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Durability Prediction And Assessment Using Deep Learning:A Comprehensive Review

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Abstract
In recent decades, the durability of concrete has become a significant area of research and continues to be a key concern in the construction field. Issues such as cracking and spalling are widespread and often stem from environmental influences, substandard construction practices, insufficient oversight, design flaws, and other contributing factors. This paper explores the latest developments in concrete durability research, addressing common issues like alkali-aggregate reactions, sulfate attacks, corrosion of steel reinforcement, and freeze-thaw cycles. These problems can lead to structural degradation or a loss of strength within just a few years. Accurately identifying the location and size of cracks can also be quite difficult. Recent advancements in deep learning have introduced highly accurate methods for crack detection. In this study, over 60 research papers published in top-tier journals and conferences within the past three years were collected through a systematic literature review. These studies were then categorized into 10 key topics based on the accuracy of their crack prediction results: trial-and-error methods, Transfer Learning (TL), Encoder-Decoder (ED), Generative Adversarial Networks (GAN), YOLO V5, LeNet-5, Mask R-CNN, Artificial Neural Networks (ANN), Support Vector Machines (SVM), Binarization, YOLO V3, 3D-SM, IPZ, and VGG-16. This survey aims to analyze the strengths and weaknesses of the models within each category, with a particular focus on the latest advancements in Convolutional Neural Networks (CNNs) and YOLO V5. Third, the study identifies the commonly used evaluation metrics and loss functions applied to CNN and YOLO V5 datasets. Finally, it examines several recurring challenges in the fields of CNN and YOLO V5, analyzes existing solutions, and offers recommendations for future research directions.
Keywords: *Convolutional Neural Network, Crack and Spalling, Deep learning, Durability, Freez-thaw Cycle*

INTRODUCTION

Each year, billions of metric tons of concrete are produced and utilized in construction projects across the globe. With the continuous growth of global economic activity, this number is expected to increase further. When properly proportioned to meet strength requirements, concrete plays a vital role in building sustainable infrastructure. Water is also a key ingredient, as it enables the hydration process that imparts strength and durability to concrete. [1]. Failure to attain the assumed compressive strength during the design stage, on the other hand, may have a negative impact on the expected performance of the reinforced concrete structural parts. The durability of Portland cement concrete refers to its ability to resist weathering, chemical attacks, abrasion, and other forms of deterioration while retaining its original shape, quality, and functionality in its intended service conditions. Durability issues often begin with the initial stages of material degradation. Although these early signs may not pose immediate safety risks, continued deterioration can eventually lead to structural damage, compromising the integrity of the structure. Concrete degradation is generally classified into three types: mechanical, chemical, and physical—each of which can lead to significant durability concerns, such as the corrosion of embedded steel. [2]. Alkali aggregate reaction, sulfate attack, steel corrosion, and freeze-thaw are all significant durability issues. Concrete's durability in a saltwater environment. The relationship between mechanical load and environmental condition affecting concrete durability. Numerous researchers have extensively investigated durability issues to identify effective solutions. Manual inspections, typically performed by experienced inspectors, rely heavily on subjective judgment and empirical knowledge, often making the process time-consuming. This delay hinders timely verification of infrastructure integrity. To address these limitations, researchers have proposed deep learning techniques. Their studies encompass various degradation phenomena, including carbonation, alkali-aggregate reactions, reinforcement corrosion, sulfate attacks, calcium hydroxide leaching, freeze-thaw cycles, cracking, and spalling. The deterioration of concrete structures is often a complex process influenced by multiple factors, including environmental conditions, mechanical stresses, and, at times, chemical reactions. [3-8]. In order to more accurately forecast the durability and functionality of concrete structures under actual conditions, researchers have been concentrating more on comprehending these coupled impacts. The durability loading carrying ability unified service life design technique or durability-based design standards [9] have been proposed by numerous countries as a consequence of durability investigations. Based on a few chosen related activities, this paper begins with a discussion of current studies related to significant durability difficulties. The next subsections address the main issues with concrete durability, such as steel corrosion, sulfate assault, alkali-aggregate reaction, and freeze-thaw.

Alkali-Aggregate Reaction In Concrete

In concrete buildings, the alkali-aggregate reaction (AAR) occurs when alkalis in pore solution mix with active compounds from aggregates. AAR attacks can be classified into two types: alkali-carbonate reaction (ACR) with active minerals from dolomitic limestone aggregate [10] and alkali-silica reaction (ASR) with active minerals from amorphous silica.The following testing methods are commonly used to evaluate AAR: autoclave testing method [11], chemical shrinkage test, concrete prism test [12], stiffness damage test [13], dynamic modulus and gel fluorescence test, mortar bar test, rock cylinder method, rapid test methods, and accelerated mortar bar method. In addition to the previously stated standard tests, Liu and Mukhopadhyay developed a method for measuring compound activation energy, as shown in Fig. 1. This method involved testing highly reactive borosilicate glass and/or various aggregate kinds with a NaOH + $Ca(OH)_2$ solution. It has been proven that when the ASR between aggregates and alkali solution advances, volume change in a closed system occurs in the form of chemical shrinkage. The authors compared the observed change volume over time to the danger potential and actual reaction degree of ASR [14].

