfar@alumni.iust.ac.ir
[6] Department of Science, Iranian Society of Philosophers, Tehran P.O. Box 14778-93855, Iran
[7] Peykareh Enterprise Development Co., Tehran P.O. Box 15149-45511, Iran
* Correspondence: afarahani@tafreshu.ac.ir (A.F.); asteris@aspete.gr (P.G.A.); Tel.: +98-91-8955-7886 (A.F.)

Abstract: The widespread application of reinforced concrete structures in different environmental conditions has underscored the need for effective maintenance and repair strategies. These structures offer numerous advantages, but are not impervious to the deleterious effects of chemical deterioration. The outcomes of this research hold significant implications for the management system of reinforced concrete structures. This study proposes the utilization of a fuzzy expert system as a means of enhancing the diagnosis of chemical deterioration in reinforced concrete structures that is a valuable tool for engineers and decision-makers involved in the maintenance and repair of these structures. The fuzzy expert system serves as an intelligent tool that can incorporate various symptoms of deterioration and inspection data to improve the accuracy and reliability of the diagnostic process. By integrating these inputs, the system evaluates 21 different data points, each representing a specific aspect of deterioration, on a scale ranging from 0 to 100. This numerical representation allows for a quantification of the level of deterioration, with 0 denoting minimal deterioration and 100 indicating severe deterioration. The effectiveness of the fuzzy expert system lies in its ability to process the vast amount of data and apply fuzzy operations on 352 fuzzy rules. These rules define the relationships between the inspection data, the type of deterioration, and its extent. Through this computational process, the fuzzy expert system can provide valuable insights into 10 distinct types of chemical deterioration, facilitating a more precise and comprehensive diagnosis. The implementation of the fuzzy expert system has the potential to revolutionize the field of diagnosing chemical deterioration in reinforced concrete structures. By addressing the limitations of traditional methods, this advanced approach can significantly improve the clarity and accuracy of the diagnostic process. The ability to obtain more precise information regarding the type and extent of deterioration is vital for developing effective maintenance and repair strategies. Ultimately, the fuzzy expert system holds great promise in enhancing the overall durability and performance of reinforced concrete structures in various environments.

Keywords: expert system; fuzzy logic; chemical deterioration; reinforced concrete structures

check for updates

Citation: Farahani, A.; Naderpour, H.; Konstantakatos, G.; Tarighat, A.; Peymanfar, R.; Asteris, P.G. Developing a Fuzzy Expert System for Diagnosing Chemical Deterioration in Reinforced Concrete Structures. *Appl. Sci.* **2023**, *13*, 10372. https://doi.org/10.3390/app131810372

Academic Editors: Angelo Luongo and Simona Di Nino

Received: 24 July 2023
Revised: 16 August 2023
Accepted: 13 September 2023
Published: 16 September 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Maintenance of structures is a crucial aspect of civil engineering, where the timing and nature of activities play a significant role. Among various forms of deterioration,

chemical deterioration poses a significant challenge, reducing the service life and performance of reinforced concrete structures. Hence, effective planning and maintenance strategies are paramount. However, the process of gathering and inferring information in traditional approaches is often characterized by uncertainty, inaccuracy, and ambiguity, further complicated by the intricate behavior and environmental conditions of the structures. Consequently, decision-making becomes challenging. To make informed decisions, accurate diagnosis of the type and extent of deterioration in reinforced concrete structures is essential.

Accurate evaluation of deterioration involves a comprehensive investigation of the structure to identify the symptoms associated with each type of deterioration. These symptoms are derived from inspections, which are often uncertain, inaccurate, and ambiguous. To address these challenges, a fuzzy expert system is developed to diagnose the types and symptoms of deteriorations based on inspection data. This system leverages information obtained from visual inspections and advanced methods, including non-destructive and semi-destructive tests. By integrating this data into the fuzzy expert system, a more reliable and accurate diagnosis can be achieved.

The development of a robust management system relies on obtaining and inferring information accurately. By addressing the uncertainties and inaccuracies in the traditional process and employing a fuzzy expert system, this research aims to enhance the decision-making process regarding the maintenance and management of reinforced concrete structures. The utilization of concrete technology literature aids in identifying the types and symptoms of deterioration, facilitating a more comprehensive understanding and diagnosis.

Jain and Bhattacharjee [1] conducted a study focusing on the application of fuzzy concepts to the visual assessment of deteriorating reinforced concrete structures. The authors recognized the subjectivity and ambiguity involved in the visual inspection process and aimed to enhance the accuracy and reliability of assessments. They proposed a fuzzy logic-based approach that incorporated expert judgment and linguistic variables to evaluate the severity of deterioration. The study demonstrated the effectiveness of the fuzzy concept application in providing more robust and consistent assessments of the condition of reinforced concrete structures. It highlighted the potential of fuzzy logic as a valuable tool for supporting decision-making in the maintenance and management of deteriorating structures [1]. In a study conducted by Yuan et al. [2], the degradation of concrete exposed to sulfuric acid attack was modeled. The objective of the research was to understand the long-term behavior of concrete in aggressive environments and develop a predictive model based on experimental data. The mathematical model developed by the authors considered various factors, including acid concentration, exposure time, and concrete properties. Through their comprehensive model, valuable insights into the mechanisms of concrete degradation were obtained, providing a reliable tool for assessing the durability of concrete structures subjected to sulfuric acid attack. This research contributes to the broader understanding of concrete performance in corrosive environments and offers practical implications for the design and maintenance of resilient structures [2].

Chiu and Lin [3] developed a multi-objective decision-making supporting system for maintenance strategies of deteriorating reinforced concrete buildings. The authors recognized the complexity of decision-making in managing the maintenance of such structures and aimed to provide a comprehensive tool for decision support. The system integrated various criteria, including cost, safety, and environmental impact, to evaluate different maintenance strategies. By utilizing a multi-objective optimization algorithm, the system identified optimal solutions that balanced the competing objectives. The study demonstrated the effectiveness of the decision-support system in aiding decision-makers in selecting appropriate maintenance strategies for deteriorating reinforced concrete buildings [3].

The deterioration of concrete in the marine environment was thoroughly examined by Santhanam and Otieno [4]. The authors explored the specific challenges faced by concrete structures in marine conditions, including exposure to seawater, waves, and aggressive

chemicals. Various degradation mechanisms, such as chloride-induced corrosion, sulfate attack, and alkali–silica reaction, were discussed in detail. The study highlighted the significance of utilizing appropriate construction materials, incorporating design considerations, and implementing effective maintenance strategies to mitigate the deterioration of concrete in marine environments. Santhanam and Otieno's research contributes to the understanding of concrete performance in marine conditions and provides valuable insights into the effective design and management of marine concrete structures [4]. Dasar et al. [5] conducted a study on the deterioration progress and performance reduction of 40-year-old reinforced concrete beams in natural corrosion environments. The authors investigated the effects of corrosion on the mechanical properties and structural performance of the beams over time. They analyzed the corrosion products, measured the corrosion depth, and conducted bending tests to assess the beams' load-carrying capacity. The study revealed a significant reduction in the load-carrying capacity of the corroded beams compared to their original state. The findings emphasized the importance of understanding the long-term effects of corrosion on the performance of reinforced concrete structures and the need for effective maintenance and repair strategies [5]. The probabilistic life prediction of reinforced concrete structures subjected to seasonal corrosion-fatigue damage was investigated by Ma et al. [6]. The authors aimed to assess the durability and remaining service life of these structures under the combined effects of cyclic loading and corrosion. They developed a probabilistic model that incorporated environmental factors, material properties, and structural parameters to estimate the fatigue life of reinforced concrete members. The study highlighted the significance of considering probabilistic approaches in predicting the life expectancy of corroded structures and emphasized the importance of maintenance strategies to mitigate the effects of corrosion-fatigue damage. Ma et al.'s research contributes to the field by providing valuable insights into the long-term performance of reinforced concrete structures and offers practical implications for the development of sustainable maintenance practices in corrosion-prone environments [6].

