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Piezoelectric Concrete: A Smart Material Approach for Energy-Harvesting Structural Technologies

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REVIEW ARTICLE

Piezoelectric Concrete: A Smart Material Approach for Energy-Harvesting Structural Technologies

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ABSTRACT

The rapid growth of urban infrastructure demands innovative materials that not only support structural performance but also contribute to sustainability through energy harvesting. Piezoelectric concrete, which integrates ceramics, polymers, nanomaterials, and bio-based fillers into cementitious matrices, has emerged as a promising solution. This review systematically explores the fundamentals of piezoelectricity in concrete, highlighting how stress-induced electromechanical coupling enables both energy harvesting and structural health monitoring. The paper critically evaluates major material systems including PZT ceramics, PVDF polymers, hybrid nanocomposites, and emerging bio-based materials, alongside their integration strategies such as embedded and surface-mounted approaches. Applications across pavements, bridges, and smart buildings are examined through national and international case studies, with a focus on powering low-energy devices, enabling self-sensing infrastructure, and supporting smart city initiatives. Persistent challenges such as low conversion efficiency, environmental durability, high cost, and limited multifunctionality are identified and matched with innovation pathways including hybrid composites, additive manufacturing, and modular low-cost designs. By linking material science with real-world engineering practice, this review provides a roadmap for advancing piezoelectric concrete from laboratory prototypes to scalable, durable, and intelligent infrastructure systems.

Keywords: Energy harvesting structures, Piezoelectric materials, Sustainability, Smart construction materials, Self-powered infrastructure, Urban resilience

1. Introduction

Rapid urbanization and the electrification of cities have intensified global energy demand while increasing the urgency to decarbonize the built environment. Civil infrastructure is not only a major consumer of energy but also a potential platform for harvesting ambient energy from mechanical vibrations, traffic loads, and pedestrian footsteps. Among the various energy-harvesting technologies such as photovoltaic (PV), thermoelectric (TE), electromagnetic (EM), and piezoelectric (PE), the piezoelectric conversion is particularly attractive for the built environment because

it directly converts mechanical stress into electrical energy, making it inherently compatible with roads, pavements, and building floors that continuously experience dynamic loads [1–3].

Piezoelectric concrete integrates functional materials such as ceramics (PZT, BaTiO₃), polymers (PVDF and copolymers), and hybrid fillers (CNTs, graphene, nanosilica) into the cementitious matrix to create multifunctional smart composites that not only carry load but also sense strain or damage and harvest energy for low-power electronics [4–6]. Recent studies by both national scholars, including prototypes of piezoelectric pavements in Malaysia and other

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Revolution Diagram

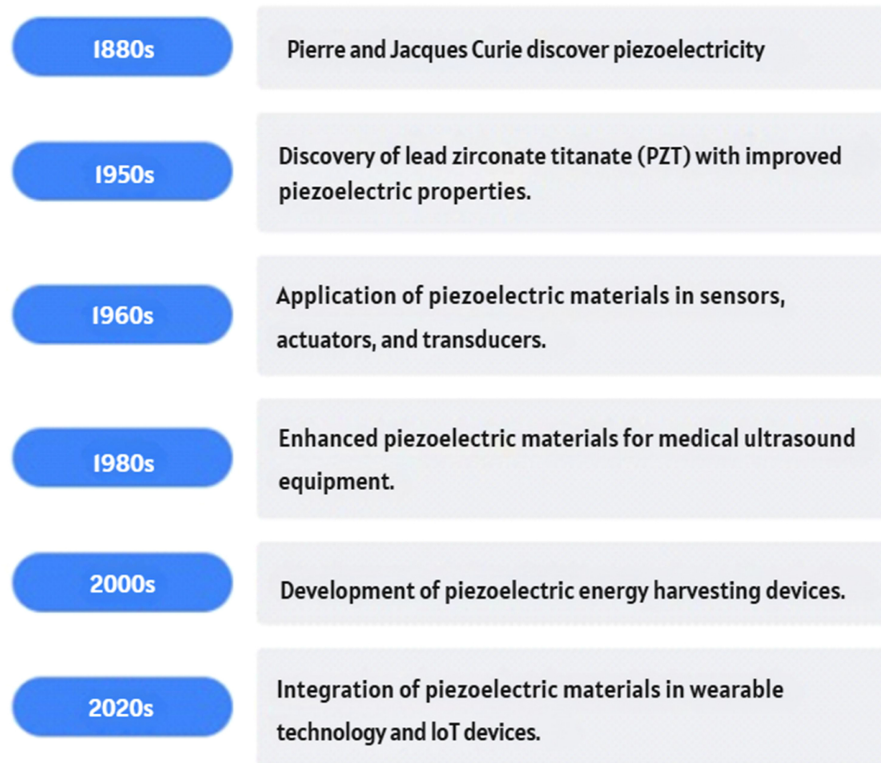


Fig. 1. Piezoelectricity revolution.

ASEAN countries, and international researchers, including large-scale road demonstrations in China, Korea, and the EU, demonstrate the potential of such systems to power street lighting, traffic monitoring devices, and self-powered sensing networks [7–10]. The evolution of piezoelectric research can be contextualized through key milestones that highlight its transition from classical zirconate titanate (PZT)-based ceramics to flexible polymers such as polyvinylidene fluoride (PVDF), and more recently to multifunctional nanocomposites reinforced with carbon nanotubes and graphene. This progression reflects not only improvements in electromechanical performance but also the growing demand for materials compatible with modern civil infrastructure. As illustrated in Fig. 1, the piezoelectricity revolution demonstrates how continuous innovation has expanded the scope of applications, ultimately laying the foundation for the development of piezoelectric concrete as a multifunctional construction material. Despite these advances, however, several barriers remain, particularly in terms of conversion efficiency, durability under harsh environmental conditions,

integration with existing construction practices, and overall cost-effectiveness [11, 12].

This review addresses these issues by providing a comprehensive and systematic synthesis that connects fundamental science with engineering practice. It begins with the principles of piezoelectricity in cementitious composites, explaining how electromechanical coupling operates at both the material and structural levels. It then examines the different classes of materials, including ceramic, polymeric, carbon-based, and emerging bio-based systems by highlighting their respective advantages and limitations. Building on this, the paper reviews integration strategies for embedding or attaching piezoelectric elements within structural components, followed by an analysis of the factors that influence overall performance, such as material properties, structural geometry, and environmental conditions. The discussion then expands to applications in smart infrastructure, ranging from pavements and bridges to intelligent building systems, with emphasis on real-world case studies. Finally, the review evaluates the challenges and limitations that currently restrict widespread

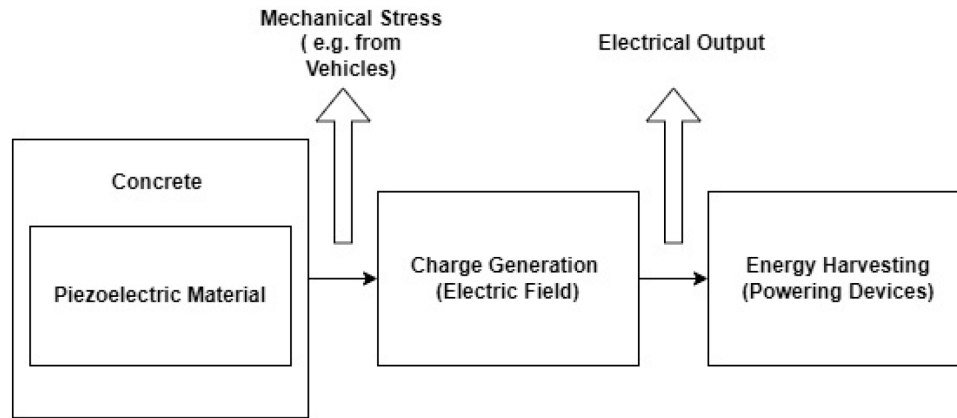


Fig. 2. Multifunctional roles of piezoelectric concrete in civil infrastructure, illustrating its capacity to act as a structural component, energy harvester, and self-powered sensing element.

adoption and sets out a research roadmap to guide future investigations toward more durable, efficient, and scalable piezoelectric concrete technologies.

2. Fundamentals of piezoelectricity in cementitious systems

2.1. Principles of piezoelectricity

Piezoelectricity is the property of certain non-centrosymmetric materials to generate electric polarization when subjected to mechanical stress (direct effect) and, conversely, to deform mechanically when exposed to an electric field (inverse effect). In cementitious composites, this dual property enables both energy harvesting and structural health monitoring (SHM) functions. The fundamental electromechanical coupling can be expressed using the strain–charge form of the constitutive equations:

$$S = s^E T + d^T E, \quad D = d T + \varepsilon^T E$$

where S is strain, T is stress, D is electric displacement, and E is electric field; s^E is the compliance matrix at constant electric field, ε^T is the permittivity at constant stress, and d is the piezoelectric coefficient tensor [13–15].

For one-dimensional loading in the common 33-mode configuration, the generated charge is approximately proportional to the applied force:

$$Q \approx d_{33} F$$

where F is the applied force and d_{33} is the piezoelectric charge constant. The corresponding open-circuit voltage can be expressed as:

$$V \approx g_{33} t T_3$$

where $g_{33} = d_{33}/\varepsilon_{33}$, t is the thickness of the piezoelectric layer, and T_3 is the applied stress. These relations illustrate how material constants such as d_{33} and ε_{33} directly affect energy harvesting performance [16–18].

The multifunctional role of piezoelectric concrete in civil infrastructure is illustrated in Fig. 2. This figure highlights how piezoelectric elements embedded within concrete can simultaneously serve as structural components and functional sensors or energy harvesters. By directly converting mechanical stress into electrical signals, these systems enable real-time monitoring of structural performance while also contributing to self-powered operation. Such integration underscores the dual role of piezoelectric concrete as both a load-bearing material and a smart energy-active system.

2.2. Materials to cementitious composites

In pure piezoelectric ceramics or polymers, energy conversion efficiency is governed primarily by intrinsic constants such as d_{33} , g_{33} , and the electromechanical coupling factor k_2 . However, in piezoelectric concrete, the performance depends not only on these intrinsic constants but also on how effectively the cementitious matrix transfers stress to the active inclusions. Strong interfacial bonding and uniform dispersion of piezoelectric phases are critical for maintaining effective stress transfer and minimizing energy loss [19–21].

