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A Review on Integrated Acoustic Emission and Piezoelectric Sensing for Real-Time Damage Characterization of Polymer Composite-Enhanced Concrete: Advances, Challenges, and Future Perspective

Anand Muthusamy[1], Kalyana Chakravarthy P.R.[2,*]

Abstract

Polymer composite reinforced concrete has been identified as an efficient material system that can enhance the mechanical properties, durability, and service life of modern structures. The combination of fiber reinforced polymers (FRPs), polymer modifiers, and hybrid composite reinforcements increases structural effectiveness. However, these systems are still vulnerable to damage processes, including matrix cracking, fiber breaking, interfacial debonding, and delamination. Thus, there is a need for structural health monitoring (SHM) strategies that could ensure early identification and real-time evaluation of damage states in these structures. Among several approaches to SHM, acoustic emission (AE) and piezoelectric (PZT) methods have proven to be especially effective. AE monitoring allows detecting active damage events based on an evaluation of transient stress waves produced during crack formation and propagation. On the other hand, the use of PZT sensors makes it possible to identify damage locations using electromechanical impedance and guided wave measurements. This review gives a detailed analysis of the latest studies conducted in the area of AE and PZT-based sensing of damage in reinforced polymer composite concrete. Special focus is laid on damage detection in fiber-reinforced polymer composite concrete and polymer modified concrete systems. The principle, application, merits, and demerits of various types of damage-sensing techniques are thoroughly analyzed, followed by a discussion on hybrid damage detection strategies that use AE-PZT combinations. Latest trends in the development of intelligent damage detection using artificial intelligence, machine learning, data fusion, and digital twin techniques are also included. Future perspectives for research related to the next generation polymer composites are also addressed.

Keywords: Polymer composite-enhanced concrete; fiber-reinforced polymers (FRPs); acoustic emission; piezoelectric sensing; health monitoring

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INTRODUCTION

Concrete made from polymer composites has attracted much interest recently owing to the ability of such type of concrete to enhance the mechanical properties, as well as to increase the longevity of the civil infrastructures. In order to enhance the mechanical characteristics of concrete, it is usually reinforced with fiber-reinforced polymers (FRPs), as well as with hybrid composites. Among different types of FRPs used in the civil engineering industry, such polymer reinforcement composites as carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), and basalt fiber-reinforced polymer (BFRP) have been widely used [1].

In spite of all the benefits listed above, however, structures utilizing polymer composite reinforced concrete can still experience different kinds of deterioration due to several factors, including mechanical loads, environmental conditions, thermal impacts, and cyclic stresses resulting in microcracking, interfacial debonding, delamination, and fiber rupture. All of these types of damage usually arise internally, therefore being hard to discover unless major problems with structural integrity occur. The importance of damage detection and monitoring is therefore growing in the modern engineering environment.

Recently, structural health monitoring (SHM) has become an important tool that allows for assessing the condition of advanced composite structures in real time. Unlike traditional methods of inspection, SHM allows for continuously monitoring of damage initiation and progression through the implementation of internal or external sensors. Today, two promising techniques for continuous monitoring are acoustic emission (AE) and piezoelectric (PZT) sensing. These non-destructive approaches to evaluating structural performance allow for monitoring of crack initiation, propagation, and size by analyzing transient stress waves and electromechanical impedance and guided waves respectively [2].

While substantial progress has been made via the individual techniques mentioned above, all of them exhibit some deficiencies. For instance, while AE sensing can be compromised by noise and problems with localization, the PZT technology can suffer from the complexity of its signal analysis and calibration process. To resolve these issues, scientists have increasingly looked into the prospect of implementing an integrated approach to AE-PZT monitoring, which would capitalize on the strengths of both methods.

Moreover, recent breakthroughs in the development of AI, machine learning, data fusion techniques, wireless sensor networks, and digital twins have greatly enriched the possibilities offered by this approach to damage monitoring [3].