Marzouk et al. [7] conducted a study aimed at resolving the deterioration of heritage building elements using an expert system. The authors acknowledged the significance of preserving heritage buildings and the challenges associated with their maintenance. They proposed the development of an expert system that integrated historical data, expert knowledge, and condition assessment to assist in diagnosing and resolving deterioration issues in heritage buildings. The expert system utilized a rule-based approach and fuzzy logic to provide recommendations for suitable repair and maintenance strategies based on the specific conditions of the building elements. The study highlighted the potential of the expert system as a valuable tool for heritage building preservation and emphasized the importance of adopting advanced technologies in the field of building pathology and adaptation [7].

A comprehensive review on the durability deterioration of concrete in marine environments was conducted by Qu et al. [8]. The authors critically examined various degradation mechanisms that affect both the material and structural levels of concrete in marine settings. Key factors such as chloride ingress, carbonation, sulfate attack, and biological deterioration were thoroughly discussed, highlighting their impact on the performance and service life of marine concrete structures. The review emphasized the importance of understanding these deterioration processes to develop effective strategies aimed at enhancing the durability and sustainability of concrete in marine environments. The study provides a valuable resource for researchers, engineers, and practitioners involved in the design, construction, and maintenance of marine concrete structures, offering insights and guidance for ensuring long-term performance and resilience [8]. Robles et al. [9] conducted a comprehensive review on the use of electrical resistivity measurements for the nondestructive evaluation of chloride-induced deterioration in reinforced concrete. The authors focused on the assessment of concrete's resistance to chloride ingress, which is a major cause of corrosion in reinforced concrete structures. They discussed various techniques and methodologies employed for electrical resistivity measurements and their correlation with chloride-induced

deterioration. The review highlighted the advantages and limitations of electrical resistivity as a nondestructive evaluation method and emphasized its potential for assessing the durability of reinforced concrete structures. The findings contribute to the understanding and development of effective monitoring and maintenance strategies for chloride-induced deterioration [9]. The deterioration of an industrial reinforced concrete structure exposed to high temperatures and dry–wet cycles was investigated by Liu et al. [10]. The authors sought to gain insights into the effects of these environmental conditions on the structural performance and durability of concrete. Through visual inspections, material testing, and structural analysis, they evaluated the extent of deterioration and identified the underlying mechanisms. The study revealed significant damage, including cracking, spalling, and strength loss, resulting from the combined effects of high temperatures and cyclic moisture changes. These findings underscored the importance of considering these factors in the design and maintenance of reinforced concrete structures exposed to harsh environments. Liu et al.'s research contributes to the understanding of the impact of extreme conditions on concrete performance and provides valuable implications for enhancing the resilience and durability of such structures [10].

Chen et al. [11] examined the structural performance deterioration of corroding reinforced concrete columns in marine environments. The authors focused on the effects of corrosion on the load-carrying capacity, stiffness, and ductility of the columns. They conducted experimental tests and numerical simulations to evaluate the deterioration mechanisms and quantify the extent of performance degradation. The study revealed that corrosion significantly reduced the strength and ductility of the columns, leading to a higher risk of structural failure. The findings emphasized the importance of corrosion protection measures and regular maintenance to ensure the safety and durability of reinforced concrete structures in marine environments [11]. The structural performance of deteriorating reinforced concrete structures was investigated by Pasha and Joshi [12]. The authors aimed to assess the influence of various deterioration mechanisms, including corrosion, cracking, and spalling, on the structural behavior of concrete elements. Through a combination of experimental tests and numerical simulations, they evaluated parameters such as load-carrying capacity, stiffness, and deformation characteristics of deteriorated structures. The study yielded valuable insights into the progressive deterioration of reinforced concrete and its implications for structural performance. The findings emphasized the significance of regular inspections, as well as the implementation of appropriate maintenance and repair strategies, to ensure the safety and long-term durability of deteriorating reinforced concrete structures. Pasha and Joshi's research contributes to the understanding of the behavior of deteriorated concrete structures and provides guidance for mitigating the adverse effects of deterioration on their performance [12]. Matthews et al. [13] provided an overview of the cyclic response of reinforced concrete members subjected to artificial chloride-induced corrosion. The authors aimed to understand the structural behavior of concrete elements under the combined effects of cyclic loading and chloride-induced corrosion. They reviewed experimental studies and numerical simulations to analyze the deterioration mechanisms, including cracking, loss of bond, and reduction in load-carrying capacity. The study highlighted the importance of considering the cyclic behavior of corroded reinforced concrete in structural design and maintenance practices. The findings contribute to the understanding of the performance of deteriorated concrete structures in chloride-rich environments [13,14]. Moreover, artificial intelligence find extensive applications in the field of structural engineering, as demonstrated by numerous studies [15–24].

In this research, the aim is to address the challenges associated with diagnosing chemical deterioration in reinforced concrete structures. Existing methods for diagnosing the type and extent of deterioration have limitations in terms of unreliability and uncertainty. To overcome these limitations, a fuzzy expert system is proposed. This system utilizes various inspection data to diagnose the most probable chemical deterioration. It incorporates 21 types of data and applies fuzzy operations on 352 fuzzy rules to determine the type and

extent of deterioration. This research contributes to improving the clarity and accuracy of chemical deterioration diagnosis in reinforced concrete structures, aiding in effective maintenance and repair planning.

2. Research Significance

The increasing prevalence of reinforced concrete structures in various environments has highlighted the critical need for effective maintenance and repair strategies. However, these structures are susceptible to the adverse effects of chemical deterioration, which can compromise their performance and longevity. Traditional methods for diagnosing the type and extent of chemical deterioration have limitations in terms of ambiguity, inaccuracy, and uncertainty. Consequently, there is an urgent requirement for more advanced approaches that can offer clearer and more accurate assessments.

In this context, this study proposes the utilization of a fuzzy expert system to enhance the diagnosis of chemical deterioration in reinforced concrete structures. The fuzzy expert system acts as an intelligent tool that integrates various symptoms of deterioration and inspection data, thereby improving the accuracy and reliability of the diagnostic process. By quantifying 21 different data points representing specific aspects of deterioration on a scale from 0 to 100, the fuzzy expert system allows for a comprehensive evaluation of the level of deterioration.

The strength of the fuzzy expert system lies in its ability to process large volumes of data and apply fuzzy operations on 352 fuzzy rules, which define the relationships between inspection data, the type of deterioration, and its extent. This computational process enables the system to provide valuable insights into 10 distinct types of chemical deterioration, enabling a more precise and comprehensive diagnosis.

By overcoming the limitations of traditional methods, the implementation of the fuzzy expert system has the potential to revolutionize the field of diagnosing chemical deterioration in reinforced concrete structures. The improved clarity and accuracy offered by this advanced approach are crucial for developing effective maintenance and repair strategies. Ultimately, the integration of the fuzzy expert system holds great promise in enhancing the overall durability and performance of reinforced concrete structures in various environments.

3. Types of Chemical Deteriorations in RC Structures

In this study, the chemical deteriorations observed in reinforced concrete structures are categorized into two main groups based on their underlying mechanisms. The first group involves deteriorations caused by a cation exchange reaction. In this type of deterioration, ions from aggressive materials replace ions present in the concrete compounds, resulting in chemical changes and subsequent degradation of the concrete structure. The second group comprises deteriorations caused by the expansion of materials resulting from various chemical reactions. These reactions induce dimensional changes in the materials, exerting pressure on the surrounding concrete and leading to cracking, spalling, and other forms of structural damage. Understanding and identifying these different types of chemical deteriorations is crucial for developing effective maintenance and repair strategies to mitigate their impact and extend the service life of reinforced concrete structures. Addressing these deteriorations at an early stage is essential to ensure the structural integrity and durability of the concrete components.