Charge transport mechanisms also differ between bulk piezoelectric materials and composites. In cement-based systems, factors such as interfacial polarization (Maxwell–Wagner–Sillars effect), filler orientation, and conductive pathways influence dielectric behavior and signal output [22–24]. For example,

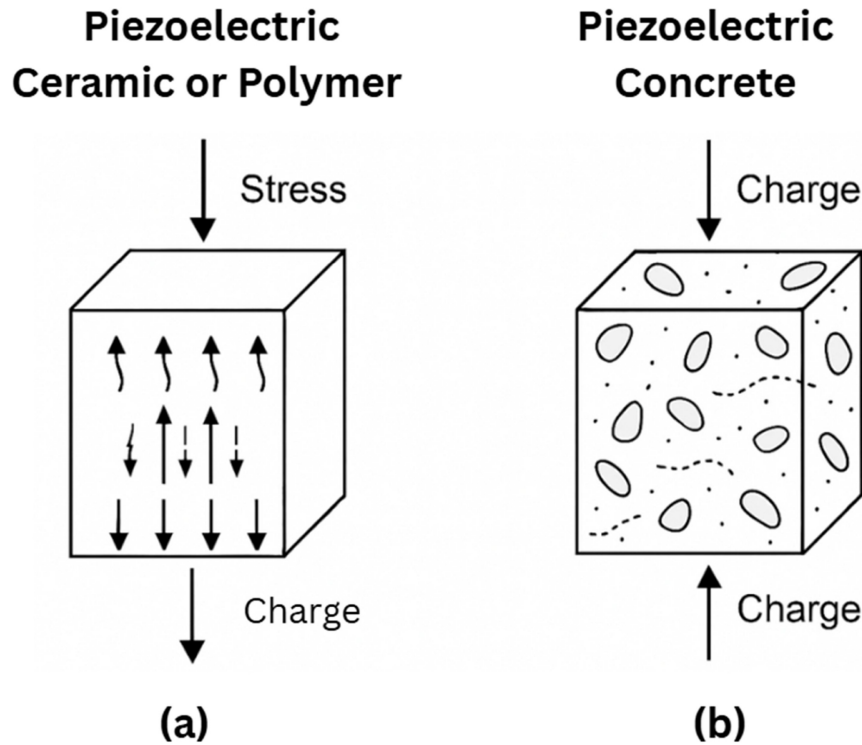


Fig. 3. Schematic illustration of the working principles of piezoelectric materials versus piezoelectric concrete.

conductive nanofillers such as CNTs can facilitate charge collection but must remain below the percolation threshold to avoid short-circuiting effects [25].

To provide a clearer understanding of these distinctions, Fig. 3 has been introduced. The schematic compares the direct stress-to-charge mechanism of bulk piezoelectric materials with the more intricate response of piezoelectric concrete. While conventional ceramics and polymers rely solely on intrinsic domain behavior, piezoelectric concrete must also contend with stress transfer through the cement matrix, interfacial polarization, and the connectivity of piezoelectric phases. This visual representation highlights the fundamental differences between homogeneous materials and composite systems, helping to explain why piezoelectric concrete often exhibits lower conversion efficiency but offers unique multifunctionality for civil infrastructure applications.

Fig. 3(a) illustrates that in bulk piezoelectric ceramics or polymers, applied stress directly polarizes domains, producing charge that is collected at electrodes. Fig. 3(b) shows that in piezoelectric concrete, stress is transferred through the cementitious matrix before reaching piezoelectric inclusions, and efficiency depends on interfacial bonding, filler dispersion, and conductive pathways.

The working principle of bulk piezoelectric materials differs fundamentally from that of piezoelectric concrete. In homogeneous piezoelectric ceramics or polymers, applied mechanical stress directly induces

the alignment of internal domains, resulting in charge generation that is readily collected by electrodes placed at opposing surfaces. This direct stress-to-charge conversion pathway reflects the intrinsic electromechanical coupling of the material, with minimal losses arising from extrinsic factors.

In contrast, piezoelectric concrete represents a heterogeneous composite system in which piezoelectric particles are dispersed within a cementitious matrix. Here, the conversion process is more complex, as mechanical stress must first be transmitted through the cement matrix before reaching the embedded particles. The efficiency of charge generation is strongly influenced by factors such as interfacial bonding between the particles and the matrix, the homogeneity of particle dispersion, and the presence of continuous conductive pathways that facilitate charge transport. Consequently, piezoelectric concrete generally exhibits lower energy conversion efficiency compared to bulk materials. Nonetheless, this composite approach offers significant practical advantages, as it enables the integration of functional energy-harvesting and sensing capabilities into large-scale structural elements, thereby extending the application of piezoelectricity into the built environment.

2.3. Relation to other energy harvesting mechanisms

Piezoelectric energy harvesting differs fundamentally from thermoelectric conversion, which relies on

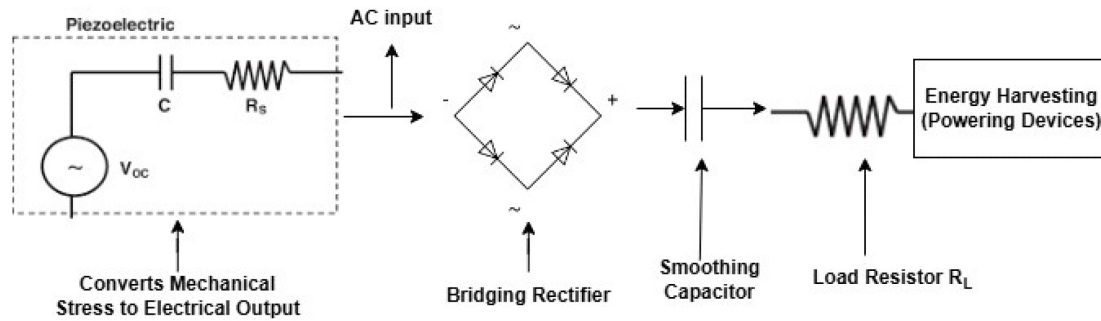


Fig. 4. Application scenarios of piezoelectric concrete in pavements, bridge decks, and building facades, demonstrating its potential for energy harvesting and structural health monitoring under dynamic loading.

temperature gradients, and from photovoltaic conversion, which depends on photon excitation. While the efficiency of thermoelectric systems is defined by the dimensionless figure of merit ($ZT = S_2\sigma T/\kappa$), piezoelectric efficiency is controlled by electromechanical parameters (d_{33} , g_{33} , k_2) and loading conditions (stress amplitude, frequency, and geometry). In infrastructure applications, piezoelectric systems are especially suitable because they exploit the naturally occurring dynamic stresses in pavements, floors, and bridges [2, 3, 7]. Hybrid approaches combining piezoelectric, thermoelectric, and photovoltaic systems have been proposed to maximize energy capture under varying environmental conditions [26].

Beyond the conceptual mechanisms presented in Fig. 3, the application potential of piezoelectric concrete in large-scale infrastructure is further demonstrated in Fig. 4. The figure depicts representative deployment scenarios, including road pavements, bridge decks, and building facades, where dynamic traffic and environmental loads can be harvested for power generation or used to activate structural health monitoring systems. These applications illustrate the adaptability of piezoelectric concrete across multiple domains, highlighting its significance as an enabling technology for next-generation smart and sustainable infrastructure.

2.4. Implications for structural applications

As research transitions from laboratory-scale investigations of piezoelectric materials to their integration within large-scale cementitious composites, several critical challenges must be addressed to ensure reliable performance. In polymer-based systems, maintaining stable poling and domain orientation over time is essential to preserve electromechanical coupling, while ceramic-based composites must overcome issues of brittleness and potential fracture under cyclic traffic loading. Additionally, cementitious matrices are inherently heterogeneous, and

their dielectric behavior is strongly influenced by interfacial polarization effects such as the Maxwell–Wagner–Sillars phenomenon, which can increase energy losses, particularly in humid or thermally fluctuating environments. These challenges are further compounded by the need for optimized electrode configurations that achieve a balance between concentrating strain for efficient charge generation and preserving the structural integrity of the host concrete. By addressing these interrelated issues, researchers can bridge the gap between material-level piezoelectric properties and structural-scale applications, ultimately enabling piezoelectric concrete systems that are capable of both sustainable energy harvesting and long-term structural health monitoring.

3. Material systems for piezoelectric concrete

The performance of piezoelectric concrete is strongly governed by the properties of the functional materials incorporated into the cementitious matrix. Over the past two decades, extensive research has explored ceramics, polymers, hybrid nanocomposites, and more recently bio-based systems, with the dual aim of achieving reliable electromechanical performance and ensuring long-term structural compatibility. This section provides a critical overview of the major material categories, their underlying principles, integration challenges, and future prospects, supported by schematic and application-based figures that illustrate the transition from fundamental mechanisms to real-world deployment.

3.1. Piezoelectric ceramics

Piezoelectric ceramics such as lead zirconate titanate (PZT) and barium titanate (BaTiO_3) remain the cornerstone of research in piezoelectric materials due to their high piezoelectric coefficients, strong electromechanical coupling, and relatively low

production costs [27–30]. These properties make them excellent candidates for transducing mechanical stress into electrical energy, which is the central requirement for energy harvesting in civil infrastructure. However, ceramics also exhibit brittleness, low strain tolerance, and susceptibility to microcracking, which restrict their durability when exposed to harsh service conditions such as cyclic traffic loading or environmental fluctuations [28, 31].

The electromechanical principle of ceramics can be visualized using the cube model shown in Fig. 5. In this schematic, a unit cube represents the crystal lattice of a piezoelectric ceramic. When mechanical stress is applied along one axis, ions inside the lattice shift slightly, creating an imbalance in the electric dipoles. This shift results in polarization and the accumulation of electrical charges on the cube's opposite surfaces. This phenomenon illustrates the direct piezoelectric effect, where stress is directly converted into electrical energy. Conversely, applying an external electric field can deform the lattice, demonstrating the converse piezoelectric effect. Although real ceramics have more complex perovskite crystal structures, this simplified model provides an accessible way for readers to grasp how microscopic structural changes produce measurable macroscopic voltage.