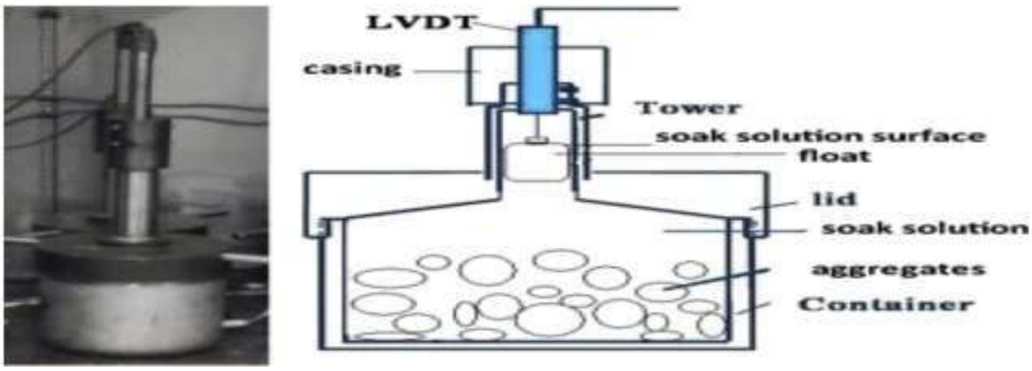

Figure 1. The compound activation energy measurement

The extent of Alkali-Aggregate Reaction (AAR) is generally affected by several factors: 1) moisture levels (since ASR primarily occurs under high relative humidity), 2) the alkali content in the mix, 3) the porosity of the concrete, and 4) temperature. To mitigate AAR, the following measures are recommended: 1) use aggregates that are non-reactive or free from harmful components, 2) opt for low-alkali Portland cement or cement blended with adequate pozzolanic materials, 3) maintain low moisture levels in the concrete, as deterioration is typically not observed below 80% relative humidity, 4) apply coatings that limit diffusion, and 5) incorporate nitrate salts as an additive.

Damage caused by sulfate violence

Sulfate attack is a major cause of concrete structural expansion and damage. This expansion is attributable to interactions between sulfate ions and various hydration products in the concrete structure.

Typically, specimens are stored in a solution of either sodium or magnesium sulfate, or a combination of the two, to test for sulfate resistance [2]. These days, a number of indications are typically used to evaluate the impact of sulfate assault, including changes in length, mass loss or gain, surface hardness [15], strength, and a decrease in elastic elasticity. However, neither of these markers can be linked to performance under actual settings, nor do they offer enough information to evaluate chemical reactions and comprehend the underlying harm mechanisms [16]. To investigate the deterioration process of concrete structures brought on by sulfate attack, novel testing techniques are essential. Electrochemical impedance spectroscopy was used by Braganca et al. to identify sulfate attack without causing any damage. The testing entailed collecting ten data points per frequency decade, utilizing an alternating current pulse with a 25 mV amplitude spanning a frequency range of 10^{6} to 5×10^{-2} Hz under open-circuit potential circumstances. The results from reinforced mortar samples exposed to a sulfate-rich environment showed that electrochemical impedance spectroscopy is useful for detecting early-stage degradation and gradual durability loss. Further investigation of the sulfate distribution and comparable electrical circuits verified the development of monosulfate byproducts inside the matrix, which impeded the typical formation of cement hydrates during curing [17]. Using a novel approach, Hachem et al. investigated the relationship between specimen size and resistance to sulfate assault. The experiment, shown in Fig. 2, was conducted under controlled conditions, with a constant pH of 7.5 and a temperature of 20 °C. To maintain the pH, a 0.5 mol/L nitric acid solution was utilized. The specimens' mass and length were measured each time the solution was replaced. Based on the experimental results, the researchers determined that the rapid sulfate attack was mostly due to higher leaching kinetics, rather than the creation of expanding reaction products [18, 19].

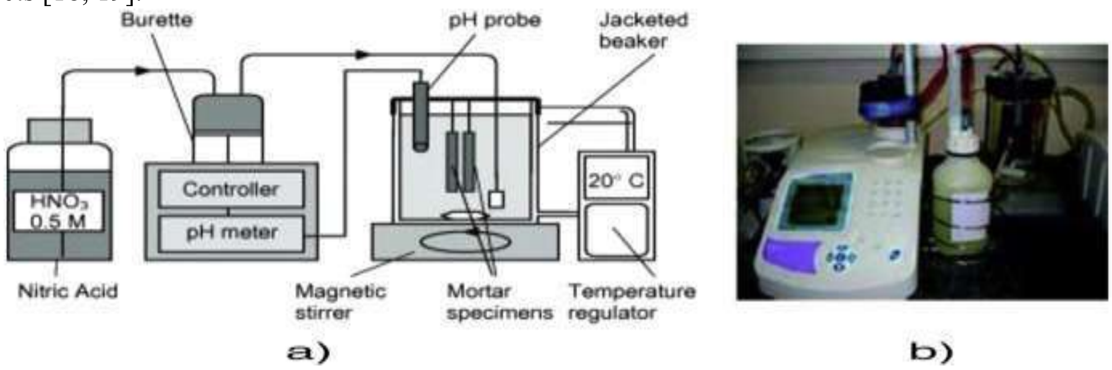

Figure 2. Sulfate test diagram

Stroh et al., using high-resolution synchrotron X-ray diffraction (SyXRD), establish that after nineteen years of concrete exposure to sulfate-rich soil, gypsum was concentrated near the surface, while ettringite emerged as the dominant crystalline phase within the inner layers of the concrete [19].

The standard external $MgSO_4$ solution immersion approach can take over a year to produce a significant volume of thaumasite for research purposes. Li et al. developed a "internal addition" strategy to expedite thaumasite production in laboratory settings. This process involved curing cement-limestone pastes with 10% magnesium sulfate in water at 5 ± 2 °C for six months. This new approach was proposed as a substantially faster option to investigating thaumasite-related sulfate assaults [20].