The first category of deteriorations can be further classified into three subgroups (referred to as types 1 to 3), while the second category consists of seven subgroups (referred to as types 4 to 10). These classifications of deteriorations allow for a comprehensive and detailed diagnosis of the specific type of deterioration. In total, there are 10 distinct types of chemical deteriorations observed in reinforced concrete structures.

1. Deteriorations caused by cation exchange reaction–formation of soluble calcium salts.
2. Deteriorations caused by cation exchange reaction–formation of insoluble and non-expandable salts.

3. Deteriorations caused by cation exchange reaction–chemical attack by magnesium salts.
4. Deteriorations caused by sulfate attack due to ingress of external sulfate ion into concrete.
5. Deteriorations caused by sulfate attack due to ingress of internal sulfate ion into concrete.
6. Deteriorations caused by alkali–silica reaction (ASR).
7. Deteriorations caused by alkali–carbonate reaction (ACR).
8. Deteriorations caused by hydration of magnesium oxide and crystalline calcium oxide.
9. Deteriorations caused by reinforced concrete corrosion in concrete due to chloride ion diffusion.
10. Deteriorations caused by reinforced concrete corrosion in concrete due to carbonation.

4. Chemical Deterioration Symptoms in RC Structures

Understanding the nature and magnitude of deterioration necessitates a comprehensive exploration of the symptoms associated with each deterioration type within the structure. These symptoms are derived from inspections and are compiled by examining existing concrete technology literature. This research aims to encompass the complexities arising from deterioration, considering both unique symptoms associated with specific deterioration types and those shared across multiple types. In total, 21 symptoms (which are explained in the following) are indicative of chemical deteriorations in reinforced concrete structures or are directly attributable to them:

1. Concrete strength reduction.
2. Concrete durability reduction.
3. Aggregate pop-outs.
4. Concrete disintegration.
5. Increase in chlorine ion concentration.
6. Concrete spalling.
7. Concrete porosity/permeability.
8. Interfacial transition zone (ITZ) strength reduction.
9. Increase in salt/ion concentration.
10. Increase in sulfate ion concentration.
11. Irregular cracks.
12. Map cracking.
13. Alkali–silica gel leakage.
14. Alkali–carbonate gel leakage.
15. Efflorescence.
16. Steel rust production (corrosion).
17. Increase in cement Na2O equivalent alkali percentage.
18. Existence of potentially active aggregates for ASR.
19. Existence of potentially active aggregates for ACR.
20. Appearance of purple region after spraying phenolphthalein (concrete carbonation).
21. Structural deformations.

The aforementioned 21 indicators, crucial for diagnosing the type and extent of chemical deteriorations, are fraught with uncertainty, inaccuracy, and ambiguity. Several factors contribute to the unreliable nature of this information, including the inspector's experience, timeliness, and expertise, as well as the definition and severity of the complications involved. Additionally, the complex environmental conditions further complicate the interpretation of these indicators [25]. Schematic representations of the study framework can be observed in Figures 1 and 2.

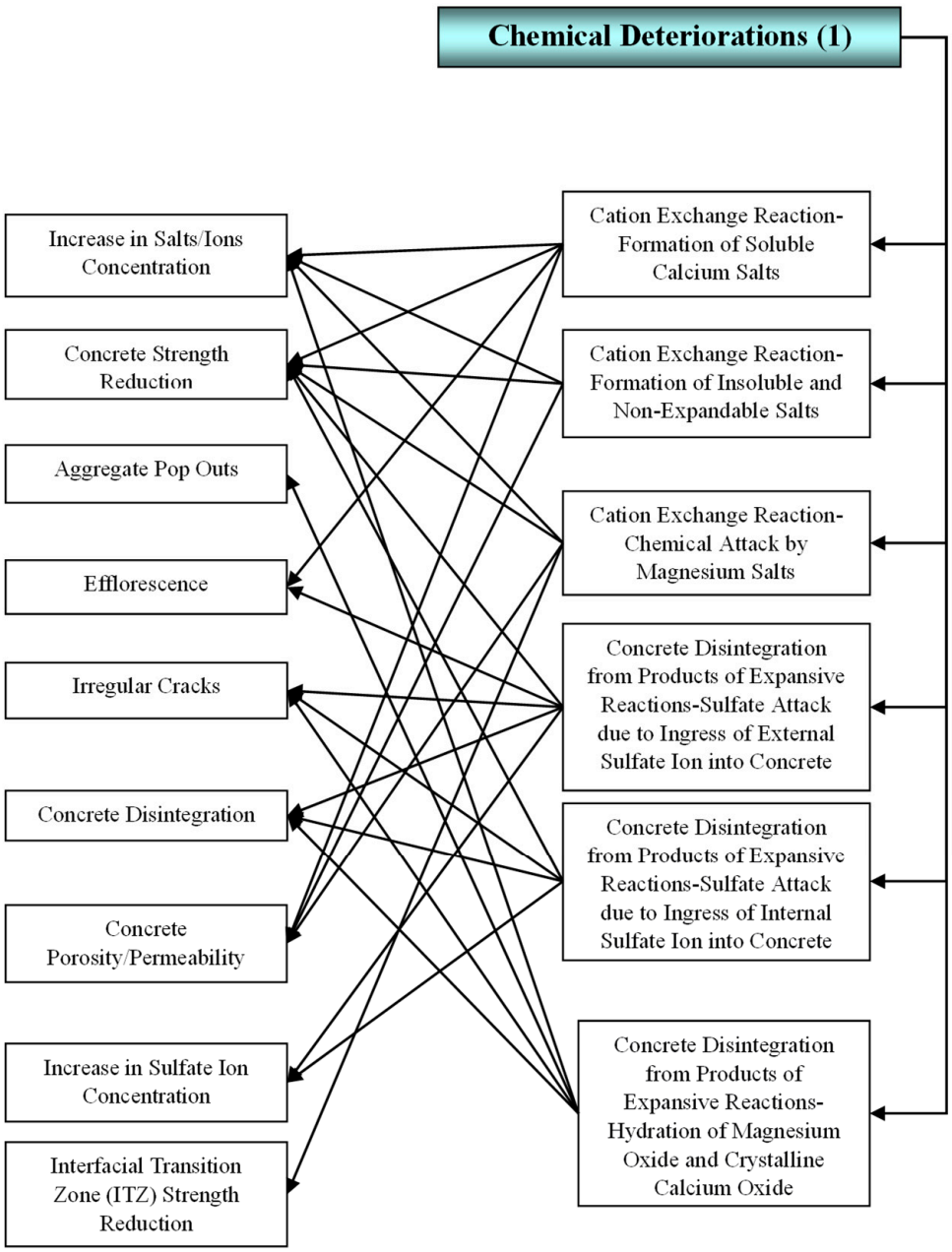


Figure 1. Symptoms and types of chemical deteriorations.