The contribution of Fig. 5 extends beyond conceptual clarity. It highlights the anisotropy of piezoelectric ceramics, meaning that their response depends on

the direction of applied stress relative to the orientation of dipoles. This explains why poling treatments (electric-field alignment of domains) are essential to maximize piezoelectric performance. In practical terms, when ceramic particles are embedded in cementitious matrices, their orientation and alignment significantly influence the efficiency of stress-to-charge conversion. Without proper alignment, dipole responses may cancel each other, resulting in reduced output.

Critically, this fundamental principle also underpins a wide range of applications in civil engineering. In piezoelectric pavements, traffic loads compress ceramic inclusions, generating power for streetlights or monitoring devices. In bridge decks, vibration-induced stress creates signals that can be harvested for energy or used for structural health monitoring. In smart buildings, ceramic-based composites embedded in flooring or walls can provide both energy harvesting and strain sensing, enabling multifunctional infrastructure systems. Therefore, Fig. 5 is not merely a schematic illustration of lattice-level behavior; it is a conceptual bridge linking the microscale science of dipole displacement with the macroscale applications of piezoelectric concrete in smart and sustainable infrastructure.

Recent advances have sought to overcome the inherent brittleness of ceramics. Porous ceramics have been developed to lower dielectric permittivity and improve voltage output efficiency [32], while doped PZT formulations have demonstrated improved fatigue resistance and domain stability [33]. Nevertheless, long-term durability under cyclic loading and moisture exposure remains a persistent challenge [34], highlighting the ongoing need for surface modifications and composite hybridization strategies.

Recent innovations include the development of porous ceramics, which reduce dielectric permittivity and enhance voltage generation efficiency [32], and doped PZT systems designed to improve fatigue resistance and stabilize domain switching under cyclic loading [33]. Despite these advances, long-term durability under harsh environmental exposure remains a barrier to widespread adoption, highlighting the need for improved surface engineering and protective strategies [34].

3.2. Piezoelectric polymers

Polymers such as PVDF and its copolymers have emerged as promising alternatives to ceramics owing to their flexibility, low density, and ease of processing [35]. Unlike brittle ceramics, polymers can better accommodate strain mismatches within

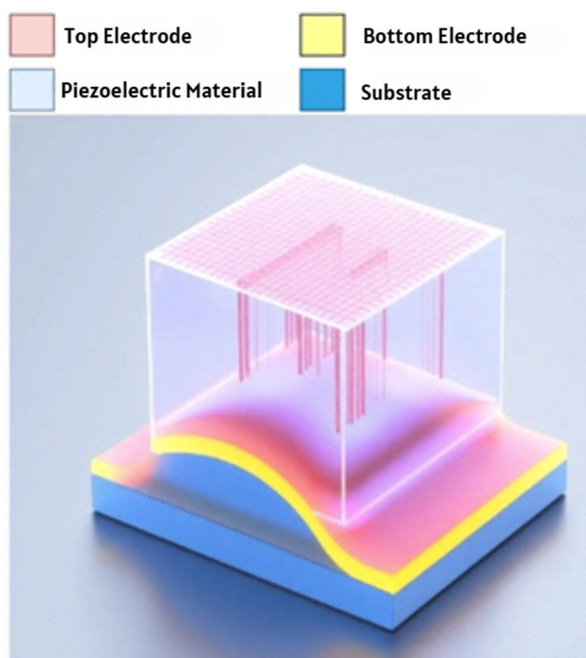


Fig. 5. Cube model showing electromechanical coupling in piezoelectric ceramics under applied stress.

the cement matrix, which reduces the risk of microcracking and debonding [36]. PVDF-based composites have demonstrated stable and repeatable signal generation under cyclic loads, making them particularly suitable for pavement and bridge deck monitoring applications [37].

Although their piezoelectric coefficients are lower than those of ceramics, recent advances have improved performance through nanostructuring strategies. For instance, electrospun PVDF nanofibers exhibit enhanced β -phase content and improved dipole alignment, resulting in greater output efficiency [38]. Similarly, the incorporation of graphene oxide into PVDF matrices has been shown to enhance polarization and electrical conductivity, thereby broadening the scope of polymer-based composites for infrastructure monitoring.

3.3. Hybrid and nanocomposite systems

Hybrid systems integrate ceramics, polymers, and nanoscale fillers such as CNTs, graphene, and zinc oxide nanowires [39]. These composites combine the electromechanical sensitivity of ceramics, the toughness of polymers, and the conductivity of nanofillers, enabling multifunctionality.

A critical concept in such systems is connectivity, illustrated in Fig. 6, which classifies piezocomposites by filler–matrix connectivity types (0–3, 1–3, 2–2, 3–3). Each connectivity mode has distinct im-

plications for stress transfer, charge distribution, and mechanical reinforcement. For example, 1–3 connectivity (aligned fibers in a continuous matrix) enhances longitudinal stress transfer, while 0–3 connectivity (random particles in a matrix) offers ease of processing but less efficient charge transport [39–41].

Recent experimental work has demonstrated that CNT-reinforced cement–PZT composites achieve higher charge output due to efficient conductive network formation [41], while graphene nanoplatelets simultaneously improve electrical response and compressive strength [42].

3.4. Bio-based and sustainable piezoelectric materials

With the increasing emphasis on sustainability, bio-derived piezoelectric materials have recently been explored as eco-friendly alternatives. Cellulose nanocrystals (CNCs), chitin, and other natural polymers offer renewable, biodegradable options for piezoelectric composites [49]. While their piezoelectric coefficients are generally lower than ceramics, their flexibility, abundance, and tunability make them attractive for integration into green construction practices.

Cellulose-based nanogenerators, for example, have demonstrated tunable dielectric properties that can be tailored for low-power energy harvesting, making them suitable for distributed sensing

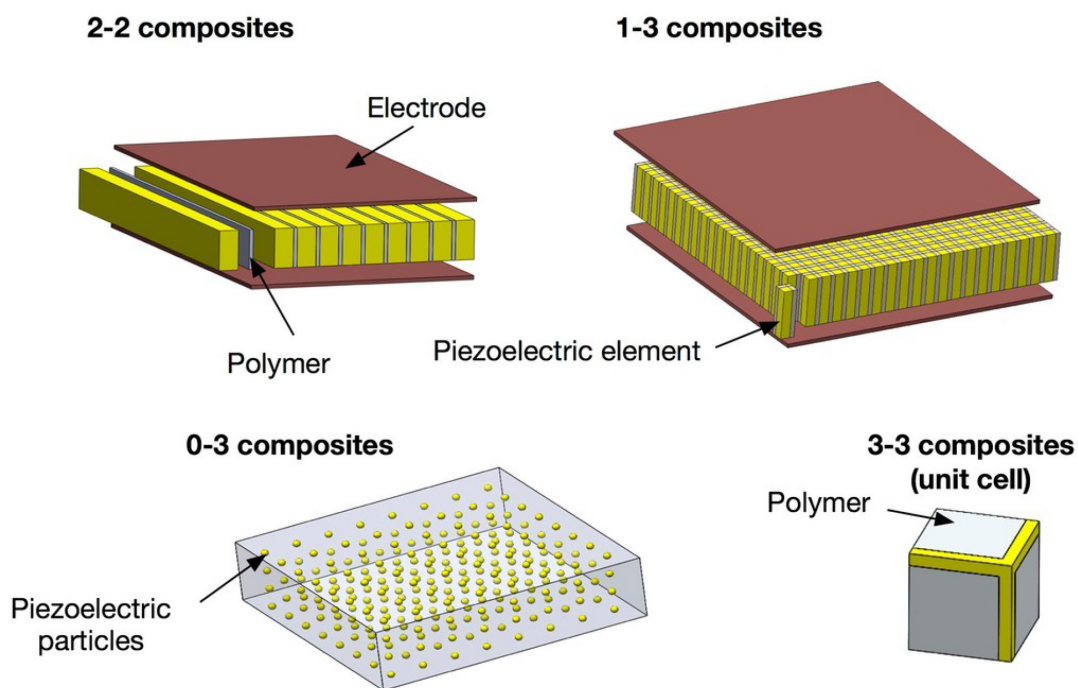


Fig. 6. Connectivity modes in piezocomposites (0–3, 1–3, 2–2, 3–3) and their influence on stress transfer and charge distribution [41].

networks in sustainable infrastructure. The shift toward bio-based systems reflects the broader need to align functional material innovation with global sustainability and circular economy goals.

3.5. Integration challenges in cementitious matrices

The successful incorporation of piezoelectric fillers into cementitious composites is complicated by several microstructural and physicochemical factors. The interfacial transition zone (ITZ), which represents the boundary between the aggregate or filler and the surrounding cement paste, is a critical determinant of stress transfer and electromechanical efficiency [43]. Due to local heterogeneity, the ITZ often exhibits increased porosity and weaker bonding, which leads to stress concentration under cyclic loads. These localized weaknesses contribute to microcracking, debonding of the piezoelectric filler, and attenuation of the electrical signal.

Another fundamental issue is dielectric mismatch between the cementitious matrix and the embedded filler. Cement paste, with relatively low dielectric properties, alters the local electric field distribution when in contact with high-dielectric piezoelectric inclusions. This mismatch can cause interfacial polarization and energy dissipation, thereby lowering the effective piezoelectric output [46]. The problem is exacerbated by moisture ingress and long-term hydration, which modify the dielectric constant of the matrix and further destabilize the electromechanical coupling.

To overcome these challenges, researchers have investigated a range of surface modification and functionalization techniques. For example, silane coupling agents and polymeric coatings have been shown to enhance bonding strength between piezoelectric particles and the cement matrix, improving both stress transfer and durability [44]. Similarly, the use of surfactants or dispersants improves filler distribution, reducing agglomeration and creating more uniform conductive pathways [45]. Optimized dispersion is particularly important for nanofillers such as CNTs and graphene, where achieving percolation without clustering is essential for forming efficient conductive networks.

Although no direct figure is presented in this subsection, the connectivity models shown in Fig. 6 indirectly reinforce these integration challenges by demonstrating how filler orientation and connectivity (e.g., 0–3 versus 1–3 composites) influence stress transfer pathways and charge transport efficiency. Thus, while the ITZ and dielectric mismatch are microstructural barriers, their effects can be interpreted within the broader framework of

composite connectivity, underscoring the need for engineered interfaces and advanced processing methods to realize the full potential of piezoelectric concrete.