Researchers recently used non-linear shock resonance sonic spectroscopy to track the evolution of exogenous sulfate attack. This approach detects changes in material qualities by measuring shifts in the resonance frequencies of a specimen's vibrational modes. The experimental setup for this procedure is shown in Fig. 3.

Figure 3. Experimental set-up - Non-linear shock resonance sonic spectroscopy

It has shown to be extremely sensitive to the existence of microcracks and is ideal for identifying low to moderate expansion damage induced by sulfate exposure. Notably, the results of this acoustic spectroscopic method nearly matched those of microstructural analysis [21]. The complex physical/chemical interaction of sulfate attack is influenced by a variety of factors, including sulfate ion concentration, ambient temperature, cement/mineral additives, water to cement ratio, concrete diffusivity and/or permeability, and the presence of additional pozzolanic admixtures [2, 22]. The following are some effective ways for mitigating the negative effects of sulfate attack. Incorporating ground granulated blast furnace slag (GGBFS) into cement can assist limit expansion in concrete structures that encounter sulfate environments because it partially consumes calcium hydroxide, resulting in lower development of gypsum and ettringite [23]. Studies have shown that adding more than 30% low-reactivity GGBFS significantly enhances mortar resistance to both sodium and magnesium sulfate attacks. After one year of exposure, Arribas et al. observed that slag-containing mortars exhibited less expansion due to sulfate attack compared to conventional control mortars. Because of the reactivity of the fine portion of the slag aggregate and the absence of internal damage, these slag mortars increased in strength more than the control mortar. In the fly ash scenario, concrete compositions containing bottom ash and circulating fluidized bed combustion ash also shown greater resistance to external sulfuric acid assault [24, 25]. Concrete deterioration against sulfate attack and thaumasite production can be slightly mitigated by increasing the depth of the buried covering [26].Mortar mixed with pulverized glass powder showed a significant enhancement in resistance to sulfate attack, thereby improving its overall durability. In sodium sulfate resistance tests, mortar specimens experienced the least weight loss when 10% of the cement was appropriately replaced with glass powder [27]. In their work on dual sulfate assault, Nehdi et al. investigated concrete that was partly submerged in a 5% sodium sulfate solution with changing temperature and humidity. They discovered that capillary action was the primary mechanism for solution flow through the partly exposed concrete. This resulted in physical sulfate assault in the upper area due to its natural pore structure, but the submerged bottom half was more prone to chemical sulfate attack [28, 29].Bentz et al. investigated two novel strategies to enhance mortar’s resistance to sulfate attack. One approach involved adding a viscosity-modifying agent to the mix to increase the pore solution's thickness, thereby slowing the ingress of sulfate ions from external sources. The other strategy utilized pre-wetted fine lightweight aggregates, which not only improved the interfacial transition zone's microstructure but also provided isolated pores that could absorb expansive products like ettringite, helping to reduce internal stress and mitigate cracking [30]. Over time, incorporating magnesium oxide into concrete can enhance its resistance to sulfate, chloride, and carbonation attacks. A higher water reduction from a sufficient quantity of superplasticizer in the concrete blend reduces sulfate attack on the concrete and provides a stronger matrix. A new technique for making sulfate-resistant cements was through the incorporation of barium carbonate to clinker. The major approach relied on barium's capacity to immobilize sulfates in the form of extremely insoluble barite.

DETERIORATION DUE TO STEEL CORROSION

Reducing the quantity of metallic corrosion is a difficult problem in real-life engineering because it is considered the most serious durability concern in building engineering [31]. Improving concrete quality has been viewed as the primary defense approach, as it appears that the mixture of concrete cover thickness and concrete quality is the most important factor influencing the rate of carbonation and chloride intrusion [32]. Protection strategies include increased concrete coverage; rebar coating, stainless steel, and corrosion inhibitors. In general, the amount of concrete covering the rebar can significantly affect how long it takes for the embedded reinforcing steel to corrode [2].

Coating reinforcing steel enhances its durability by forming a barrier that prevents aggressive agents from reaching the steel surface and partially shielding it from electrical currents. Recent research has shown that epoxy coatings applied either as a liquid or as a heat-fused powder offer significantly better protection against steel corrosion compared to traditional zinc or red oxide primer coatings. ASTM A775/A775M-04a specifies the main specifications for electrostatically sprayed epoxy-coated reinforcing bars. However, one of the key factors contributing to lower effectiveness is the damage incurred by the epoxy coating prior to the pouring of the concrete [33]. Training is required to properly create, handle, and apply the coating, as well as repair field damage to epoxy-coated bars. Furthermore, the link between concrete and epoxy-coated rebar needs to be strengthened because it is weaker than the link between concrete and normal rebar. Stainless steel bars have been the topic of several researches [34, 35]. Non-welded AISI 304 (a form of stainless steel) reinforcement has been shown to have a three to five-fold greater chloride threshold value for corrosion onset than conventional rebar. Nonetheless, the critical chlorine level was reduced by 50% after the bar was welded. It is crucial to realize that employing stainless rebar is an expensive option.