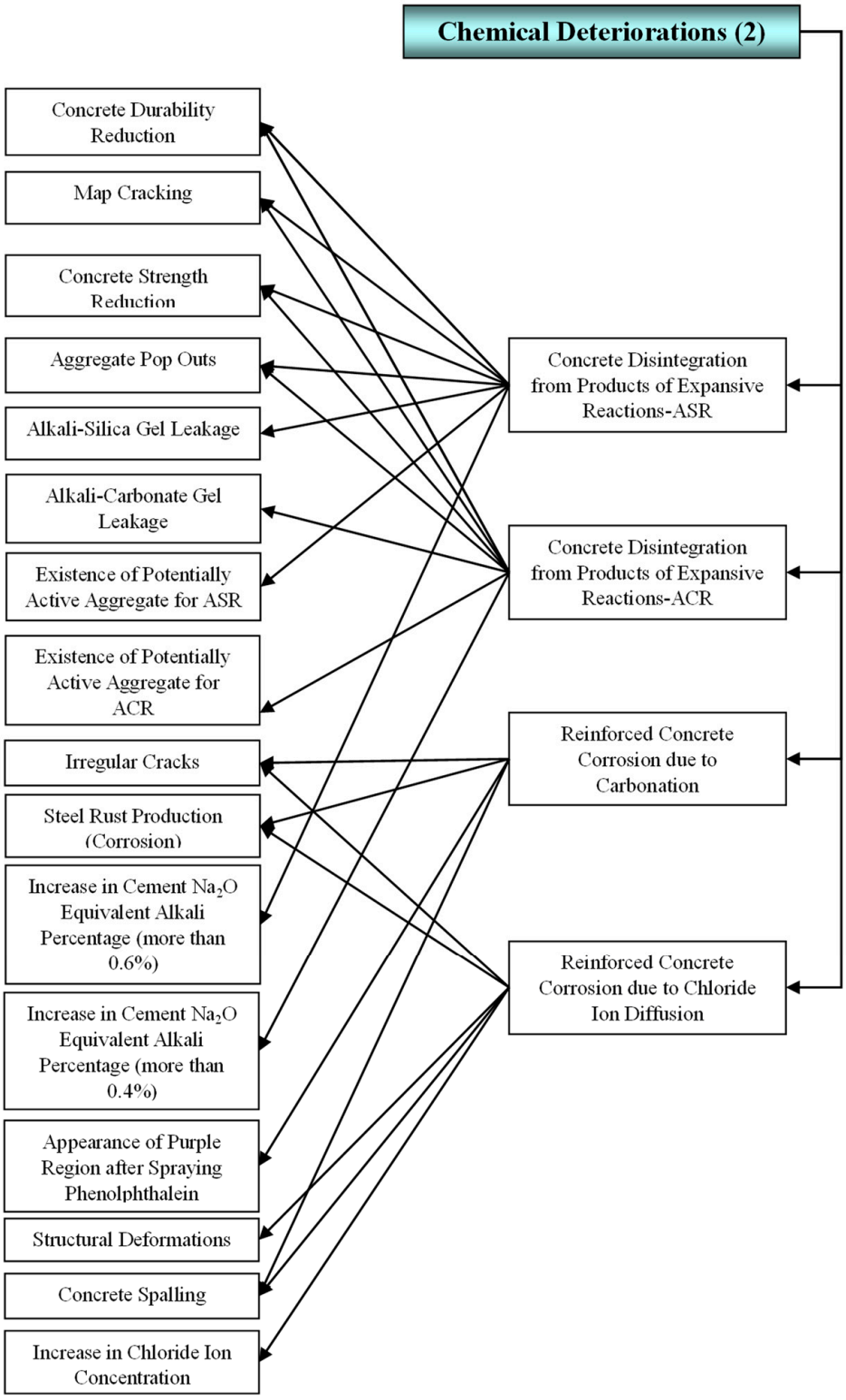


Figure 2. Symptoms and types of chemical deteriorations.

5. Fuzzy Expert System

Expert systems leverage knowledge and inference techniques to address complex problems that typically require human expertise. These systems offer several advantages, including rapid response, enhanced reliability, cost reduction and flexibility [26].

Numerous studies have explored the application of expert systems in examining different forms of deterioration. For instance, Zain Al Abedin [27] proposed an expert

system that utilizes a non-phase if–then algorithm to assess the types of deterioration in reinforced concrete structures. Vagiotas et al. [28] put forward an expert system designed to facilitate the maintenance of reinforced concrete bridges in Greece, acknowledging the inherent uncertainty and ambiguity in the information and decision-making process. In a similar vein, Tarighat and Miyamoto [29] developed a fuzzy model specifically tailored for ranking the condition of concrete bridge decks.

In this research, the expert system employed is built upon the principles of fuzzy logic. Unlike traditional binary logic, which categorizes propositions as either true or false, fuzzy logic operates on a spectrum of values, allowing for more nuanced and continuous evaluation [30]. The foundations of fuzzy logic were laid by Zadeh [31], who introduced the concept in his influential 1965 paper titled "Fuzzy Sets." Fuzzy theory encompasses various approaches that utilize fundamental concepts of fuzzy sets and membership functions. According to Zadeh [31], membership functions are used to determine the degree to which an element belongs to a set. Unlike crisp sets, where membership is strictly binary, membership degrees in fuzzy sets range between zero and one, allowing for partial membership (Equation (1)). A membership degree of zero indicates that an element does not belong to the set, while a degree of one denotes complete membership. The introduction of fuzzy theory has provided a novel means of expressing and handling uncertainties [32].

$$\begin{aligned} &\mathrm{m_A}(x) : x \in [0,1] \quad \text{where :} \\ &\mu_{\mathrm{A}}(x) = 1 \quad \text{if } x \text{ is totally in A;} \\ &0 < \mu_{\mathrm{A}}(x) < 1 \quad \text{if } x \text{ is partly in A;} \\ &\mu_{\mathrm{A}}(x) = 0 \quad \text{if } x \text{ is not in A.} \end{aligned} \tag{1}$$

Fuzzy logic employs linguistic terms to represent variables, with each linguistic variable being a fuzzy variable that incorporates uncertainty. Input and output fuzzy variables can be expressed using conditional terms (Equation (2)). For instance, consider the conditional term "If the room temperature is higher, then the cooler will work at a higher speed." In this example, the words "temperature" and "speed" are linguistic variables, while "higher" and "more" are fuzzy values that encompass uncertainty.

$$\text{If } (x \text{ is } \mathrm{A}) \text{ Then } (y \text{ is B}) \tag{2}$$

The fuzzy inference system (FIS) relies on if–then rules to establish relationships between input and output variables. It serves as a simulated model for scenarios involving uncertain input and output data, as classical methods are unable to account for such uncertainty. In this study, the Mamdani method, the most commonly used technique for FIS development, is employed. Unlike the Sugeno method, the Mamdani method can handle input and output uncertainty, enabling a more intuitive and systematic simulation of expert knowledge [31].

The proposed fuzzy expert system is developed and is implemented in four steps, as follows.

5.1. Step 1. Fuzzification of Inputs and Outputs

In this step, the inputs of the system are 21 symptoms of chemical deteriorations (Table 1) and the outputs are 10 types of chemical deteriorations (Table 2), for each of which a range of linguistic changes is defined. In the design of this system, the set of linguistic changes A is used for the symptoms of deteriorations 1 to 11 and all ten types of chemical deterioration, and the set of deteriorations B is used for the symptoms of deteriorations 12 to 21.

$$\mathrm{A} = \{\text{Low, Moderate, High}\};\ \mathrm{B} = \{\text{No, Yes}\} \tag{3}$$

A continuous numerical range from 0 to 100 is considered for the symptoms and types of chemical deterioration that are inputs and outputs of the program, with 100 as the maximum value and 0 as the minimum value of the symptom of deterioration.

A membership function is considered for each range of linguistic changes. The membership functions considered for the symptoms of deteriorations are triangular (Figures 3 and 4), and the Gaussian membership function is selected for the types of chemical deteriorations (Figure 5).

Table 1. Fuzzy symptoms of chemical deteriorations.

Symptoms of Chemical Deteriorations	Symbol	Associated Fuzzy Set
Concrete strength reduction	DS	{Low, Medium, High}
Concrete durability reduction	Du	{Low, Moderate, High}
Aggregate pop-outs	PA	{No, Maybe, Yes}
Concrete disintegration	Di	{No, Maybe, Yes}
Increase in chloride ion concentration	IC	{Low, Moderate, High}
Concrete spalling	Sp	{No, Maybe, Yes}
Concrete porosity/permeability	IP	{Low, Moderate, High}
Interfacial transition zone (ITZ) strength reduction	ST	{Low, Moderate, High}
Increase in salt/ion concentration	Sa	{Low, Moderate, High}
Increase in sulfate ion concentration	So	{Low, Moderate, High}
Irregular cracks	Cr	{Low, Moderate, High}
Map cracking	TC	{No, Yes}
Alkali–silica gel leakage	JS	{No, Yes}
Alkali–carbonate gel leakage	JC	{No, Yes}
Efflorescence	Ef	{No, Yes}
Steel rust production (corrosion)	CS	{No, Yes}
Increase in cement Na_2O equivalent alkali percentage	AS	{No, Yes}
Existence of potentially active aggregate for ASR	SG	{No, Yes}
Existence of potentially active aggregate for ACR	CG	{No, Yes}
Appearance of the purple region after spraying phenolphthalein (concrete carbonation)	Fn	{No, Yes}
Structural deformations	Df	{No, Yes}

Table 2. Fuzzy types of chemical deteriorations.