3.6. Future prospects

Future progress in piezoelectric concrete is expected to be driven by additive manufacturing and the development of flexible, multifunctional composites. Advances in 3D printing allow precise control of filler distribution and orientation, offering the potential to maximize electromechanical response at the structural scale [47]. Similarly, printable and flexible composites broaden design possibilities for smart and adaptive infrastructure [48].

The application-oriented potential of these systems is demonstrated in Fig. 7, which showcases representative energy-harvesting devices integrated into pavements, bridges, and facades. This figure emphasizes that piezoelectric materials, once optimized, are not confined to laboratory prototypes but are actively shaping real-world infrastructure applications. It also illustrates how device design and placement directly influence energy output and sensing efficiency, reinforcing the importance of aligning material innovation with engineering practice.

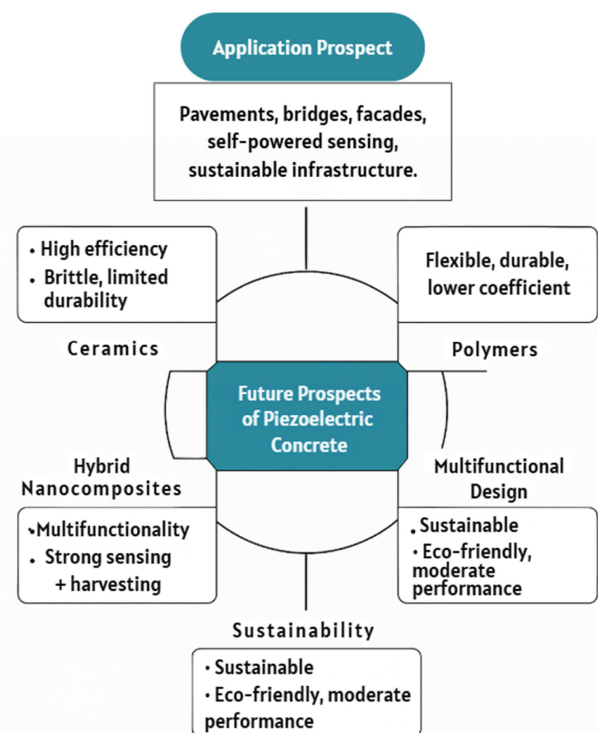


Fig. 7. Emerging trends in piezoelectric materials and their application domains for future infrastructure.

Looking further ahead, sustainable bio-based piezoelectric systems are likely to play an increasingly important role, particularly as the construction industry transitions toward carbon neutrality. Ultimately, the future of piezoelectric concrete lies in the convergence of material innovation, scalable integration techniques, and infrastructure-oriented design strategies that collectively enable durable, efficient, and intelligent built environments.

4. Integration strategies in concrete

The successful implementation of piezoelectric concrete depends not only on material selection but also on the strategy used to integrate piezoelectric elements into structural components. Integration approaches determine how effectively stress is transferred to the active phase, how well the system resists environmental degradation, and how scalable the technology is for civil engineering applications. Broadly, two main strategies are employed: embedded integration, where piezoelectric inclusions are incorporated directly into the cementitious matrix, and surface-mounted integration, where discrete piezoelectric devices are attached to the exterior of concrete elements. Recent innovations also point toward hybrid and adaptive systems, which combine these strategies to balance sensitivity, durability, and adaptability [50–52].

To provide a conceptual roadmap, the emerging material and system-level innovations are summarized in Fig. 8. This figure highlights the evolution of piezoelectric concrete research from traditional ceramics to polymers, nanostructured composites, and sustainable hybrid systems. It visually reinforces that integration strategies must evolve in parallel with material development, ensuring that new functionalities such as flexibility, multifunctionality, and durability are effectively harnessed within civil infrastructure.

4.1. Embedded strategies

Embedding piezoelectric materials within the concrete matrix ensures direct load transfer and provides protection from environmental wear. Common approaches include dispersing piezoelectric powders such as PZT or BaTi₃, embedding ceramic plates,

or incorporating polymeric and hybrid nanocomposites [53]. These strategies allow the piezoelectric elements to deform simultaneously with the matrix, ensuring efficient electromechanical coupling.

Advantages include enhanced durability due to protection from abrasion and weathering, as well as, compatibility with large-scale casting processes [54]. Embedded sensors also enable long-term SHM as they remain permanently integrated into the load-bearing system. However, challenges include difficulties in aligning particles to maximize anisotropic response, stress shielding caused by cement hydration products, and weak interfacial bonding that can reduce signal stability [55]. In addition, embedded systems are more difficult to repair or replace once deterioration occurs.

A key example of embedded strategies is the use of PVDF-based polymer films. Their flexibility and compatibility with cementitious matrices offer an alternative to brittle ceramics. Fig. 9 demonstrates the simulated thickness variation of PVDF under an applied 25 V field, showing its electromechanical response. The deformation pattern illustrates how electrical excitation can directly influence structural geometry at the microscale, validating PVDF's suitability for embedded energy harvesting and sensing applications. Importantly, such electromechanical responsiveness makes PVDF composites attractive for multifunctional infrastructure systems, where adaptability and resilience are as critical as energy conversion efficiency [56, 57].

4.2. Surface-mounted strategies

Surface-mounted systems involve attaching piezoelectric modules such as patches, films, or tiles onto the exterior of concrete structures. This approach enables straightforward installation and replacement, as well as the ability to position devices at stress concentration zones such as pavement wheel paths, bridge decks, or façade panels [57]. Materials used include lead zirconate titanate plates, PVDF polymer films, and flexible hybrid laminates.

The key advantage is accessibility. Devices can be serviced, replaced, or upgraded without disturbing the host structure. Surface-mounted systems also exhibit higher sensitivity to localized stresses, which is useful for energy harvesting from footsteps or

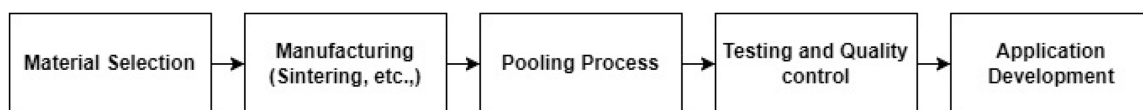


Fig. 8. Emerging trends in piezoelectric materials and integration strategies.

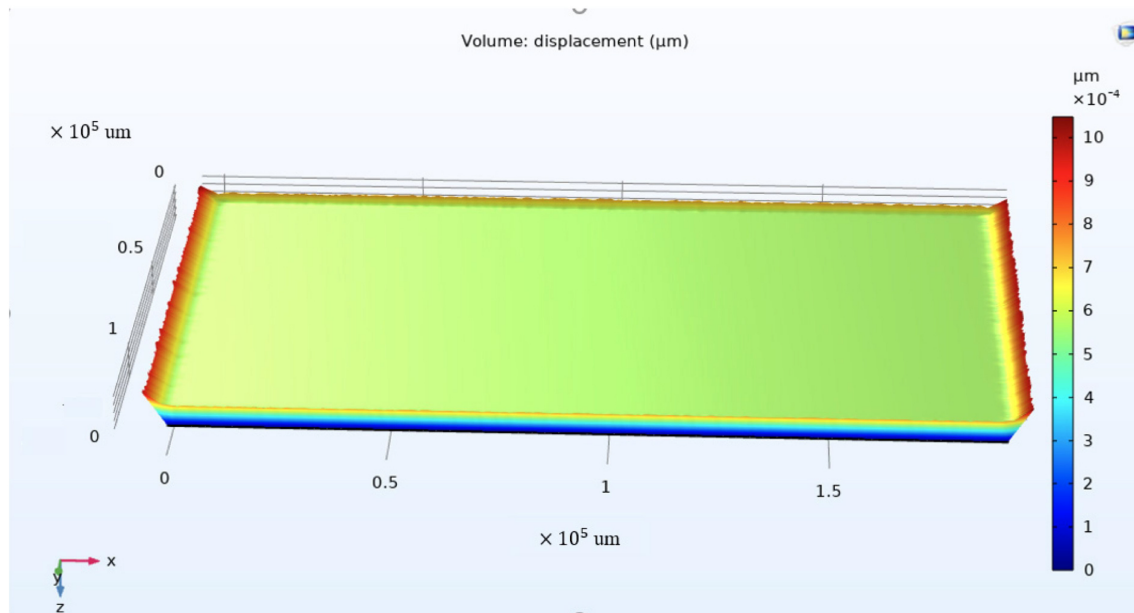


Fig. 9. Simulation of thickness variation in PVDF under applied voltage [57].

Table 1. Comparison of embedded vs. surface-mounted integration strategies for piezoelectric concrete.

Feature	Embedded Piezoelectric Materials	Surface-mounted Piezoelectric Devices
Installation	Inserted during construction; requires significant modifications	Can be installed on existing structures; minimal modifications needed
Visual Impact	Seamless and unobtrusive; integrated into the concrete	May be visible; designed to blend with the environment
Energy Harvesting Efficiency	Generally more efficient due to strategic placement in high-stress zones	May be less efficient, particularly in areas with lower mechanical stress
Application	Ideal for new constructions or major renovations	Suitable for retrofitting existing structures (e.g., sidewalks, parking lots)
Cost	Higher initial costs due to construction requirements	Lower initial costs; more economical for existing infrastructure
Flexibility	Limited to new projects; not adaptable to existing structures	Highly adaptable; can be implemented in various urban settings
Deployment Time	Longer deployment time due to construction schedules	Quicker installation; can be deployed rapidly
Performance	Optimized for high-performance energy generation	Performance may vary based on location and mechanical stress
Suitability	Best for projects emphasizing efficiency and long-term energy harvesting	Best for areas with existing infrastructure where retrofitting is needed

monitoring crack initiation at specific points [58]. However, disadvantages include vulnerability to wear, delamination under repeated traffic loads, and exposure to moisture or temperature fluctuations, which can degrade long-term performance [59].

4.3. Comparative analysis

A comparative understanding of embedded and surface-mounted strategies is crucial for selecting the appropriate method in a given application. Embedded systems prioritize durability and integration, while surface-mounted systems emphasize flexibility and accessibility. To highlight these trade-offs, the comparative data from earlier studies are summarized in Table 1.