Considering the above, this review aims at evaluating Acoustic Emission and Piezoelectric sensor techniques together for real-time damage monitoring of composite-reinforced concrete structures. Emphasis will be made on the monitoring of FRP-reinforced and polymer-infused concrete structures. The theory behind AE and PZT sensors, their applications, pros and cons, and recent advancements in the combination of these two techniques will be discussed. Artificial intelligence-based damage detection using combined AE and PZT sensors will be reviewed to conclude the paper with existing limitations, gaps, and directions for future research. The advancement in intelligent sensor techniques for monitoring composite reinforced concrete structure is presented in Figure 1. The unique contribution of this review is the comprehensive evaluation of integrated AE–PZT sensing frameworks for polymer composite-enhanced concrete structures. Particular emphasis is placed on the synergistic capabilities of hybrid sensing, artificial intelligence-based diagnostics, data fusion strategies, and digital twin integration, which have not been collectively addressed in previous review studies.

POLYMER COMPOSITE-ENHANCED CONCRETE AND DAMAGE MECHANISMS

Polymer composite strengthened concrete is an example of an advanced cementitious composite material wherein reinforcement using polymer is done in order to increase its structural strength and durability. Carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP) and basalt fiber reinforced polymer (BFRP) composite systems, for instance, are some of the most common examples of polymer composite strengthened concrete that have been commonly used for rehabilitation and reinforcing of concrete structures.

Polymer modified concrete, on the other hand, includes concrete with latexes, epoxies and other polymers wherein they show improvements in cracking resistance, bonding and impermeability. Due to such benefits, polymer composite strengthened concrete systems have been utilized widely in different areas [4].

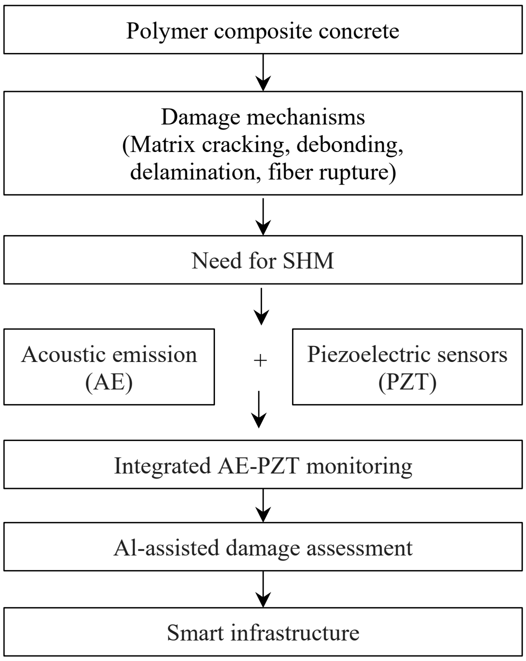

Figure 1. Evolution of smart monitoring in polymer composite-enhanced concrete structures.

Though they perform better than concrete alone, the composite-concrete structures are prone to various forms of damage throughout their useful life. The composite-concrete systems being heterogeneous in nature, failure of these systems is often due to failure modes of both the concrete substrate and the reinforcing composite. In case of monotonous or cyclic loads, failures occur due to the initiation of micro-cracks in the concrete body followed by macro-cracks and finally debonding at the interface of composite and the concrete body leading to reduced load transfer capabilities of the structure.

For fiber-reinforced polymer structures, the failure can further be due to delamination of the composite layers and ultimate failure of the fibers due to overloading. External environmental factors like thermal changes, moisture intrusion, freezing and thawing cycles, ultra-violet light and chemical attacks speed up these deterioration processes. These damage mechanisms are hard to identify using visual inspection as damage starts occurring inside before it becomes evident externally [5].

The progression aspect of damage development in polymer composite enhanced concrete buildings necessitates effective Structural Health Monitoring (SHM) systems that would enable detection of damage initiation at its earliest stage. [6]Continuous monitoring methods offer essential data about crack initiation and propagation, debonding phenomenon, and structural degradation. In this regard, among different SHM methods, acoustic emission (AE) and piezoelectric (PZT) sensing are relatively effective methods due to their real-time continuous monitoring capability while not disturbing building activities. The damage development in polymer composite enhanced concrete building is shown in Figure 2. Properties of common polymer composites are described in Table 1. The interaction between composite reinforcement and concrete substrate plays a critical role in damage evolution. Microcracks originating in the concrete matrix alter the stress distribution at the composite–concrete interface, resulting in progressive debonding and reduced load transfer efficiency. As loading continues, interfacial degradation may trigger delamination within FRP laminates and eventually fiber rupture. Therefore, damage evolution in composite-strengthened concrete should be considered as a coupled mechanism involving both concrete deterioration and composite reinforcement failure. Recent studies have explored the use of recycled waste materials and fibreboard fillers as sustainable reinforcing agents in polymer-based composites, demonstrating improved mechanical performance, resource efficiency, and environmental sustainability [16].