Types of Chemical Deteriorations	Symbol	Associated Fuzzy Set
Cation exchange reaction–formation of soluble calcium salt	CCa	{Low, Moderate, High}
Cation exchange reaction–formation of insoluble and non-expandable salt	CIS	{Low, Moderate, High}
Cation exchange reaction–chemical attack by magnesium salt	CMg	{Low, Moderate, High}
Concrete disintegration from products of expansive reactions-sulfate attack due to ingress of external sulfate ion	EAS	{No, Maybe, Yes}
Concrete disintegration from products of expansive reactions–sulfate attack due to ingress of internal sulfate ion	IAS	{No, Maybe, Yes}
Concrete disintegration from products of expansive reactions—ASR	ASR	{No, Maybe, Yes}
Concrete disintegration from products of expansive reactions—ACR	ACR	{No, Maybe, Yes}
Concrete disintegration from products of expansive reactions–hydration of magnesium oxide and crystalline calcium oxide	HMC	{Low, Moderate, High}
Reinforced concrete corrosion due to chloride ion diffusion	CCl	{Low, Moderate, High}
Reinforced concrete corrosion due to carbonation	CSC	{Low, Moderate, High}

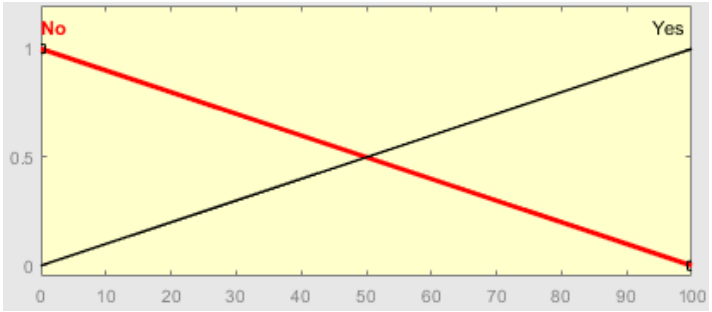


Figure 3. Membership function of chemical deterioration symptoms.

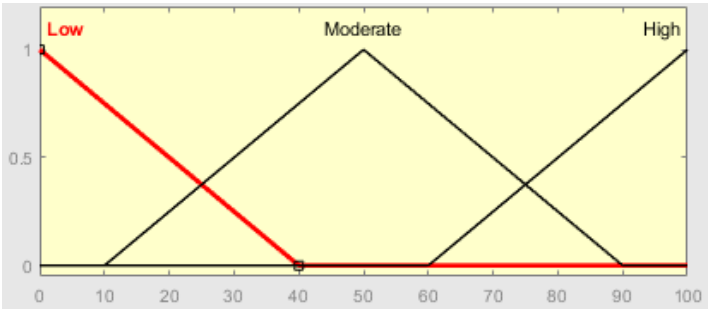


Figure 4. Membership function of chemical deterioration symptoms.

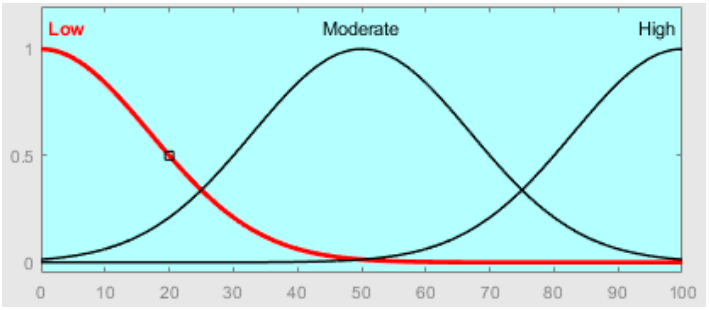


Figure 5. Membership function of chemical deterioration types.

5.2. Step 2. Development of If–Then Rules

During this stage, if–then rules are formulated based on scientific, specialized, and experimental principles provided by the expert. These rules outline the relationships between each symptom and the type of deterioration [33,34]. Initially, rules are created individually for each symptom and type of deterioration, and subsequently consolidated. A total of 352 fuzzy rules are established for the expert system. These rules employ the logical AND operator, which denotes the minimum value aggregation method when summarizing the symptoms of deteriorations. One of the rules is given below as an example:

Rule: If [(Irregular cracks are high)] and (corrosion is yes) and (spalling is high) and (structural deformations is yes) and (chloride ion concentration is high)] then [(reinforced concrete corrosion due to chloride ion diffusion is high)]. (4)

5.3. Step 3. Summary of Outputs of Rules

Every fuzzy function has an output that has a specific level according to its membership function. These levels are summarized by logical "and" operator, which takes the minimum value into account.

5.4. Step 4. Defuzzification of Outputs

The output of the system must be an uncertainty-free number so that this fuzzy system can be used properly. This number between 0 and 100 represents the extent of each type of chemical deterioration. The center of sums (COSs) method is used to achieve this value in such a way that a surface emerges from the summarization of the outputs of the rules whose center of the surface is a number that shows the extent of each of the ten types of chemical deterioration.

6. Analysis of Fuzzy Expert System Results

The fuzzy toolbox can draw 3D and 2D graphs, allowing the user to compare inputs and outputs and examine the effect of a symptom of deterioration on its type (Figures 6–9). As can be seen, the graphs are completely non-linear, and the extent of chemical deterioration increases mainly with the increase in the symptom of deterioration.

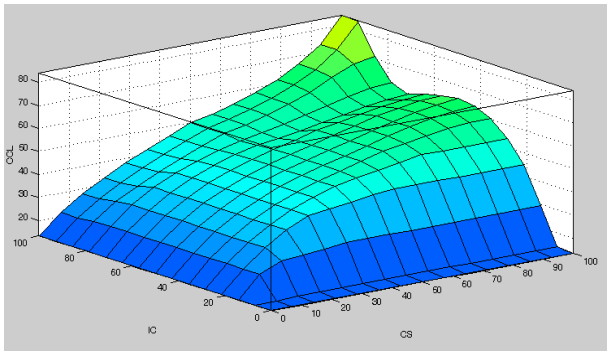


Figure 6. 3D graph of inputs (CS: steel corrosion, IC: chlorine ion), and output (CCL: reinforced concrete corrosion due to chlorine ion diffusion).

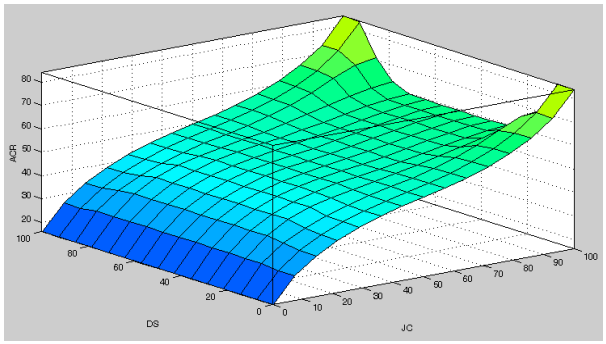


Figure 7. 3D graph of inputs (DS: reduction of concrete strength, JC: ACG leakage) and output (ACR: alkali–carbonate reaction of aggregates).