The table highlights that embedded systems are better suited for long-term monitoring in harsh environments such as bridge decks and pavements, whereas surface-mounted systems are advantageous for pilot projects and applications requiring frequent device replacement. Ultimately, integration choice depends on balancing cost, durability, sensitivity, and maintainability.

4.4. Hybrid and adaptive systems

Emerging research trends point toward hybrid and adaptive systems that combine the strengths of both integration strategies. For example, flexible piezoelectric laminates can be partially embedded beneath the surface to enhance protection while

maintaining accessibility for replacement [60]. Self-healing polymers and conductive adhesives are also being explored to improve the bonding between surface-mounted modules and the host concrete, reducing delamination risk.

Adaptive systems are being developed that integrate energy harvesting and SHM functions simultaneously. In these designs, embedded inclusions capture global strain and load distribution, while surface-mounted modules focus on localized crack detection and high-frequency vibration monitoring [61]. Such multifunctional networks align with the vision of smart infrastructure, where concrete elements serve as both structural supports and self-powered sensory systems.

5. Mechanism of electricity generation from piezoelectric concrete

5.1. Generator theory of piezoelectric materials

The working principle of piezoelectric materials is governed by two fundamental mechanisms: the direct effect, where mechanical stress generates electrical charge, and the inverse effect, where applied voltage induces mechanical deformation. These mechanisms are the cornerstone of all piezoelectric applications, from actuators to energy harvesters, and form the theoretical basis for extending piezoelectricity into concrete systems [63, 64].

Fig. 10 presents a conceptual illustration of the direct piezoelectric effect. When external compressive or tensile stress is applied to a piezoelectric crystal or polymer film, internal electric dipoles become realigned. This alignment creates polarization within the material, leading to the accumulation of electrical charges on opposing surfaces. Electrodes connected to the material then collect these charges, producing a measurable voltage. This effect has been widely documented in PZT ceramics, which exhibit high piezoelectric coefficients ($d_{33} \sim 330$ pC/N), making them highly sensitive to stress-induced electrical responses [65]. Similarly, polymers such as PVDF, though exhibiting lower d_{33} values (~ 33 pC/N), have

demonstrated stable voltage output under repeated mechanical loading, particularly in flexible devices [66].

Fig. 11 illustrates the complementary nature of the direct and inverse piezoelectric effects. On the left, the figure shows how compressive and tensile stresses induce polarization and generate charges across electrodes (direct effect). On the right, it depicts how an external electric field applied to the material causes mechanical deformation (inverse effect). This bidirectional coupling is critical for multifunctional applications: in energy harvesting, the direct effect is exploited, while in vibration control or actuation, the inverse effect is utilized [67]. Past studies have shown that the inverse effect is particularly valuable in structural control, where piezoelectric actuators embedded in beams or slabs can mitigate vibrations [68].

Critically reviewing the literature, the theoretical framework represented in Figs. 9 and 10 has been validated across decades of piezoelectric research. For instance, Shrout and Zhang [64] highlighted the superior electromechanical coupling of PZT ceramics for sensing and energy conversion, while Wu et al. [65] emphasized the potential of lead-free alternatives such as potassium–sodium niobate to provide environmentally sustainable replacements. In the polymeric domain, Bairagi et al. [66] confirmed that PVDF and its copolymers, despite lower coefficients, offer unmatched flexibility and adaptability in dynamic environments. These findings underscore that while the fundamental mechanisms are universal, the material selection strongly influences application performance.

In summary, Figs. 10 and 11 visually reinforce the generator theory by showing how stress and electric fields interact with piezoelectric materials. The critical insights from past research confirm that these principles are reliable across material classes, but their efficiency, durability, and adaptability vary significantly depending on whether ceramics, polymers, or composites are used. This understanding lays the groundwork for applying piezoelectric theory to the more complex case of concrete composites in the following sections.

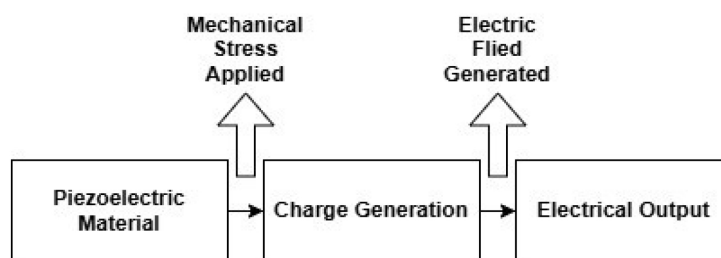


Fig. 10. Conceptual illustration of the direct piezoelectric effect.

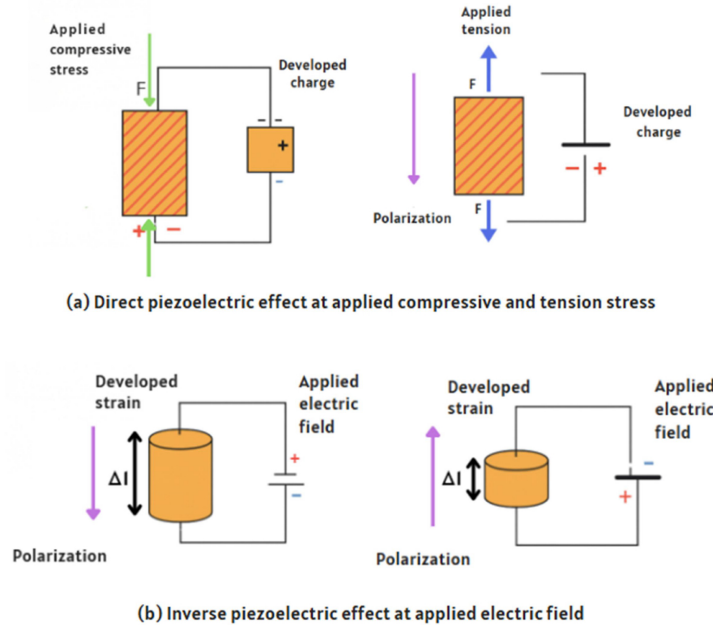


Fig. 11. Schematic of the direct and inverse piezoelectric effects.

5.2. Transition to piezoelectric concrete

When piezoelectric materials are incorporated into concrete, their behavior differs from that of bulk ceramics or polymers. The cementitious matrix introduces heterogeneity, stress dissipation, and interfacial effects that influence how efficiently applied loads are transferred to the piezoelectric inclusions. This means that the overall energy conversion efficiency depends not only on the intrinsic material properties but also on the mechanical characteristics of the surrounding concrete [66, 67].

The charge generated by embedded piezoelectric elements under mechanical loading can be described by the following relationship:

$$Q = d/c \cdot F$$

where Q is the generated charge (C), d is the piezoelectric charge constant (C/N), c is the stiffness of the piezoelectric element (N/m), and F is the applied force (N). This equation highlights that greater force or higher piezoelectric sensitivity produces more charge, while higher stiffness reduces deformation and lowers charge intensity. In concrete composites, this means that the stiffness of the cement matrix, interfacial bonding, and load transfer pathways strongly influence actual charge output compared with ideal bulk materials [68].

Fig. 12 illustrates this principle by showing how stress-induced polarization develops in inclusions embedded within concrete. External loading causes

deformation of the inclusions, leading to dipole realignment and localized charge accumulation that can be harvested at electrodes. However, the stress distribution in concrete is non-uniform due to aggregate contact points, cement paste stiffness, and microcracks, which reduces the effective stress acting on the inclusions and therefore lowers output compared to theoretical predictions [69].

Fig. 13 expands this understanding by showing charge distribution during repeated loading cycles. Localized polarization within the inclusions produces uneven charge accumulation, which can fluctuate with microstructural changes in the concrete. Over time, repeated cycles may lead to fatigue at the interface between inclusions and the cement paste, resulting in reduced stability of the electrical output. Xu et al. [67] demonstrated that cyclic loading caused progressive signal degradation in PZT-based cement composites, while Kang et al. [68] reported that environmental cycling (freeze–thaw and wet–dry) further accelerated this decline. In contrast, PVDF-based systems maintained relatively stable output under cyclic loading, albeit at lower energy levels [70].

The generated charge can also be linked to the measurable voltage output through the relationship:

$$V = Q/C$$

where V is the output voltage (V), Q is the generated charge (C), and C is the capacitance of the circuit (F). This equation shows that the final voltage is not only a function of the piezoelectric properties and applied

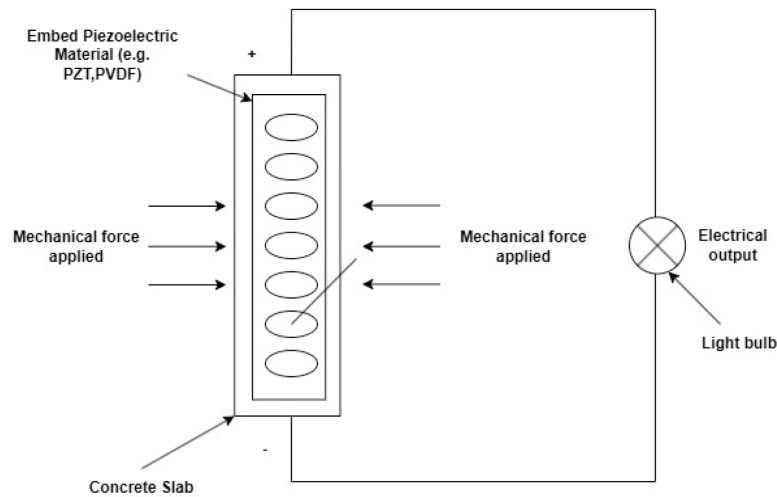


Fig. 12. Stress-induced polarization in piezoelectric inclusions embedded in concrete, showing how applied loads generate localized charge distribution.