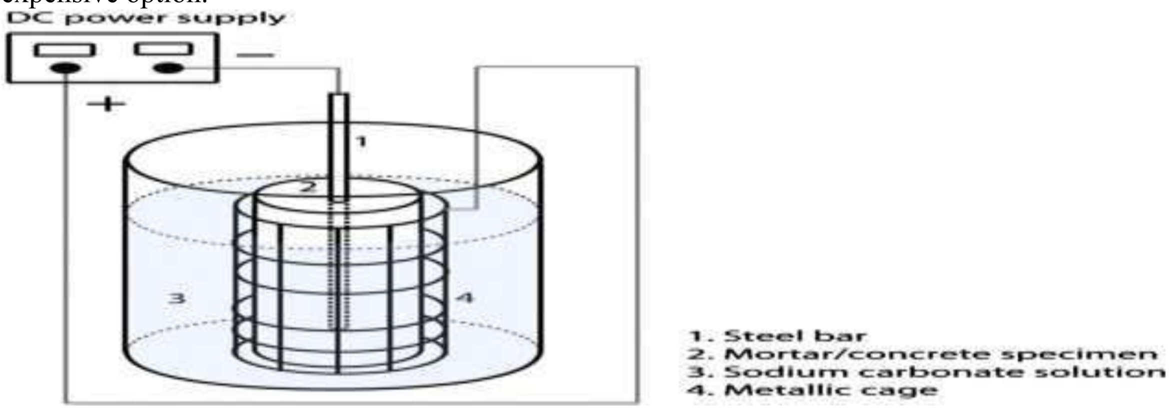

Figure 4. Set-up for electrochemical treatment

Galvanized steel, which is steel coated with zinc, is widely regarded as an effective method for corrosion protection. It serves both as a barrier and as a sacrificial coating, offering dual protection. However, a key limitation is that the zinc layer gradually corrodes over time, similar to other metallic coatings. The rate at which the coating degrades, thus its longevity depends on the specific environmental conditions. In industrial environments, the relationship between the thickness of the zinc coating and the steel's effective service life is typically close to linear [36]. Zinc's stability is highly dependent on the pH of the surrounding environment. Corrosion products can form on the zinc surface, creating a protective layer that helps passivate the coating and prevent the release of hydrogen gas. However, when ungalvanized and galvanized steel blocks are used together in the similar structure, it is essential to ensure complete electrical isolation between them to prevent galvanic corrosion [37]. Fibrous composites have been used in place of reinforcing steel in concrete since the 1990s. Fibrous composites are typically composed of polymers (polyester and epoxy) as the matrix and uninterrupted fibers (carbon and stable glass) as reinforcement. The corrosion issue can be totally resolved by applying fiber composites. Nevertheless, these composites' high cost and great temperature sensitivity are disadvantages [2].

A study found that deep penetration of cement-based mortars and concrete with ethyl silicate the solution. This is combined with electrochemical treatments with sodium carbonate solution, can improve bond strength of embedded plain steel bars in present buildings without requiring demolition or re-alkalization. Figure 4 illustrates the electrochemical treatment setup. Corrosion testing showed that immersion treatment reduced mortar corrosion risk from high to low [38].

A low-coherent fiber optic sensor array was developed to detect steel corrosion-related deterioration at an early stage. This apparatus effectively monitored corrosion-induced expansion with sub-micro strain accuracy by revolving the detecting optical fiber in two different configurations. One technique was to wire the fiber straight onto a steel rock bolt, while the other was to wrap the fiber around a mortar cushion. In contrast to these two arrangements, an interface-dominated corrosion mechanism was more sensitive to the steel's interface's regularity [39].

Freeze–thaw

While water in concrete is closely linked to freeze-thaw damage, the expansion of water during freezing alone does not fully account for the deterioration. Common indicators of damage include a drop in dynamic modulus or a decrease in mass. In recent times, innovative testing techniques have emerged, enabling the monitoring of freeze-thaw degradation through supplementary physical evaluations.

By varying the ultrasonic pulse velocity during the freeze-thaw cycle, Guneyisi et al. examined the degradation of concrete. They came to the conclusion that variations in ultrasonic pulse velocity could be caused by changes in the morphology of pore structures during the freeze-thaw cycle [41]. However, when the Aghabaglou study group evaluated the freeze-thaw resistance of large-scale fly ash concrete, it was demonstrated that the dynamic modulus of elasticity correlated with the weight change percentage in freeze-thaw cycles [42]. Furthermore, Bui et al. examined two different non-linear acoustics techniques—the indirect transmission, which uses incident waves at 90°, and the semi-direct transmission, which uses incident waves at 45°—for mortar samples that had varied levels of damage from freeze-thaw cycles [43]. The test findings for both of these approaches shown a high sensitivity to the onset of cracking caused by a freeze-thaw attack. Dai and Ng rapidly acquired high-resolution (30 nm) in situ images of capillary holes and the emergence of micro-damage using a transmission X-ray microscope (TXM). A 3D digital model was produced by stacking TXM slice images of consistent thickness, as illustrated in Fig. 5. This nanoscale digital representation can be used to investigate damage mechanisms and improve fracture models. The study found that the actual fracture paths shown in the TXM pictures matched the predefined pattern of crack propagation under theoretically computed pore pressure. The method also demonstrated how ice crystallization pressures in nanoscale holes could cause interior damage to cement paste due to frost action [44].