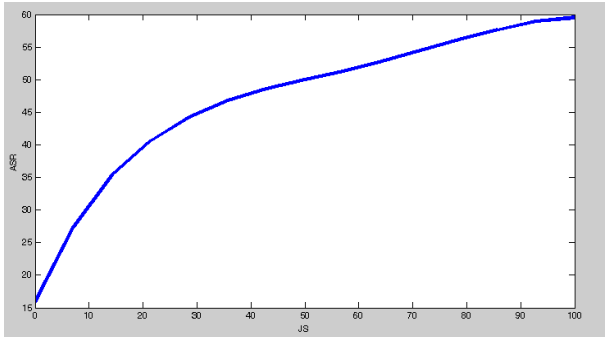


Figure 8. 2D graph of input (JS: ASG leakage) and output (ASR: alkali–silicate reaction of aggregates).

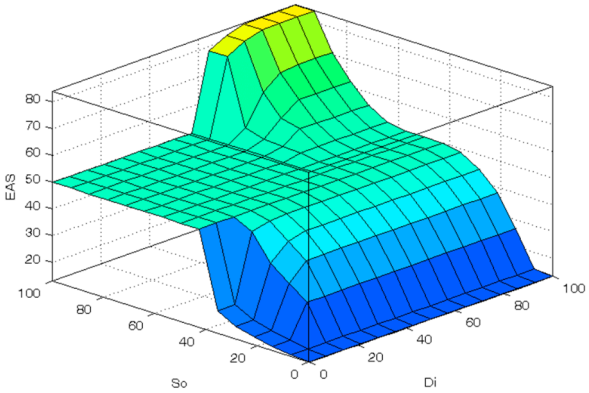


Figure 9. 3D graph of inputs (So: sulfate ion concentration, Di: concrete disintegration) and output (EAS: corrosion due to sulfate attack).

7. Case Study

Costa and Appleton [35] pointed out the deterioration symptoms of a bridge at the Sado River coastal pier in Portugal (Figure 10). In this research, the observations of the mentioned bridge deterioration symptoms [35] have been investigated to validate the developed fuzzy expert system. Table 3 indicates the values of each symptom of chemical deterioration in a bridge at the Sado River coastal pier in Portugal. According to Table 3, the most severe chemical deterioration symptoms are "steel rust production (corrosion)" and "increase in chloride ion concentration." Also, according to Table 4 and Figure 11, the results of developed fuzzy expert system diagnose the deterioration type of "reinforced concrete corrosion due to chloride ion diffusion" as the most severe deterioration type.

Table 3. Symptoms of chemical deteriorations value of a bridge in Portugal: case study.

	Symptoms of Chemical Deteriorations	Value
1	Concrete strength reduction	33
2	Concrete durability reduction	42
3	Aggregate pop-outs	55
4	Concrete disintegration	50
5	Increase in chloride ion concentration	78
6	Concrete spalling	76
7	Concrete porosity/permeability	57
8	ITZ strength reduction	58
9	Increase in salt/ion concentration	70
10	Increase in sulfate ion concentration	68
11	Irregular cracks	60
12	Map cracking	70
13	Alkali–silica gel leakage	45
14	Alkali–carbonate gel leakage	46
15	Efflorescence	36
16	Steel rust production (corrosion)	79
17	Increase in cement Na2O equivalent alkali percentage	51
18	Existence of potentially active aggregate for ASR	52
19	Existence of potentially active aggregate for ACR	52
20	Concrete carbonation	64
21	Structural deformations	10

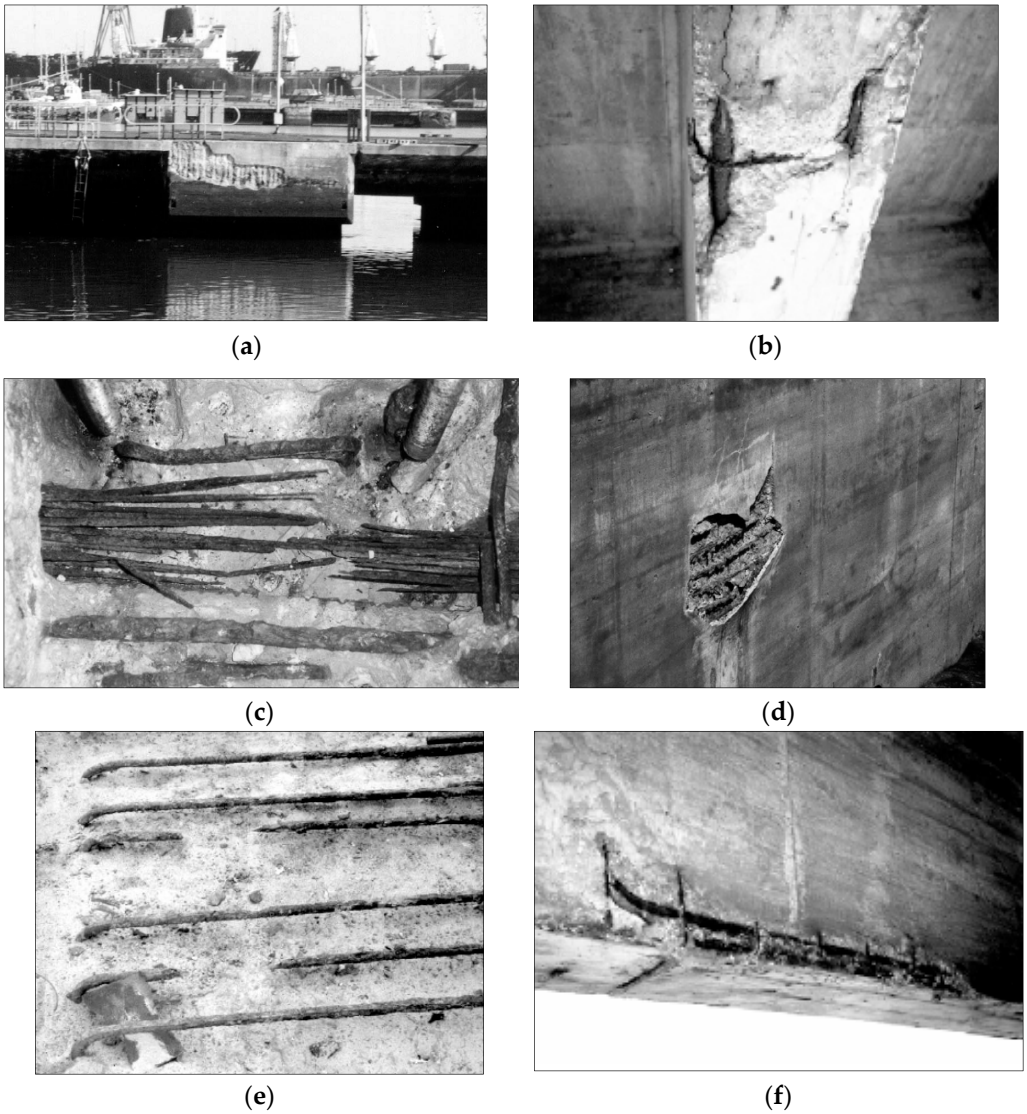


Figure 10. (**a**) Typical deterioration observed for a bridge in Sado River, Portugal in the splash and tidal zones; (**b**) concrete spalling in a construction joint; (**c**) corrosion of prestressing steel in ungrouted ducts; (**d**) macro-corrosion cell in dock walls; (**e**) bars with 25 mm diameter totally corroded; (**f**) concrete spalling in a low cover zone [35].

Table 4. Fuzzy types of chemical deteriorations value of a bridge in Portugal: case study.