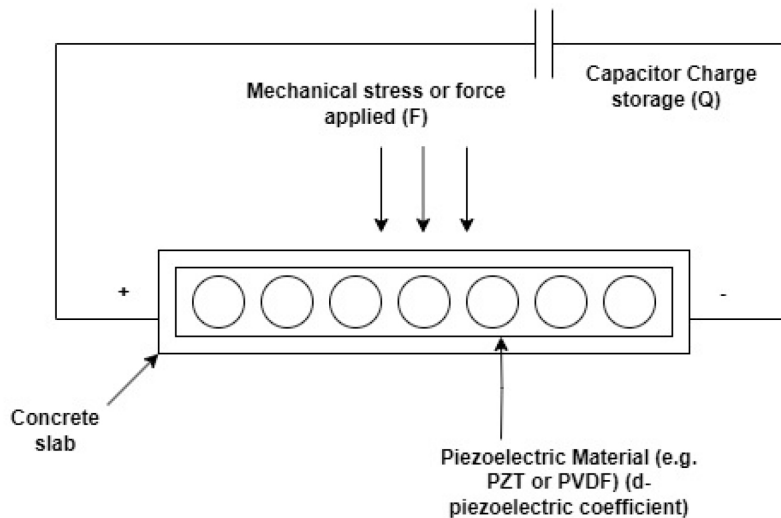


Fig. 13. Charge generation and distribution in piezoelectric concrete under repeated loading cycles, illustrating localized polarization and interfacial effects.

load but also of the electrical design of the harvesting system. In concrete applications, this highlights the importance of considering both material-level factors and system-level electrical integration.

Together, Figs. 12 and 13 demonstrate how theoretical predictions from the charge equation are modified in practice when piezoelectric elements are embedded in concrete. They highlight the importance of considering stiffness, interfacial bonding, and environmental durability in designing piezoelectric concrete systems capable of consistent energy harvesting.

5.3. Working principles and differences

The piezoelectric effect in bulk materials and in cementitious composites is governed by the same the-

oretical principles but differs significantly in practice due to the heterogeneous structure of concrete. In bulk ceramics such as PZT, applied stress results in uniform dipole alignment, producing a predictable and stable electrical response. In contrast, when these materials are integrated into concrete, the stress transfer is highly non-uniform because of the presence of aggregates, pores, and the interfacial transition zone (ITZ). These heterogeneities dissipate mechanical energy, reducing the effective stress transmitted to piezoelectric inclusions and consequently lowering energy conversion efficiency [67, 68].

Fig. 14 schematically compares the working mechanisms of piezoelectric materials versus piezoelectric concrete. In pure piezoelectric materials (left side),

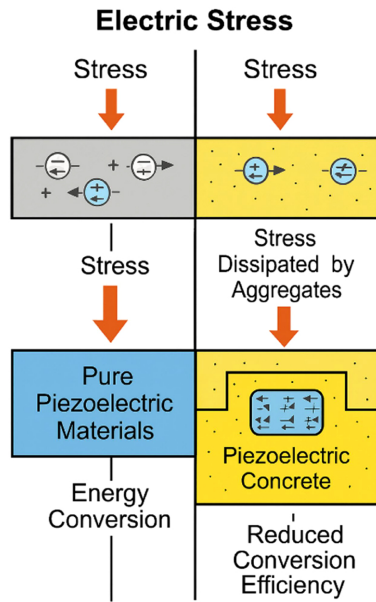


Fig. 14. Comparison of piezoelectric materials and piezoelectric concrete, showing uniform stress–charge conversion in pure materials versus attenuated response in composites.

external mechanical loads are uniformly distributed across the lattice structure, generating consistent polarization and surface charge. However, in piezoelectric concrete (right side), the load applied to the bulk structure is dispersed through aggregates and microcracks before reaching the inclusions, which reduces the degree of dipole alignment. This attenuation results in smaller and less stable voltage outputs compared with isolated piezoelectric materials.

Past research has validated this observation. Xu et al. [67] demonstrated that stress transfer inefficiencies caused by ITZ microcracking led to significant performance loss in PZT-modified cement. Kang et al. [68] observed that environmental cycling exacerbated these effects by weakening interfacial bonds, further disrupting charge stability. Conversely, PVDF inclusions, due to their flexibility, maintained more consistent though lower outputs under dynamic loading [70]. These studies collectively highlight that while the fundamental mechanism is preserved, the practical performance differs significantly between standalone piezoelectric materials and their composite counterparts.

5.4. Factors influencing performance

The performance of piezoelectric concrete systems is governed by a complex interplay of material properties, structural mechanics, environmental exposure, and geometric design. Each factor plays a decisive

role in determining both energy harvesting efficiency and long-term durability.

(a) Material properties. PZT ceramics exhibit high piezoelectric coefficients ($d_{33} \sim 330$ pC/N), which provide strong electrical responses. However, they are brittle and prone to chemical degradation in the alkaline concrete environment [72]. In contrast, PVDF polymers offer lower piezoelectric constants ($d_{33} \sim 33$ pC/N) but higher flexibility and environmental stability, making them better suited for cyclic or outdoor applications [71]. Emerging nanomaterials such as CNTs and graphene have been shown to enhance permittivity and conductivity of the cement matrix, thereby improving charge collection and sensitivity [73].

(b) Mechanical properties of concrete. Effective stress transfer is crucial for energy conversion. The stiffness of the matrix, microstructural homogeneity, and interfacial bonding between inclusions and cement paste determine how much load is transmitted to the piezoelectric elements. Poor interfacial adhesion or microcracking weakens stress transfer and leads to unstable outputs. Reinforcements such as fibers or supplementary binders (e.g., silica fume, fly ash) can improve bonding and enhance the electromechanical response [74].

(c) Environmental durability. Field applications expose piezoelectric concrete to moisture ingress, freeze–thaw cycling, and temperature variations. PZT inclusions are vulnerable to hydrothermal degradation and require encapsulation, while PVDF shows resilience against moisture and temperature fluctuations [75]. Studies by Kang et al. [68] confirmed that without protective encapsulation, PZT systems experienced rapid performance loss under environmental cycling.

(d) Geometric configuration. The placement, orientation, and depth of piezoelectric inclusions directly influence efficiency. Fig. 15 illustrates embedded versus surface-mounted strategies: embedded designs ensure better structural protection but suffer stress attenuation, while surface-mounted designs experience higher stresses but reduced durability. Fig. 16 shows modular pavement systems with regularly spaced piezoelectric units, where optimized spacing and orientation improve energy harvesting by over 40% in simulation studies [76].

Critical evaluation of these factors suggests that no single material or configuration can maximize both efficiency and durability. Instead, hybrid approaches such as combining ceramics and polymers, or integrating piezoelectric harvesting with photovoltaic or thermoelectric systems represent promising future directions [77].

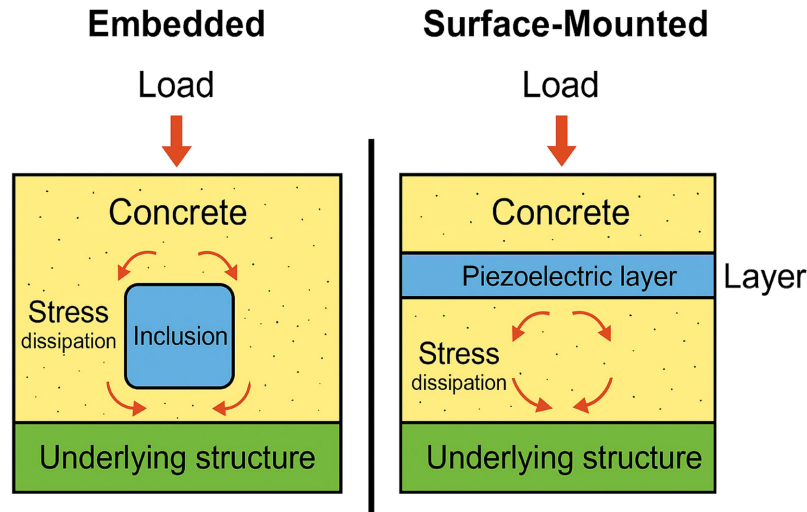


Fig. 15. Embedded versus surface-mounted piezoelectric concrete systems, showing trade-offs between protection and efficiency.

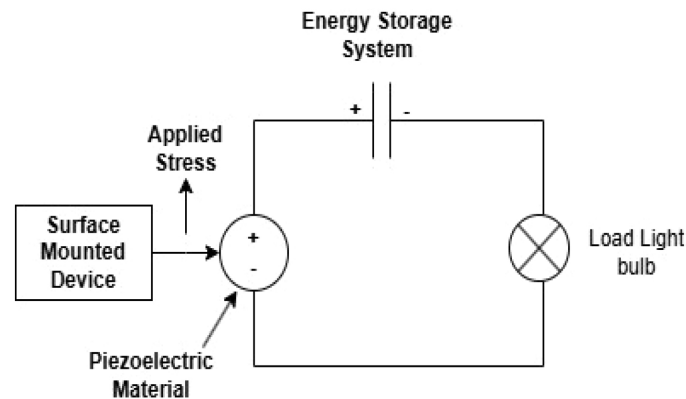


Fig. 16. Modular pavement system illustrating optimized distribution of piezoelectric units for improved harvesting efficiency.

5.5. Consolidated insights on piezoelectric mechanisms

The concept of piezoelectric concrete demonstrates significant potential for transforming civil infrastructure into energy-harvesting and self-sensing systems. However, translating laboratory findings into large-scale applications requires careful consideration of multiple challenges. The discussion below synthesizes key insights from previous subsections and situates them within the broader research landscape.

Despite encouraging laboratory results, the energy output from piezoelectric concrete remains modest compared to conventional renewable sources such as photovoltaics or wind. PZT-based composites can generate high initial voltages due to their superior piezoelectric coefficients, but their brittleness and environmental vulnerability reduce their long-term viability [67, 72]. PVDF-based systems, although more stable under cyclic loading and environmental

stress, produce lower charge outputs [71]. Hybrid composites that integrate ceramics, polymers, and conductive nanofillers show promise, but optimization is required to avoid percolation thresholds that may short-circuit the system [73].

Environmental degradation remains one of the most critical barriers to commercialization. Studies confirm that repeated freeze–thaw cycling, moisture ingress, and high temperatures accelerate the deterioration of piezoelectric ceramics in cementitious environments [68, 74]. Encapsulation and polymeric alternatives can mitigate these issues, but long-term monitoring under real-world conditions is still scarce. More extensive field trials, such as those conducted in Korea and China, are needed to evaluate durability over service lifetimes [69, 75].

Embedding piezoelectric inclusions into pavements or bridge decks raises engineering questions related to spacing, orientation, and load distribution. As shown in Figs. 15 and 16, optimized configurations

can significantly improve efficiency, yet scaling from small test specimens to full-scale pavements introduces non-uniform stress distributions and maintenance challenges [76]. Furthermore, the integration of electrodes, wiring, and protective casings must be designed to withstand heavy traffic without compromising structural performance.