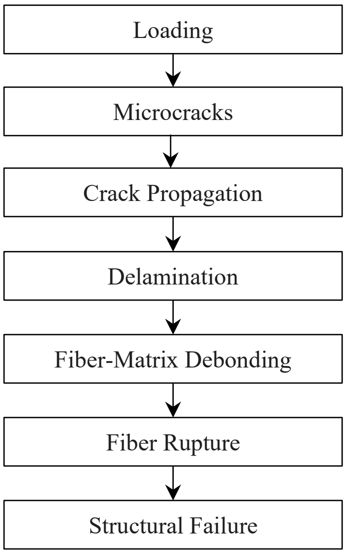

Figure 2. Typical damage mechanisms in polymer composite-enhanced concrete.

Table 1. Comparative characteristics of polymer composite systems.

Composite type	Advantages	Applications	Limitations
CFRP	High strength	Strengthening	High cost
GFRP	Economical	Bridges	Lower stiffness
BFRP	Corrosion resistant	Marine structures	Limited field data
Polymer-Modified Concrete	Durability	Repair works	Cost

ACOUSTIC EMISSION MONITORING FOR DAMAGE CHARACTERIZATION

Amongst non-destructive testing approaches for evaluating the damage status of polymer composite enhanced concrete structures in real time, Acoustic Emission (AE) technique appears to be one of the most efficient. In brief, AE monitoring is grounded on detection of transient elastic stress waves released when some energy is rapidly released due to damage processes, which can manifest themselves in the form of microcracks, crack development, fiber failure, matrix cracking, or debonding between layers. In contrast to other conventional inspection techniques, AE technique can be used to evaluate structure's integrity continuously, which provides information on active damage processes [7].

For studying the behavior of reinforced concrete structures strengthened with fibers under different loads, the Acoustic Emission technique has already found wide application in many previous investigations. It was shown that AE monitoring allows detecting the process of evolution of damage at different stages from initial microcracking in the concrete matrix to the debonding of FRP reinforcing from the concrete substrate. Amongst others, Acoustic Emission analysis can be efficiently used for monitoring the behavior of CFRP, GFRP, and BFRP reinforced members.

The efficiency of acoustic emission monitoring highly depends on the analysis of characteristic parameters of signals such as amplitude, counts, energy, duration, rise time, and frequency content, which reveal important information about the stage of structural damage. For example, high signal amplitudes and energies can be indicative of the development of cracks and failures within the structure, while low amplitudes can reveal the early onset of microcracks. The use of AE signal parameters for damage detection allows detecting the critical states of structures prior to their failure [8].

With recent developments in machine learning tools and signal processing techniques, AE monitoring can be further improved by implementing data classification based on acoustic emission signals. In particular, machine learning algorithms have become a popular way of classifying AE signals that helps to identify various types of damages caused by composite materials incorporated in the concrete structures. Moreover, AE monitoring can be effectively combined with other sensor technologies to eliminate its drawbacks regarding noise sensitivity and damage localization.

Though AE monitoring technique offers many benefits, yet it has to face certain problems like interference from environmental noises, signal attenuation, sensor positioning, and analysis of a large amount of data. All these issues may hamper AE monitoring technique, especially when dealing with damage characterization in large scale infrastructures. However, advancements made in the field of sensors and data analysis continue to extend the utility of AE system in modern composite materials. The mechanism of AE monitoring technique is illustrated through Figure 3 below. AE parameters useful for damage assessment are given in Table 2.

PIEZOELECTRIC SENSING TECHNOLOGIES FOR DAMAGE CHARACTERIZATION

Piezoelectric sensor technology has developed as an efficient means for Structural Health Monitoring (SHM), which enables the detection of damage in concrete structures reinforced by polymer composites. The advantage of PZT sensors is that they have the ability not only to produce but also to receive mechanical waves, thus identifying such types of damage as cracks, debonding, and stiffness changes.