	Types of Chemical Deteriorations	Value
1	Cation exchange reaction–formation of soluble calcium salt	55
2	Cation exchange reaction–formation of insoluble and non-expansion salt	56
3	Cation exchange reaction–chemical attack by magnesium salt	50
4	Concrete disintegration from products of expansive reactions–sulfate attack due to ingress of external sulfate ion	53
5	Concrete disintegration from products of expansive reactions–sulfate attack due to ingress of internal sulfate ion	53
6	Concrete disintegration from products of expansive reactions—ASR	40

Table 4. *Cont.*

	Types of Chemical Deteriorations	Value
7	Concrete disintegration from products of expansive reactions—ACR	16
8	Concrete disintegration from products of expansive reactions—hydration of magnesium oxide and crystalline calcium oxide	56
9	Reinforced concrete corrosion due to carbonation	51
10	Reinforced concrete corrosion due to chloride ion diffusion	57

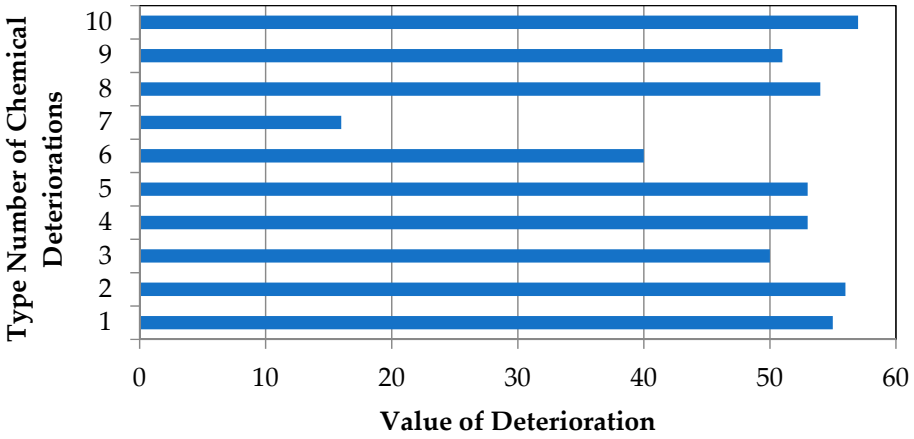


Figure 11. Deteriorations types diagnosis of a bridge in Portugal by a fuzzy expert system: case study.

The outputs of the developed fuzzy expert system indicate that the deterioration type occurring is correctly diagnosed according to its coastal environment and the observations of the bridge deterioration symptoms.

8. Limitations and Future Work

The fuzzy expert system shows promising results in diagnosing chemical deterioration in reinforced concrete structures, but there are certain limitations that need acknowledgment to drive further improvements and developments in this field. Firstly, the accuracy and reliability of the system heavily rely on the quality of data collected from inspections and other sources. Inaccuracies in data recording or insufficient data availability can impact the system's performance. Future work should focus on enhancing data collection methods and ensuring the consistency and completeness of the input data.

Secondly, the effectiveness of the fuzzy expert system depends on the rules and knowledge base it operates upon. Fine-tuning and expanding the rule base with additional concrete technology expertise could lead to more precise and comprehensive diagnoses. Collaboration with domain experts to refine the rules can be a valuable step in this direction.

While the fuzzy logic approach helps manage uncertainties to some extent, the system may still face challenges in dealing with extreme or rare cases. Future research should explore advanced fuzzy logic techniques or consider incorporating other machine learning approaches to further improve the system's ability to handle uncertainty. Additionally, the developed fuzzy expert system requires rigorous validation and calibration to ensure its accuracy and reliability across various scenarios and environments. Conducting extensive case studies and comparing the system's outputs with real-world data will be crucial to validate its performance.

Future efforts should focus on optimizing the system's performance to provide real-time or near-real-time results. A user-friendly interface that allows easy input of data and interpretation of results is vital for the practical implementation of the fuzzy expert system. Ensuring accessibility and usability for engineers and practitioners with varying

levels of expertise is crucial. Extending the fuzzy expert system to support multi-attribute decision-making can enhance its capabilities. By considering multiple factors, such as cost, feasibility, and urgency, the system can aid in prioritizing maintenance actions more effectively. To gauge the long-term effectiveness of the fuzzy expert system in practical applications, continuous monitoring and assessment of repaired structures over time are necessary. This feedback loop will help refine and improve the system's performance based on real-world outcomes.

9. Conclusions

Different types of chemical deteriorations are of significant concern in the maintenance of reinforced concrete structures, as they can lead to a reduction in the service life of structures. The need for effective strategies to prevent or mitigate chemical deterioration is crucial to ensure the long-term performance and durability of these structures. Proper planning and maintenance play a vital role in managing the impact of chemical deterioration, thereby minimizing the risk of structural failure. Diagnosing the type and extent of chemical deterioration is essential for developing appropriate maintenance and repair strategies. However, the process of diagnosis is often complicated by the uncertain and ambiguous nature of the information involved. Factors such as the variability in data collected from inspections, the expertise and experience of the individuals involved, and the complex environmental conditions further contribute to the challenges of accurate diagnosis.

To address these issues, this study introduces a novel approach using a fuzzy expert system. By integrating fuzzy logic and knowledge from the field of concrete and reinforced concrete structure technology, this intelligent software aims to minimize uncertainties and ambiguities in the diagnosis process. The fuzzy expert system provides a systematic and structured framework for analyzing deterioration data, allowing for more reliable and accurate diagnoses. The advantage of utilizing a fuzzy expert system lies in its ability to effectively handle the inherent uncertainties in the data. By employing fuzzy logic, the system can capture and process imprecise and vague information, enabling a more comprehensive understanding of the extent and type of chemical deterioration. The system utilizes a wide range of input data, including various symptoms and inspection results, and applies fuzzy operations to derive meaningful insights.

The outcomes of this research hold significant implications for the management system of reinforced concrete structures. The development of the fuzzy expert system offers a valuable tool for engineers, practitioners, and decision-makers involved in the maintenance and repair of these structures. The system's ability to provide more precise and reliable information regarding the type and extent of chemical deterioration can greatly enhance the planning and implementation of maintenance strategies. By utilizing the fuzzy expert system, stakeholders can make informed decisions, allocate resources effectively, and prioritize maintenance actions based on accurate and detailed diagnoses. This in turn leads to improved structural integrity, extended service life, and reduced life-cycle costs of reinforced concrete structures. In conclusion, the introduction of a fuzzy expert system represents a significant advancement in the field of diagnosing chemical deterioration in reinforced concrete structures. The utilization of fuzzy logic and concrete technology knowledge contributes to overcoming the challenges of uncertainty and ambiguity in the diagnosis process. By providing a systematic and reliable approach, the fuzzy expert system enhances the understanding of chemical deterioration and supports the development of effective maintenance strategies.

Author Contributions: Conceptualization, A.F., H.N. and A.T.; methodology, A.F. and A.T.; software, A.F. and R.P.; validation, A.F., A.T. and P.G.A.; formal analysis, G.K. and P.G.A.; investigation, A.F., A.T., R.P. and H.N.; resources, H.N., A.F.; data curation, A.T., G.K. and H.N.; writing—original draft preparation, A.F., P.G.A. and H.N.; writing—review and editing, A.F., A.T., R.P. and G.K.; visualization, A.F.; supervision, R.P., H.N. and P.G.A. All authors have read and agreed to the published version of the manuscript.