Multifunctionality and hybridization is one of the most compelling opportunities lies in the multifunctional role of piezoelectric concrete. In addition to harvesting energy, stress-induced signals can act as self-powered sensors for SHM, enabling real-time detection of crack initiation, vibration patterns, and load histories [77, 78]. Combining piezoelectric harvesting with thermoelectric or photovoltaic systems could address intermittency issues and improve total energy yield. For example, Liu et al. [77] demonstrated the feasibility of hybrid systems that harvest mechanical and thermal energy simultaneously in pavement applications.

In conclusion, piezoelectric concrete remains a promising but evolving technology. While challenges of energy density, durability, and cost persist, the advances in material science, system integration, and hybrid energy harvesting are paving the way for its adoption in future sustainable infrastructure. The dual functionality of energy harvesting and SHM makes it particularly attractive for smart city applications, where multifunctional materials will be essential to reducing energy consumption and enabling real-time monitoring.

6. Applications of piezoelectric concrete

Piezoelectric concrete has emerged as a multifunctional material capable of harvesting ambient mechanical energy while simultaneously acting as a sensing medium for structural health monitoring. Applications span across transportation infrastructure, civil engineering structures, and building systems. This section critically reviews both national and international advancements, consolidating experimental findings, pilot projects, and modelling studies to highlight the current state of application and future opportunities.

6.1. Pavement and transportation infrastructure

The most extensively studied application of piezoelectric concrete is in pavement systems, where vehicular and pedestrian loads provide continuous dynamic excitation.

International studies have demonstrated considerable progress. In Korea, field-scale piezoelectric pavements were deployed using PZT modules encased in protective layers. Park et al. [69] reported sustained electricity generation sufficient to power LED streetlights under open-traffic conditions. Similarly, large-scale demonstrations in China integrated arrays of piezoelectric ceramics into highways, producing several watts per vehicle at optimal speeds. The European Union's "Smart Road" projects have further explored modular piezoelectric tiles combined with wireless transmission systems, showing scalability for road networks.

Regional and national research in ASEAN has also advanced this field. In Malaysia, prototype piezoelectric tiles embedded with PVDF sheets were tested in pedestrian walkways, demonstrating stable voltage output under tropical environmental conditions. Indonesian researchers have piloted hybrid PZT-polymer blocks in urban crossings, highlighting cost-effectiveness and adaptability for developing regions. These efforts emphasize that while large-scale trials dominate international projects, low-cost and climate-adapted designs are being pioneered in Southeast Asia.

Fig. 17 provides a visual overview of the diverse application domains of piezoelectric concrete, consolidating the discussion into a single comparative framework. Panel (a) illustrates the integration of piezoelectric modules within highway pavements, where dynamic loads from moving vehicles generate mechanical stress that is converted into electrical energy. This concept has been validated in several international field trials, including large-scale demonstrations in Korea and China, where embedded PZT modules produced outputs in the watt range per vehicle. Such outputs were sufficient to sustain street lighting and traffic sensors [69, 76]. These implementations demonstrate the feasibility of roadway energy harvesting while also highlighting durability challenges, particularly the need for protective encapsulation against cracking and moisture ingress.

Panel (b) depicts pedestrian walkways incorporating modular tiles. Unlike highways, these systems are exposed to lower loading magnitudes but benefit from high-frequency excitations in urban and campus environments. Experimental prototypes in Malaysia and Europe demonstrated that footstep-induced voltages, though relatively modest (μW to tens of mW per tile), can reliably power environmental sensors and wireless communication modules [51]. The modular design of these tiles enables easier installation, replacement, and scalability. This approach offers a cost-effective solution for developing regions where large-scale roadway integration may not be practical.

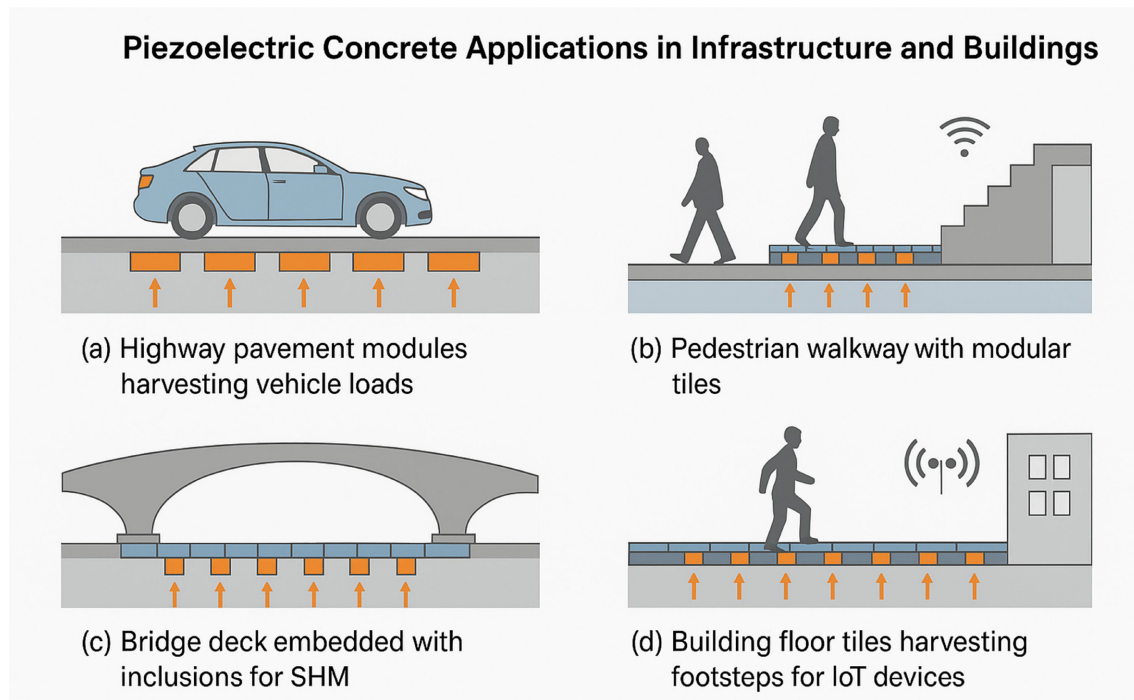


Fig. 17. Illustrates different pavement-level applications, ranging from embedded modules in highways to modular tiles in pedestrian pathways.

Panel (c) shows bridge decks embedded with piezoelectric inclusions, representing the application of piezoelectric concrete for SHM. In this case, the role of the material extends beyond energy harvesting to include real-time sensing of vibration, stress distribution, and crack initiation. Case studies in Japan and the United States demonstrated that piezoelectric sensors embedded in bridge girders provided high-fidelity data on fatigue and loading patterns, enabling predictive maintenance and extending structural service life [78]. This panel underscores the unique advantage of piezoelectric concrete in multifunctionality, where monitoring and energy harvesting can coexist within the same structural system.

Panel (d) illustrates building flooring systems, where piezoelectric concrete is deployed as part of “smart” infrastructure. PVDF-based films and hybrid fillers integrated into flooring layers capture footstep energy that can be used to power IoT devices, occupancy sensors, or wireless lighting systems. These applications are particularly suited to high-traffic areas such as airports, malls, and office buildings, where human movement is continuous and predictable. Although the energy yield remains relatively low, the combination of sustainability, user interaction, and smart building integration highlights the growing role of piezoelectric concrete in urban energy ecosystems.

Taken together, Fig. 17 demonstrates the versatility of piezoelectric concrete, from high-power roadway harvesting to low-power sensing in smart environments. By comparing across these four domains, the figure highlights the key trade-offs in the field, such as power density in relation to durability, scalability in relation to cost, and energy harvesting in relation to sensing. This visual synthesis not only enhances reader comprehension but also reinforces the argument that piezoelectric concrete must be developed within application-specific frameworks to maximize its impact.

6.2. Structural health monitoring (SHM)

Beyond energy harvesting, piezoelectric concrete serves as a self-powered sensing platform. When embedded in structural components, stress-induced signals can indicate load variations, vibration patterns, and early crack formation.

Wu et al. (2020) [78] reported that piezoelectric inclusions in bridge decks successfully detected fatigue-induced microcracks under repeated traffic loading. In Japan, smart bridge girders incorporating PZT arrays provided real-time vibration monitoring, enabling predictive maintenance. In the United States, pilot projects have explored piezoelectric concrete overlays on runways for simultaneous energy harvesting and strain monitoring.

Table 2. Comparative assessment of piezoelectric concrete applications.

Application Domain	Key Advantages	Reported Outputs (Typical Range)	Limitations	Innovation Opportunities
Pavement & Transportation	High load frequency; potential for large-scale harvesting; proven field pilots (China, Korea, EU)	10 mW – several W per vehicle depending on configuration	Durability issues (freeze–thaw, cracking), high installation cost, stress attenuation	Hybrid with PV/TE; modular low-cost ASEAN tiles; improved encapsulation
Structural Health Monitoring (SHM)	Self-powered sensing; low power demand; proven crack/vibration detection	μ W – mW (sufficient for sensors)	Lower energy output; requires sensitive circuitry; interfacial fatigue	Multi-sensor integration; SHM + energy harvesting multifunctionality
Building Applications	Constant pedestrian activity; lightweight PVDF integration; sustainable for IoT devices	μ W – tens of mW per tile	Limited efficiency; only supports small electronics; deployment costs	Smart flooring for IoT; integration with wireless networks; occupant-responsive systems

Critical review shows that SHM applications often require lower power but higher signal fidelity compared to energy harvesting. PVDF inclusions, while less efficient in harvesting, are particularly well-suited for sensing due to their flexibility, stability under cyclic loading, and resilient in humid or temperature-varying environments. This makes SHM one of the most practical near-term applications of piezoelectric concrete.

6.3. Building energy and indoor applications

In the built environment, piezoelectric concrete has been applied in flooring systems to harvest energy from human footsteps. PVDF-based composites are commonly used due to their lightweight and flexible nature. Qin et al. [51] first demonstrated microfibre–nanowire hybrids for footstep energy capture, while later prototypes in smart buildings have shown potential for powering wireless sensors and IoT devices.