Fundamentals of Piezoelectric Sensing

Piezoelectric sensors work according to the principle of transforming mechanical energy into electrical energy and vice versa by means of piezoelectric materials. Of the different kinds of piezoelectric materials, one material that has extensively been used for structural health monitoring applications is Lead Zirconate Titanate (PZT), owing to its efficient electromechanical coupling and high sensitivity [9]. The PZT sensor can also work as an actuator, thus allowing the creation and detection of stress waves in the structure under test. In concrete structures enhanced with polymer composite materials, PZT sensors can be attached to the structure either externally or internally [17].

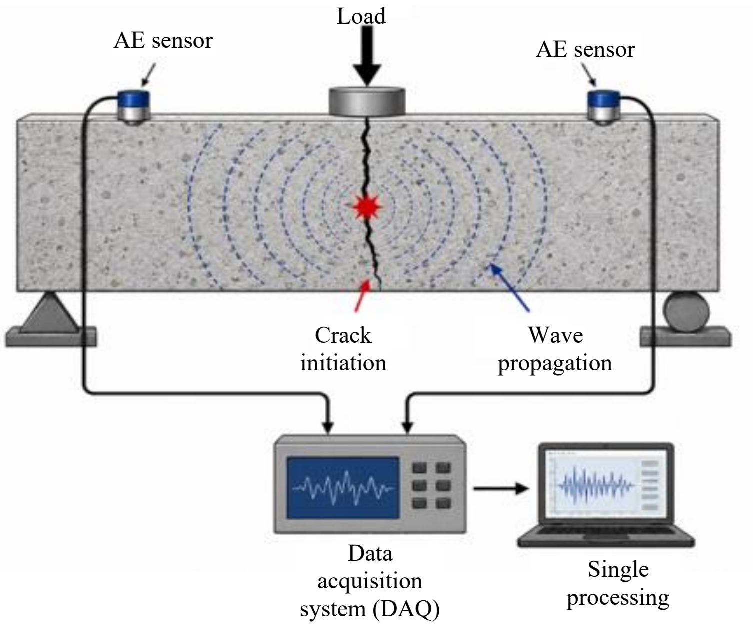

Figure 3. Working principle of acoustic emission monitoring.

Table 2. Common AE parameters for damage assessment.

Parameter	Description	Damage information
Amplitude	Signal intensity	Crack severity
Counts	Number of hits	Damage activity
Energy	Released energy	Failure progression
Duration	Signal length	Crack growth

Electromechanical Impedance-Based Damage Detection

The Electromechanical Impedance (EMI) is one of the most popular PZT-based damage detection techniques. The basic idea behind the method is that the impedance characteristic of a PZT transducer is related to the mechanical impedance of the structure. When there is any structural damage, such as cracking or debonding, there will be a change in the local dynamic behavior of the structure, which will manifest itself in the impedance curve. EMI has been shown to be especially suitable for early-stage damage detection in fiber-reinforced polymer (FRP)-strengthened and polymer modified concrete structures due to its high sensitivity.

Guided Wave-Based Monitoring

Guided wave technologies employ stress waves produced by PZT transducers that propagate in structural members and interact with defects that exist in the structures. With damage, the propagating waves will have reflections, scattering, attenuations, and mode conversions, resulting in signal variations that can be used to locate and assess the extent of the damages. Guided wave inspection has been used successfully for CFRP-reinforced concrete beams, composite panels, and hybrid systems to detect cracks, delaminations, and debonds. In comparison with traditional inspection technologies, guided wave inspection provides greater coverage and better damage localization [10].

Advantages, Limitations, and Recent Developments

Piezoelectric sensing technology using PZT sensors has several merits like high sensitivity, real-time monitoring abilities, compact sensor sizes, low power consumption, and their applicability to embedded sensing system applications. The above features make them ideal for monitoring reinforced concrete structures due to the necessity of detecting any damage early enough. However, the use of PZT sensors may be limited by certain factors in the environment, including temperature changes, presence of moisture, and external pressure. Besides, interpreting the signals from such sensors needs specialized skills.

Several advances in wireless sensing networks, smart aggregate, nanocomposites piezoelectric sensors, and assisted artificial intelligence signal processing have improved the performance of the PZT monitoring systems significantly [11].

INTEGRATED AE–PZT FRAMEWORKS FOR REAL-TIME DAMAGE CHARACTERIZATION

The combination of Acoustic Emission (AE) and Piezoelectric (PZT) sensor systems is an integration of the benefits of the passive as well as active sensors. Hybrid AE–PZT sensor systems are known to have higher levels of precision when detecting damage, localization ability as well as continuous monitoring of deterioration in structures.