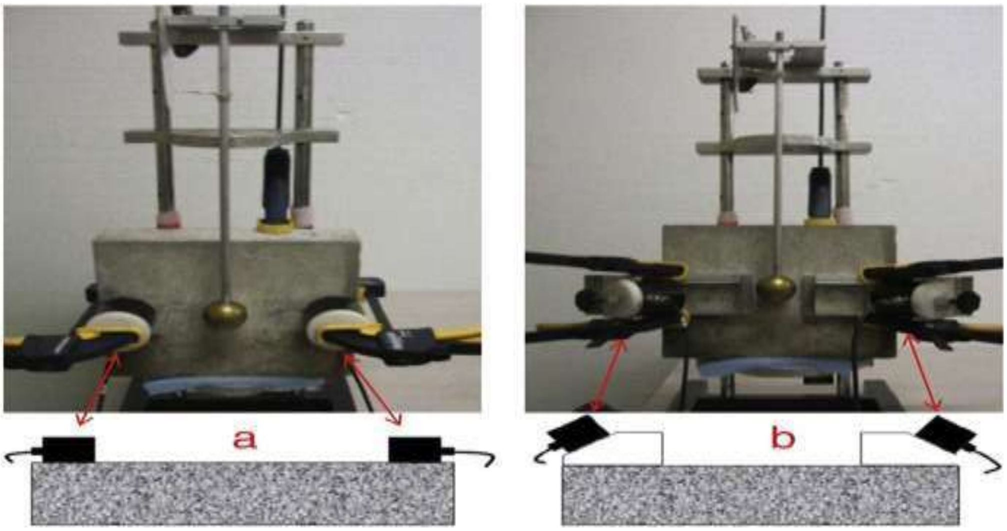

Figure 5. Non-linear acoustics techniques - (a) indirect transmission, (b) semi-direct transmission

Despite the fact that there are still many unanswered problems regarding frost damage, not much research has been done on the fundamental mechanisms. This condition may be the result of expertise with the ideal mix proportions and the application of air-entraining agents, which in practice can prevent harm [45]. In addition to traditional air-entraining chemicals, recent studies have shown that certain additives, in the right amounts, can improve freeze-thaw resistance. Synthetic zeolite, fiber, encapsulated siloxane, organic resins, and nanoparticles are some examples of these additions [46].

Durability Issue In A Marine Environment

Many concrete structures, such as long-span bridges, offshore drilling platforms, and undersea tunnels, are located in marine environments. These environments can be categorized into submerged, tidal, splash, and atmospheric zones, depending on the specific deterioration mechanisms affecting the concrete [47]. In the 1980s, P.K. Mehta identified the tidal zone of concrete structures as the most hazardous, as it experienced both physical and chemical environmental attacks. This zone was commonly associated with concrete spalling and steel reinforcement corrosion. Furthermore, Safehian et al. observed that the atmospheric zone was considerably less aggressive compared to other exposure conditions, with the tidal zone being the most severe, followed by the splash zone [48]. In tidal zones, the intrusion of harmful ions primarily occurs through advective transport, making the material's liquid permeability and diffusion coefficient particularly important. Additionally, concerns about the deterioration of concrete structures are inevitable due to the physical impact, erosion, and abrasion resulting from the continuous motion of waves and tides [2].

Crack And Spalling

The high concentrations of sulfates and chlorides in seawater typically cause hostility toward concrete structures. Chloride seeping into concrete is the main cause of steel reinforcement corrosion because it causes the steel surface to expand and concentrate strain. More ettringite crystals have developed as a result of the chemical reaction between the AFm in the concrete construction by the sulfate ions in the water. However, the quick disintegration of these crystals in seawater and subsequent leaching out of concrete structures may result in some material loss [49]. Therefore, limited permeability concrete is recommended to prevent sulfate and chloride degradation caused by the maritime environment.

Concretes incorporating certain mineral additives in appropriate proportions may exhibit a reduced chloride threshold for corrosion. This is often attributed to a decline in the cement's chloride-binding ability, a lower pH within the concrete's pore solution, and a weakened buffering capacity. In the case of fly ash, ternary Portland cements that include both fly ash and activated paper sludge have shown resistance to sodium sulfate attack. Sulfate ingress and the ensuing secondary reactions cause the alkaline activation of the additives' pozzolanic reactions, which in turn causes the creation of non-expansive ettringite within the pores, which is responsible for the enhanced performance. Fly ash concrete with a water-to-binder ratio of 0.45 and a fly ash replacement level of 15–35% by weight shown good performance at a maritime site, according to Cheewaket et al. [50]. When subjected to tidal marine conditions, Arribas et al. discovered that concrete created using slag aggregates from electric arc furnaces had more chloride penetration than concrete prepared with limestone aggregates. Furthermore, steel reinforcement in the slag aggregate concrete exhibited a greater propensity to corrode than that in the limestone-based reference concrete following a year of interaction with seawater in the tidal zone. Consequently, it is crucial to carefully choose the kind and amount of pozzolanic materials in maritime environments.. According to Zaccardi et al. [51], the effects of relative humidity and ambient temperature were crucial for future research on corroding structures in marine environments. Since relative humidity reflects the quantity of water vapour present, it has slight effect on the level of corrosion on its own. Through its effect on resistivity, the amount of evaporable (liquid) water regulates corrosion. Safehian et al. looked into how construction techniques affected the performance of chloride dispersion in silica fume concrete under harsh marine environments. They discovered that deep cracks created by construction flaws in reinforced concrete structures could increase chloride penetration and, as a result, prevent the structures from reaching their anticipated service life.

Deep Learning Techniques For Durability Prediction

Introduction to Deep Learning

A form of artificial intelligence (AI) called deep learning or machine learning enables software programs to improve their result prediction accuracy without being specifically designed to do so. By safeguarding the structure, skilled inspectors perform manual inspections, which take a lot of time and rely on their subjective and empirical expertise. This drawn-out procedure further jeopardizes the structural integrity of the infrastructure. We can use deep learning technology in the construction sector to overcome these constraints. Deep learning (DL)-based crack detection techniques have received a lot of attention in recent years because of their effective use in the computer vision (CV) and image fields.