In Europe, PVDF film tiles have been integrated into office floors to support lighting control systems. In Malaysia, experimental walkways in university campuses demonstrated enough energy capture to power environmental sensors. These applications highlight the suitability of piezoelectric concrete for low-power electronics, especially where continuous human activity is present.

6.4. Comparative assessment and innovation

Comparing across applications reveals both achievements and persistent limitations. Pavement applications generate higher outputs but face challenges of durability, interfacial fatigue, and cost. SHM applications, while lower in power, provide robust and practical sensing capabilities, especially when PVDF is used. Building applications emphasize sustainability and low-power harvesting but remain constrained by efficiency.

The comparative assessment presented in Table 2 highlights the varying potentials and challenges of piezoelectric concrete applications across pavement systems, SHM, and building environments. Pavement applications stand out for their ability to capture significant mechanical energy from frequent vehicular traffic. Field trials in Korea and China demonstrated outputs in the range of several watts per vehicle, sufficient for powering streetlights or roadside electronics [69, 76]. However, these systems face persistent durability concerns, including degradation under freeze–thaw cycling and high installation costs, which limit widespread adoption [68]. Innovation in this area is being led by modular, low-cost prototypes in Southeast Asia, which focus on encapsulated PVDF-based tiles better suited for tropical climates.

By contrast, SHM applications exploit piezoelectric concrete's sensitivity rather than its energy density. While typical outputs range from microwatts to milliwatts—much lower than in pavements—these are sufficient for powering self-sensing systems that monitor vibrations, crack formation, and fatigue in bridges and decks [77, 78]. Wu et al. [78] reported that PZT inclusions provided high-fidelity signals for detecting microcracks, though their long-term stability required encapsulation. PVDF-based inclusions, with lower piezoelectric coefficients but higher resilience, are increasingly being adopted for monitoring in variable environments [71]. The main innovation opportunity lies in multifunctional integration, where SHM can be combined with energy harvesting to improve cost-effectiveness.

Building applications, particularly in flooring systems, offer sustainable energy harvesting from footstep loads. Outputs typically range from microwatts to tens of milliwatts per tile, which can reliably power low-energy devices such as environmental sensors or IoT modules [51]. Although efficiency remains limited, these systems present attractive opportunities for smart buildings, where continuous pedestrian activity can support distributed sensor

networks. Recent prototypes in Europe and Malaysia have demonstrated feasibility, but further optimization is required to reduce costs and ensure user comfort.

Overall, the table underscores that each application domain has a different value proposition: pavements for higher energy yield, SHM for durability and sensing, while buildings for sustainability and user-oriented integration. Critical innovation across all domains will depend on advancing materials durability, improving interfacial engineering, and adopting hybrid systems that combine piezoelectric harvesting with complementary renewable technologies.

7. Integrated discussion and future perspectives

Research on piezoelectric concrete has advanced considerably over the past two decades, moving from laboratory prototypes to field-tested systems in pavements, bridges, and buildings. Earlier sections of this review have examined the principles, material formulations, integration strategies, and application-specific performances. Building upon this foundation, the present section synthesizes the state of the art into a critical narrative that highlights both achievements and persistent challenges, while also identifying innovation opportunities and future research directions.

A consistent theme across the literature is the trade-off between energy output and durability. PZT-based composites provide high power density, as demonstrated in roadway harvesters that achieved watt-level outputs per vehicle in China and Korea [69, 76]. However, the brittle nature of ceramics and their susceptibility to fatigue under repeated loading raise questions about long-term reliability. In contrast, polymeric materials such as PVDF yield lower electrical outputs but exhibit greater flexibility and stability under cyclic stresses, making them attractive for sensing applications in bridge decks and flooring systems [71]. Hybrid approaches that combine

ceramic fillers with polymer matrices have shown promise in balancing these performance metrics, yet scalability and cost remain significant barriers.

Another key limitation is environmental resilience. Studies have shown that freeze–thaw cycles, humidity exposure, and thermal fluctuations can degrade the electromechanical properties of piezoelectric composites [68]. This issue is particularly acute for outdoor applications such as highways and bridges, where constant exposure to environmental stressors accelerates material deterioration. Addressing this challenge requires advanced encapsulation strategies, durable interfacial bonding techniques, and lifecycle testing protocols that more accurately reflect real-world conditions.

From an application perspective, piezoelectric concrete demonstrates versatility across domains, but each use case emphasizes different value propositions. Pavements are most promising for large-scale energy harvesting, although high costs and installation challenges remain obstacles. Structural health monitoring represents the most practical near-term deployment, given that sensing requires lower energy thresholds and offers immediate benefits in predictive maintenance [78]. Building applications, while less mature, align strongly with sustainability and smart city agendas, particularly in the context of powering distributed IoT networks in high-traffic indoor environments [51].

These challenges and innovation opportunities are systematically summarized in Table 3. The table highlights five major barriers that continue to hinder practical deployment: low energy conversion efficiency, durability under environmental conditions, high installation costs, lack of multifunctionality, and insufficient real-world validation. Each challenge is linked with supporting evidence from past research, its impact on applications, and suggested research directions. For instance, the efficiency gap between PZT and PVDF underscores the need for hybrid composites incorporating nanofillers such as carbon nanotubes or graphene to enhance performance.

Table 3. Critical challenges and future research directions for piezoelectric concrete.

Challenge	Current Evidence	Impact on Applications	Suggested Research Direction
Low energy conversion efficiency	PZT high power but brittle; PVDF stable but weak [69, 71]	Limits scalability in pavements and buildings	Hybrid composites, nanofillers, interfacial optimization
Durability under environment	Degradation in freeze–thaw and humidity [68]	Reduces lifespan of roadway/bridge harvesters	Advanced encapsulation, lifecycle testing
High installation cost	Roadway field trials remain expensive [76]	Restricts adoption in developing regions	Modular, low-cost ASEAN prototypes; prefabricated tiles
Limited multifunctionality	Sensing and harvesting often separated	Prevents added value for SHM + energy	Design multifunctional composites with dual roles
Lack of real-world validation	Most studies remain lab-based [78]	Unclear long-term viability	Large-scale pilot projects, smart city integration

Durability issues under freeze–thaw and humidity cycles [68] emphasize the importance of advanced encapsulation and lifecycle testing. Cost remains prohibitive in roadway applications [76], but modular tile systems trialed in ASEAN countries illustrate promising alternatives. The separation of energy harvesting and sensing functions continues to limit multifunctional value, although recent studies suggest these roles can be combined in integrated systems. Finally, the lack of large-scale field trials [78] highlights the urgent need for pilot projects that validate laboratory findings in real-world conditions.

Taken together, the findings in Table 3 emphasize that the future of piezoelectric concrete lies not only in improving material-level efficiency but also in addressing cross-cutting issues such as cost, durability, and multifunctionality. A balanced approach that combines laboratory innovation with field-scale testing will be essential to transition from experimental novelty to practical adoption in sustainable infrastructure.

In summary, piezoelectric concrete has evolved from a conceptual innovation to a demonstrably functional material system. Its future impact depends not only on enhancing efficiency but also on ensuring durability, reducing cost, and embedding multifunctionality within infrastructure. With sustained research on materials, design, and system integration, piezoelectric concrete can contribute meaningfully to the transition toward resilient, intelligent, and sustainable civil infrastructure.

8. Conclusion

This review has critically examined the development, integration, and applications of piezoelectric concrete, consolidating knowledge from fundamental principles to real-world deployments. The following key conclusions can be drawn:

1. **Material performance:** Piezoelectric concrete integrates ceramics, polymers, and hybrid fillers to achieve multifunctionality. While ceramics such as PZT deliver high power density, their brittleness limits long-term use. Polymers such as PVDF provide greater stability and flexibility but at the cost of reduced energy output. Hybrid composites offer balanced performance, though cost and scalability remain major obstacles.
2. **Applications:** Research has demonstrated successful applications in pavements, bridges, and building systems. Pavements show the greatest potential for large-scale harvesting, but face durability and cost barriers. Structural health monitoring offers a practical near-term application, as

energy demands are lower and sensing benefits are immediate. Building applications align with smart infrastructure agendas, enabling low-power IoT networks.

3. **Challenges:** The main barriers to adoption include low conversion efficiency, environmental degradation, high installation costs, and limited multifunctionality. These issues restrict the transition from laboratory prototypes to widespread infrastructure deployment.
4. **Innovation pathways:** Promising research directions include the development of hybrid systems that combine piezoelectric, photovoltaic, and thermoelectric technologies; multifunctional composites that integrate energy harvesting and sensing; and modular, low-cost designs tailored to regional contexts.
5. **Future perspectives:** To ensure practical viability, future studies must prioritize durability testing under real-world conditions, system-level integration into smart infrastructure, and lifecycle cost analysis. Large-scale pilot projects are essential to validate laboratory findings and accelerate adoption.

In conclusion, piezoelectric concrete represents a transformative material for sustainable infrastructure. Its ability to simultaneously harvest energy and provide sensing functions positions it as a key contributor to the development of smart, resilient, and low-carbon cities. Continued innovation, coupled with robust field validation, will be critical for realizing its full potential.

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Conflict of interest

The authors declare that there are no conflicts of interest with any potential reviewers.

Data availability statement

All data supporting the findings of this study are contained within the manuscript. No additional datasets were generated or analyzed during the current study.

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Authors contribution

- **Dianah Mazlan (First Author):** Conceptualization, methodology, study design, data collection, data analysis, manuscript drafting, and major revisions.
- **Vynotdni Rathinasamy (Corresponding Author):** Project administration, supervision, validation of results, critical revision of the manuscript, manuscript review, manuscript editing, and responsibility for correspondence with the journal.
- **Naveen Kumar:** Literature review, technical input on experimental framework, critical revision of the manuscript, manuscript review, and editing.
- **Liu Chunpeng:** Data interpretation, preparation of figures, and assistance in manuscript review.
- **Elango:** Provision of resources, validation of data, and assistance in manuscript preparation and review.

All authors reviewed, edited, and approved the final version of the manuscript.

Ethics

Not applicable

Dataset statement

No new datasets were generated or used in this study. The work presented is based on a comprehensive review of existing literature, and all data discussed are derived from previously published sources that are duly cited within the manuscript.

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