Need for Integrated AE–PZT Monitoring

Even though the Acoustic Emission (AE) and Piezoelectric (PZT) techniques have proved to be efficient in Structural Health Monitoring (SHM), there are still shortcomings associated with each of these techniques. While AE technology is very efficient in detecting any damage event such as the formation and spread of cracks, it can experience challenges in terms of localizing damage and interference from noise. On the other hand, PZT systems offer accurate detection of damage and continuous monitoring of structure conditions, yet they can be hindered by signal complexity and limited local detection. Thus, the use of both AE and PZT techniques in concrete structures enhanced with polymer composites can be an ideal solution.

Complementary Damage Detection Mechanisms

The efficiency of the AE-PZT sensor systems is due to their sensing capabilities, which complement each other in functionality. The working principle of the AE sensor involves its usage as a passive monitoring tool for capturing the wave stresses emanating from the point where damage begins. On the contrary, PZT sensors are active sensing tools since they not only emit but also receive guided or impedance waves. The simultaneous use of both the types of sensors will help in achieving more efficient damage identification compared to using individual sensing technologies [12].

Data Fusion and Multi-Sensor Integration

Data fusion is essential for integrated AE-PZT monitoring systems. Data acquired from several sensors may be fused at different stages, including signals, features, or decisions, to increase damage identification precision and minimize the uncertainty that is related to each of these damage detection methods. Signal processing techniques allow the extraction of significant features from AE and PZT waves to make the damage evaluation process more reliable [18].

Applications in Polymer Composite-Enhanced Concrete Structures

The application of integrated AE-PZT monitoring systems has increased for polymer composite-reinforced concrete structures such as those reinforced with CFRP, GFRP, and BFRP. These systems are highly effective in monitoring damage progression under monotonic, cyclic, and fatigue loads [13]. The integration of these sensing systems allows early detection of microcracks, identification of debonding between composite and concrete, evaluation of layer separation in composite materials, and an overall evaluation of the integrity of the structure. Integrated AE–PZT monitoring has been successfully applied to several civil infrastructure systems, including highway bridges strengthened with CFRP laminates, reinforced concrete buildings subjected to seismic loading, tunnel linings exposed to environmental degradation, and pavement systems experiencing fatigue damage. These applications demonstrate the capability of hybrid sensing systems to provide continuous condition assessment, early damage detection, and predictive maintenance support for large-scale infrastructure assets.

Advantages, Challenges, and Future Opportunities

The integrated AE-PZT system provides several benefits such as improved damage detection sensitivity, improved damage localization accuracy, enhanced monitoring reliability, and complete evaluation of damage modes. However, some problems may exist when it comes to installation of sensors, durability issues, synchronization of diverse databases, data management, and computational processing [14]. The latest trends in wireless sensing, cloud computing, machine learning, and digital twin models can solve these problems effectively. The future work should be focused on designing smart hybrid monitoring systems for automatic diagnosis and maintenance of modern infrastructure using polymer composites. Table 3 gives a comparison of AE, PZT, and AE-PZT systems' capabilities [19].

ARTIFICIAL INTELLIGENCE AND ADVANCED DATA ANALYTICS IN AE–PZT MONITORING.

AI technology and data analytics have greatly contributed to the analysis of AE and PZT sensors data for Structural Health Monitoring purposes. Machine learning, deep learning, and data fusion technologies allow automated damage detection, predictive structure condition forecasting, and decision making. They have provided assistance in real-time detection of damages in polymer composite reinforced concrete structures.

Table 3. Comparison between AE, PZT, and integrated AE–PZT systems.

Feature	AE	PZT	AE–PZT
Crack detection	High	Medium	High
Damage localization	Medium	High	Very High
Real-time monitoring	High	High	Very High
Reliability	Medium	Medium	High

Machine Learning for Damage Classification

There is an increase in the application of AE and PZT sensing systems, leading to the creation of a significant amount of monitoring data which requires sophisticated techniques for its proper analysis. Machine learning (ML) techniques can serve as a useful tool in automating the process of damage classification and assessing the condition of structures. The algorithms that can be used in this process include SVM, ANN, Decision Trees, and Random Forests.