Convolutional Neural Network (CNN)

Convolutional neural networks, or CNNs, are deep learning models that are frequently used to analyze picture data, especially for tasks like facial recognition, object detection, and image categorization. CNNs are used in this study to identify and categorize pavement cracks from photos by using layers including convolution, pooling, and fully connected layers to learn hierarchical features. To identify patterns, the network is trained using captioned photos of pavements that have been broken and those that have not. Furthermore, to detect and delineate fracture borders, semantic segmentation employs Fully Convolutional Networks (FCNs), a CNN version. FCNs are useful for both crack detection and localization because they substitute convolutional layers for fully connected ones while maintaining spatial information for pixel-wise classification.

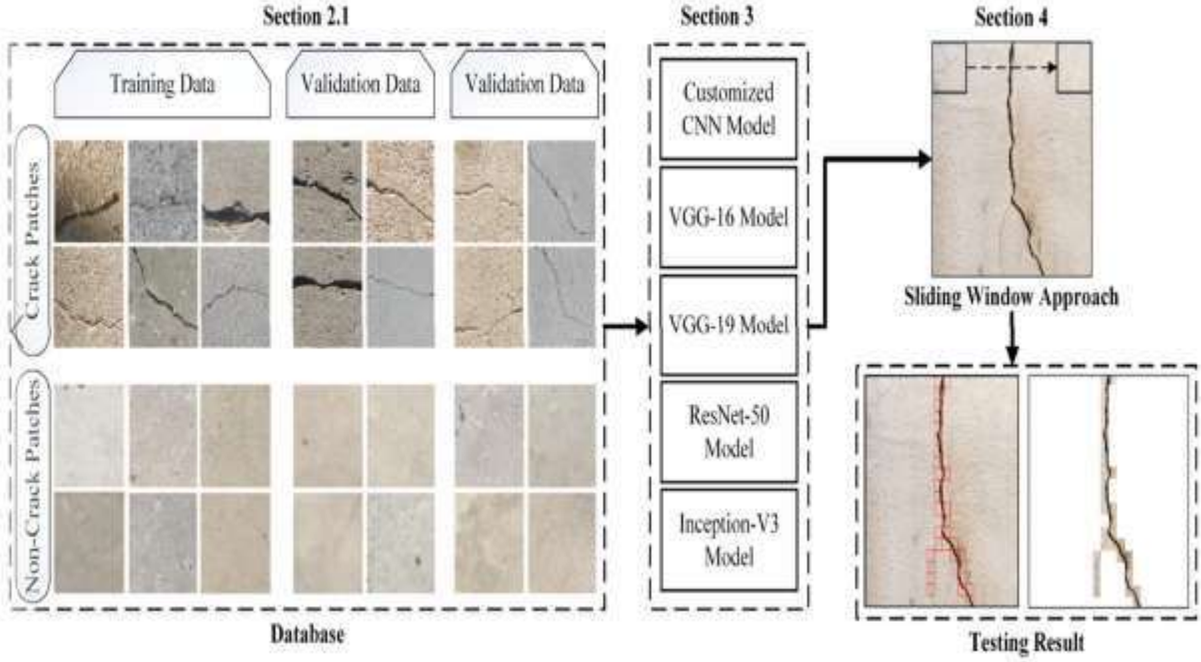

Figure 6. Outline of the proposed work

Luqman Ali et al. used a convolutional neural network to investigate the deterioration of concrete structures using a pre-trained model (VGG16) to automatically decay and find concrete fractures. Part 3 provides an explanation of the CNN and other pre-trained models, while Section 4 discusses and displays the results of our experiments. This section concludes with a summary. A flowchart of the proposed system is shown in Figure 6. The first module illustrates the database preparation step, while the second module shows the architecture and use of deep learning algorithms for crack identification in concrete structures. The last lesson describes how various measures are used to assess and compare the models [52].

Automatic crack detection is made possible by the suggested method, which has major advantages for concrete structure inspection. It illustrates how several deep learning models may be used to analyze concrete surfaces. Nevertheless, the existing system is unable to identify and track cracks in real time. A real-time robotic video inspection system prototype might be created by integrating the model with Internet of Things (IoT) devices [53]. The recommended method is unable to evaluate particular fracture properties including width, length, and direction. Based on factors like network complexity, training data size, sample variability, and the number of epochs needed to reach the specified test accuracy, this study assessed the performance of five deep learning models. The primary benefit of the suggested approach is its capacity to automatically identify and find cracks with little input data and processing. To detect distinct concrete flaws, the system can be improved by adding data from other structures. Real-time detection and localization capabilities are currently absent, though. The model could be used as a prototype for a real-time robotic video inspection system with IoT integration.. Image Processing Techniques (IPTs), introduced by Young-Jin Cha et al., have been employed to detect defects in civil infrastructure, offering an alternative to manual inspections. These methods process images to identify fault features like cracks on steel and concrete surfaces [54However, there may be obstacles to the widespread use of IPTs due to the vastly different real-world scenarios (such as variations in lighting and shadows). This article suggests a vision-based approach that uses a deep architecture of convolutional neural networks (CNNs) to detect concrete fractures without figuring out the fault features in order to get around these difficulties. The suggested approach does not require the conjugation of IPTs for feature extraction because CNNs can autonomously learn image features. 40 K photos with 256 × 256 pixel resolutions are used to train the proposed CNN, which records with an accuracy of roughly 98%. The findings demonstrate that the suggested approach performs noticeably better and is capable of detecting concrete cracks in practical settings. The complete process of our framework is summed up in this figure. Training phases (solid lines) and testing steps (dashed lines) illustrate the overall flow of the process is mentioned in Figure 7.