Funding: This study received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jain, K.K.; Bhattacharjee, B. Application of Fuzzy Concepts to the Visual Assessment of Deteriorating Reinforced Concrete Structures. *J. Constr. Eng. Manag.* **2012**, *138*, 399–408. [CrossRef]
2. Yuan, H.; Dangla, P.; Chatellier, P.; Chaussadent, T. Degradation Modelling of Concrete Submitted to Sulfuric Acid Attack. *Cem. Concr. Res.* **2013**, *53*, 267–277. [CrossRef]
3. Chiu, C.-K.; Lin, Y.-F. Multi-Objective Decision-Making Supporting System of Maintenance Strategies for Deteriorating Reinforced Concrete Buildings. *Autom. Constr.* **2014**, *39*, 15–31. [CrossRef]
4. Santhanam, M.; Otieno, M. Deterioration of Concrete in the Marine Environment. In *Marine Concrete Structures*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 137–149.
5. Dasar, A.; Hamada, H.; Sagawa, Y.; Yamamoto, D. Deterioration Progress and Performance Reduction of 40-Year-Old Reinforced Concrete Beams in Natural Corrosion Environments. *Constr. Build. Mater.* **2017**, *149*, 690–704. [CrossRef]
6. Ma, Y.; Guo, Z.; Wang, L.; Zhang, J. Probabilistic Life Prediction for Reinforced Concrete Structures Subjected to Seasonal Corrosion-Fatigue Damage. *J. Struct. Eng.* **2020**, *146*, 04020117. [CrossRef]
7. Marzouk, M.; ElSharkawy, M.; Elsayed, P.; Eissa, A. Resolving Deterioration of Heritage Building Elements Using an Expert System. *Int. J. Build. Pathol. Adapt.* **2020**, *38*, 721–735. [CrossRef]
8. Qu, F.; Li, W.; Dong, W.; Tam, V.W.Y.; Yu, T. Durability Deterioration of Concrete under Marine Environment from Material to Structure: A Critical Review. *J. Build. Eng.* **2021**, *35*, 102074. [CrossRef]
9. Robles, K.P.V.; Yee, J.-J.; Kee, S.-H. Electrical Resistivity Measurements for Nondestructive Evaluation of Chloride-Induced Deterioration of Reinforced Concrete—A Review. *Materials* **2022**, *15*, 2725. [CrossRef]
10. Liu, X.; Ma, E.; Liu, J.; Zhang, B.; Niu, D.; Wang, Y. Deterioration of an Industrial Reinforced Concrete Structure Exposed to High Temperatures and Dry-Wet Cycles. *Eng. Fail. Anal.* **2022**, *135*, 106150. [CrossRef]
11. Chen, H.-P.; Jiang, Y.; Markou, G. Structural Performance Deterioration of Corroding Reinforced Concrete Columns in Marine Environments. *Ocean Eng.* **2022**, *262*, 112155. [CrossRef]
12. Younus Pasha, M.; Prasad Joshi, S. Structural Performance of Deteriorating Reinforced Concrete Structure. *Mater. Today Proc.* **2023**, *72*, 3201–3208. [CrossRef]
13. Matthews, B.; Palermo, A.; Scott, A. Overview of the Cyclic Response of Reinforced Concrete Members Subjected to Artificial Chloride-induced Corrosion. *Struct. Concr.* **2023**, *24*, 100–114. [CrossRef]
14. Ben Seghier, M.E.A.; Keshtegar, B.; Mahmoud, H. Time-Dependent Reliability Analysis of Reinforced Concrete Beams Subjected to Uniform and Pitting Corrosion and Brittle Fracture. *Materials* **2021**, *14*, 1820. [CrossRef]
15. Kumar, A.; Arora, H.C.; Kumar, K.; Garg, H. Performance prognosis of FRCM-to-concrete bond strength using ANFIS-based fuzzy algorithm. *Expert Syst. Appl.* **2023**, *216*, 119497. [CrossRef]
16. Naderpour, H.; Sharei, M.; Fakharian, P.; Heravi, M.A. Shear Strength Prediction of Reinforced Concrete Shear Wall Using ANN, GMDH-NN and GEP. *J. Soft Comput. Civ. Eng.* **2022**, *6*, 66–87. [CrossRef]
17. Guo, Z.; Guo, R.; Yao, G. Multi-factor model to predict surface chloride concentration of concrete based on fuzzy logic system. *Case Stud. Constr. Mater.* **2022**, *17*, e01305. [CrossRef]
18. Shaffiee Haghshenas, S.; Shaffiee Haghshenas, S.; Abduelrhman, M.A.; Zare, S.; Mikaeil, R. Identifying and Ranking of Mechanized Tunneling Project's Risks by Using A Fuzzy Multi-Criteria Decision Making Technique. *J. Soft Comput. Civ. Eng.* **2022**, *6*, 29–45. [CrossRef]
19. Rogulj, K.; Pamukovic, J.K.; Jajac, N. Knowledge-Based Fuzzy Expert System to the Condition Assessment of Historic Road Bridges. *Appl. Sci.* **2021**, *11*, 1021. [CrossRef]
20. Sharma, S.; Aroa, H.C.; Kumar, A.; Kontoni, D.P.N.; Kapoor, N.R.; Kumar, K.; Singh, A. Computational Intelligence-Based Structural Health Monitoring of Corroded and Eccentrically Loaded Reinforced Concrete Columns. *Shock Vib.* **2023**, *2023*, 9715120. [CrossRef]
21. Ghanizadeh, A.R.; Ghanizadeh, A.; Asteris, P.G.; Fakharian, P.; Armaghani, D.J. Developing Bearing Capacity Model for Geogrid-Reinforced Stone Columns Improved Soft Clay Utilizing MARS-EBS Hybrid Method. *Transp. Geotech.* **2023**, *38*, 100906. [CrossRef]
22. Nuhu, B.K.; Aliyu, I.; Adegboye, M.A.; Ryu, J.K.; Olaniyi, O.M.; Lim, C.G. Distributed network-based structural health monitoring expert system. *Build. Res. Inf.* **2021**, *49*, 144–159. [CrossRef]

23. Naderpour, H.; Rezazadeh Eidgahee, D.; Fakharian, P.; Rafiean, A.H.; Kalantari, S.M. A New Proposed Approach for Moment Capacity Estimation of Ferrocement Members Using Group Method of Data Handling. *Eng. Sci. Technol. Int. J.* **2020**, *23*, 382–391. [CrossRef]
24. Barkhordari, M.S.; Armaghani, D.J.; Fakharian, P. Ensemble Machine Learning Models for Prediction of Flyrock Due to Quarry Blasting. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 8661–8676. [CrossRef]
25. Graybeal, B.A.; Rolander, D.D.; Phares, B.M.; Moore, M.E.; Washer, G.A. Reliability and Accuracy of In-Depth Inspection of Highway Bridges. *Transp. Res. Rec. J. Transp. Res. Board* **2001**, *1749*, 93–99. [CrossRef]
26. Ghazanfari, M. *Principles of Expert Systems*; Iran University of Science and Technology Press: Tehran, Iran, 2003.
27. Al Abedin, H.M.Z.; Eldin, A.S. Toward an Expert System for the Evaluation of Damage in Concrete Structures in Saudi Arabia. In Proceedings of the Dunde Congress; Cambridge University Press: Cambridge, UK, 1999; pp. 645–657.
28. Vagiotas, P.; Chassiakos, A.P.; Theodorakopoulos, D.D. Modelling Expert Decisions for Highway Bridge Maintenance. In Proceedings of the Seventh International Conference on the Application of Artificial Intelligence to Civil and Structural Engineering; Civil-Comp Press: Stirlingshire, UK, 2003; p. 13.
29. Tarighat, A.; Miyamoto, A. Fuzzy Concrete Bridge Deck Condition Rating Method for Practical Bridge Management System. *Expert Syst. Appl.* **2009**, *36*, 12077–12085. [CrossRef]
30. Shabaninia, F.; Saeednia, S. *Fundamental of Fuzzy Control Textbox Using MATLAB*; Khaniran Press: Tehran, Iran, 2006.
31. Zadeh, L.A. Fuzzy Sets. *Inf. Control* **1965**, *8*, 338–353. [CrossRef]
32. Tanyildizi, H. Fuzzy Logic Model for the Prediction of Bond Strength of High-Strength Lightweight Concrete. *Adv. Eng. Softw.* **2009**, *40*, 161–169. [CrossRef]
33. Kim, Y.M.; Kim, C.K.; Hong, G.H. Fuzzy Set Based Crack Diagnosis System for Reinforced Concrete Structures. *Comput. Struct.* **2007**, *85*, 1828–1844. [CrossRef]
34. Palanci, M. Fuzzy Rule based Seismic Risk Assessment of One-Story Precast Industrial Buildings. *Earthq. Eng. Eng. Vib.* **2019**, *18*, 631–648. [CrossRef]
35. Costa, A.; Appleton, J. Case Studies of Concrete Deterioration in a Marine Environment in Portugal. *Cem. Concr. Compos.* **2002**, *24*, 169–179. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.