These algorithms can help in identifying patterns of damage from AE and PZT data sets. Using such algorithms on polymer composite strengthened concrete structures can lead to effective classification of the various damage modes such as matrix cracking, interfacial debonding, delamination, and fiber breakage.

Deep Learning for Signal Interpretation

In recent years, new developments in deep learning technology have added to the functionality of SHM systems by automatically extracting features from sensor data. CNNs, RNNs, and LSTM networks have shown great promise when used on AE waveforms and PZT responses. The major advantage offered by deep learning techniques is that they greatly reduce the dependence on manual extraction of features compared to other machine learning techniques. With regard to polymer composite-strengthened concrete structures, there has been extensive use of deep learning technologies to detect cracks, localize damages, and determine their severity.

Data Fusion and Intelligent Decision-Making

The combination of AE and PZT monitoring systems provides complementary data sets, which can be fused using data fusion methods for obtaining better structure diagnostics. Data fusion can be conducted either at the signal level, the feature level, or the decision level, according to the purpose of structure monitoring and its implementation. Using data from various types of sensors allows an intelligent monitoring system to decrease uncertainty, increase the precision of damage detection, and improve the overall reliability of damage diagnostics. The application of machine learning and deep learning tools additionally facilitates the automation of processing multiple sensor data [20].

CHALLENGES, RESEARCH GAPS, AND FUTURE PERSPECTIVES

In spite of the substantial progress made in monitoring with AE sensors and PZT technology, a number of issues remain unresolved and stand in the way of implementing these approaches into concrete reinforced with polymer composites structures. Firstly, it is important to mention the problem of sensor resistance to adverse environmental influences, such as moisture, varying temperatures, and chemical and mechanical stresses [15].

Secondly, there is the issue associated with signal processing and data handling. It is important to note that AE monitoring and PZT sensing produce a significant amount of sophisticated data, and special techniques are needed in order to interpret the information and identify damage correctly.

Recent studies have also shown the absence of standard measurement processes for composite-infused concrete structures. Different sensor arrangements, test processes, signal processing techniques, and criteria used for evaluating damage indices make it challenging to compare findings from different studies. Thus, there is still a great need for developing standard practices and performance metrics.

Future studies should concentrate on creating multifunctional smart polymer composite sensors, robust wireless measurement systems, and artificial intelligence-based diagnostic models. More attention needs to be paid to real-world applications, extended validation studies, and incorporating digital twins into the process. This would create a synergy of innovative materials, intelligent sensors, and automated diagnostic solutions that can revolutionize the structural health monitoring industry.

CONCLUSIONS

Polymer composite reinforced concrete is an innovative type of building material that can offer high levels of structural efficiency and durability, as well as greater resistance against environmental corrosion than conventional concrete. With fiber-reinforced polymers, polymer modifiers, and hybrid composite reinforcements, modern constructions become more efficient and durable; however, the complicated nature of the damage phenomena experienced by these materials – such as matrix fracture, fiber breakage, interfacial debonding, and delamination – makes it necessary to use monitoring methods for damage characterization purposes.

This literature review highlights the effectiveness of Acoustic Emission and Piezoelectric techniques for monitoring damages in polymer composite reinforced concrete. Acoustic emission has been proven to be a powerful method of real-time damage detection and monitoring the progression of the damage process; Piezoelectric sensors have proved to be effective in detecting stiffness variations, localized damage zones, and general structure deterioration. Combining these two different types of sensors will provide a powerful tool for comprehensive monitoring of damages in polymer composite reinforced concrete structures.

With the help of recent innovations in machine learning, data fusion, wireless sensor networks, and digital twin technology, the efficiency of AE-PZT combined structural monitoring systems has been increased. With their help, it is possible to achieve precise damage estimation, automation of diagnostic procedures, and the implementation of prediction-based maintenance programs in complex composite structures. However, various obstacles to the application of these technologies, including issues of sensors' durability, vulnerability to external conditions, analysis of signals, management of data, and broad-scale deployment, persist.

Further scientific activity should be concentrated around the creation of hybrid intelligent systems, self-sensing composite polymers, standardized approaches to testing, and artificial intelligence-supported decision-making procedures. The need to pay more attention to field-level tests and comprehensive long-term evaluations is necessary for overcoming the existing gap between scientific experiments and practical application. As can be seen, the combination of AE and PZT technologies can become a key area for further investigation.

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