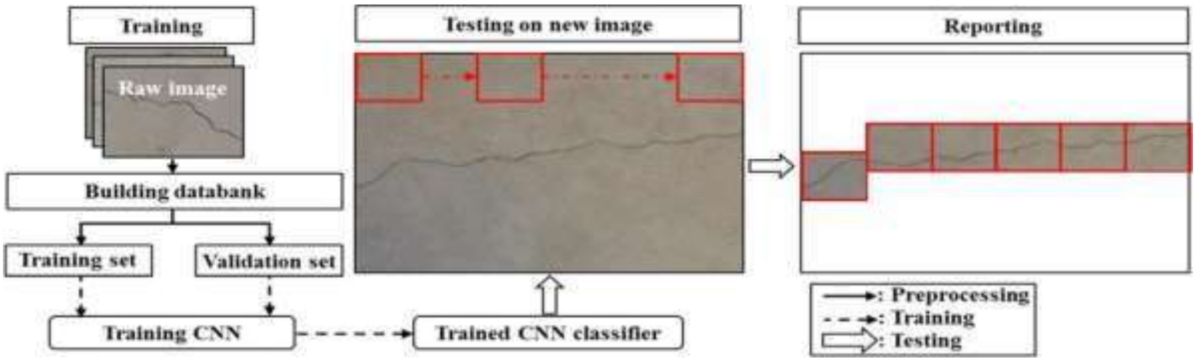

Figure 7. Training phases (solid lines) and testing steps (dashed lines)

Shengmin Wang and colleagues suggested a segmentation technique that can be applied to two typical structural problems in reinforced concrete structures: showing steel bars and concrete spalling. Training and testing on real structural surface disease images and public datasets confirms the detection method's accuracy and feasibility. It offers cutting-edge techniques and approaches for detecting the safety of reinforced concrete structures. Significant difficulties are presented by the common problems of showing steel bars and concrete spalling in RC constructions [55]. Using machine vision and deep learning algorithms, automatic identification methodology is put forth to identify showing steel bars and concrete spalling. Figure 8 illustrates the fundamental procedure.

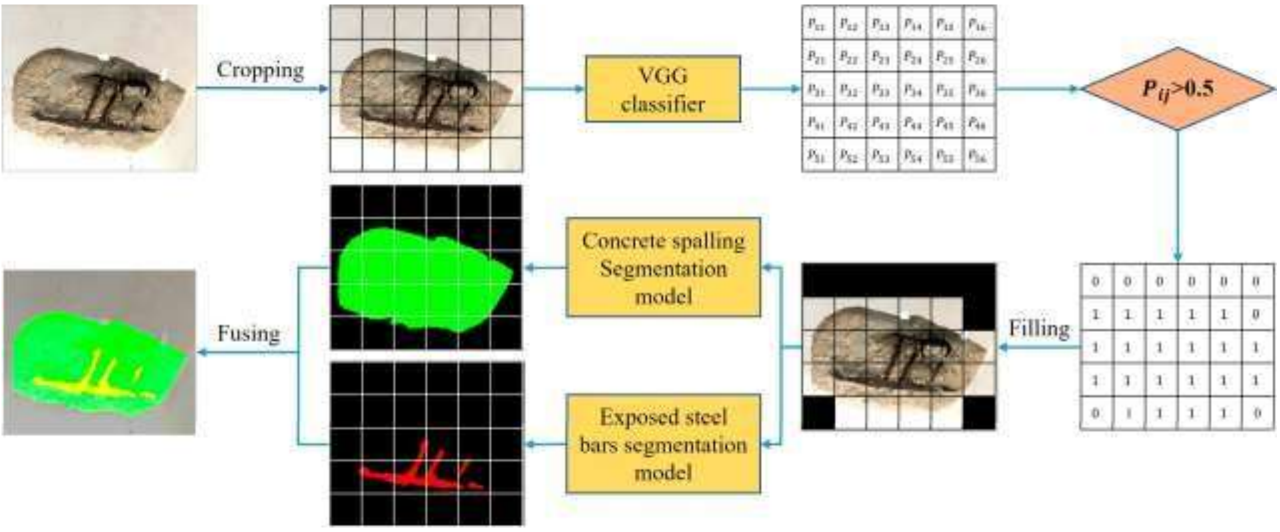

Figure 8. Overall flowchart.

The input for the detection algorithm is an image of the surface of the RC structure that has to be detected. Typically, inspectors take clear pictures of the surface damage status of a structure using photographic technology such as smartphones, portable cameras, or drones. In particular, the VGG network-based image classifier determines the probability that every image patch in the input image domain has peeling and provides the corresponding probability matrix Pij. The probability matrix used to identify the peeling area in the picture domain is transformed into a binary matrix using a probability threshold of 0.5. Solid color pixels are used to fill image patches without peeling in order to conserve processing power. To save computational resources, solid colour pixels are used to fill image patches without peeling. The segmentation model processes image patches showing exfoliation to classify pixels at a detailed level. Specifically, the models for segmenting exposed steel bars and concrete spalling aim to detect and map the pixel characteristics linked to steel bars and areas of spalling in the input images. Mask pictures are used to express semantic details for these two traits. In the end, the information regarding exposed steel bars and concrete spalling that was recorded in the structural surface photos is combined using image fusion algorithms. For identifying flaws in reinforced concrete (RC) constructions, a cascade approach is presented. First, the image's visual domain is separated into regions with defects and the backdrop. Then, exposed steel bars and concrete spalling are precisely identified using pixel-level semantic segmentation. In addition to improving RC surface image analysis accuracy, this layered detection approach lowers the possibility of background interference. In the test photos, the suggested segmentation models perform exceptionally well for both exposed steel bars and concrete spalling. The average accuracy, IOU, recall, and F1-scores of the models employed to forecast exposed steel bars and concrete spalling were 0.925, 0.871, 0.936, and 0.924, and 0.904, 0.819, 0.898, and 0.854, respectively. Segmentation models were created using four distinct encoders—VGG-19, ResNet-50, DenseNet-121, and EfficientNet-B7—in order to assess the detection method's computational efficiency. The results show that EfficientNet-B7 has the lowest computing efficiency but the highest detection accuracy. When it comes to processing efficiency, VGG-19 is better suitable for segmenting exposed steel bars, while ResNet-50 is better suited for concrete spalling segmentation.

Yolov5

YOLOv5 (You Only Look Once version 5) is a fast and accurate deep learning model used for real-time object detection, including pavement crack detection. It is a single-stage detector that simultaneously predicts object classes and their locations using a convolutional neural network (CNN). YOLOv5 treats cracks as objects, requiring a labelled dataset with bounding boxes around cracks. The model is trained to recognize features associated with cracks, enabling it to detect and localize them in real-time. After training, performance is evaluated using metrics like Precision, Recall, F1-score, and Mean Average Precision (mAP). YOLOv5 is available in various sizes: YOLOv5s (small) offers faster speed with lower accuracy, while YOLOv5x (extra-large) provides the highest accuracy but is slower. The choice of model version depends on the application's need for speed versus detection precision, making YOLOv5 a flexible and effective tool for automated crack detection in pavements and similar surfaces.

Applications of deep learning in durability

In order to assess and forecast the longevity of materials, structures, and systems, deep learning a subfield of machine learning based on neural networks is essential. Its strength lies in processing complex, large-scale data for accurate insights. In structural health monitoring, CNNs detect cracks in materials like concrete and steel, while RNNs and LSTM models predict fatigue under cyclic loading. For material degradation forecasting, deep learning predicts corrosion in metals and evaluates concrete durability factors such as carbonation and freeze-thaw resistance. In lifetime prediction, neural networks estimate the remaining useful life (RUL) of components and analyze accelerated test data for long-term performance projections. Smart maintenance systems use deep learning for predictive maintenance and drone-based automated inspections in inaccessible areas. In design optimization, AI supports the creation of durable materials and enhances topology optimization by considering durability alongside structural efficiency. Overall, deep learning enhances reliability, efficiency, and longevity in engineering applications.

Challenges in Construction Industry

Integrating multi-modal data will enhance the robustness of deep learning-based defect detection by enabling systems to operate effectively under varying conditions (lighting, temperature, and noise) and identify diverse damage types such as cracks, corrosion, and spalling. Real-time detection will support proactive maintenance, reducing downtime, improving safety, and lowering repair costs by addressing issues early. This approach also helps tackle data scarcity by leveraging both labelled and unlabelled data, improving model scalability and accuracy. Generative Adversarial Networks (GANs) will aid in creating realistic training datasets, especially for rare or complex damages, boosting detection performance. The fusion of different data types will enable detection of not just visible cracks but also underlying issues like stress or degradation, leading to holistic health monitoring. Explainable AI will increase trust by clarifying detection results, aiding better decisions. Real-time analysis at inspection points will streamline maintenance workflows, making infrastructure monitoring more efficient, scalable, and effective for smart cities and critical assets.

CONCLUSION

This review highlights recent advancements in durability research, focusing on materials, monitoring methods, and design standards. A key consensus among studies is that the inclusion of optimal types and amounts of pozzolanic materials is a cost-effective way to enhance the durability performance of construction materials. These materials improve resistance to environmental deterioration, making structures more long-lasting. In terms of steel corrosion, innovative developments such as self-powered corrosion monitoring systems utilizing the minute energy produced by corrosion reactions offer a novel direction in durability assessment. Additionally, the exploration of natural green inhibitors for corrosion protection presents an environmentally friendly and sustainable alternative, opening a promising area for future research. However, because they don't adequately account for the combined impacts of complex environmental interactions and mechanical stress, current durability design codes frequently have drawbacks. These shortcomings suggest the need for a new and unified design approach that integrates both structural load-bearing capacity and durability over time. Such a framework would allow for a more accurate estimation of service life and more effective long-term performance planning. Ultimately, addressing these challenges through interdisciplinary research and innovative solutions will significantly enhance the reliability, sustainability, and cost-efficiency of modern infrastructure systems.

FUTURE INNOVATIONS

Future crack detection systems will integrate data from ultrasonic, acoustic, infrared, and optical sensors to deliver more accurate structural analysis. These systems will become increasingly autonomous through the use of drones, robots, and IoT sensors, enabling real-time monitoring powered by embedded deep learning models. Transfer learning will support adaptability across various infrastructure types, while self-supervised learning and GAN-generated synthetic data will reduce the need for large labeled datasets. Integration with Structural Health Monitoring (SHM) systems will allow continuous assessment using real-time strain and vibration data, improving reliability and maintenance efficiency.

Deep reinforcement learning will optimize maintenance strategies, while edge computing will enable on-site analysis for faster response times. Beyond detection, advanced models will assess damage severity and localize cracks in 3D. Continued progress in instance segmentation and interpretability tools will enhance model reliability and transparency. Within smart city ecosystems, these innovations will transform infrastructure monitoring by enabling automation, real time decision making, and predictive maintenance. The result will be safer, more efficient, and cost-effective infrastructure management, supporting long-term sustainability and resilience in urban environments.

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