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Research paper

Piezoelectric materials for sustainable building structures: Fundamentals and applications

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ABSTRACT

Piezoelectric materials are capable of transforming mechanical strain and vibration energy into electrical energy. This property allows opportunities for implementing renewable and sustainable energy through power harvesting and self-sustained smart sensing in buildings. As the most common construction material, plain cement paste lacks satisfactory piezoelectricity and is not efficient at harvesting the electrical energy from the ambient vibrations of a building system. In recent years, many techniques have been proposed and applied to improve the piezoelectric capacity of cement-based composite, namely admixture incorporation (*e.g.* lead zirconate titanate, barium zirconate titanate, carbon particles, and steel fibers) and physical treatments (*e.g.* thermal heating and electrical field application). The successful application of piezoelectric materials for sustainable building development not only relies on understanding the mechanism of the piezoelectric properties of various building components, but also the latest developments and implementations in the building industry. Therefore, this review systematically illustrates research efforts to develop new construction materials with high piezoelectricity and energy storage capacity. In addition, this article discusses the latest techniques for utilizing the piezoelectric materials in energy harvesters, sensors, and actuators for various building systems. With advanced methods for improving the cementitious piezoelectricity and applying the material piezoelectricity for different building functions, more renewable and sustainable building systems are anticipated.

1. Introduction

Building structures are constructed for the purposes of residential, official, and commercial activities, all of which make great contributions to the socio-economic development of a nation. During their life cycle, buildings demand a large amount of energy, including the direct energy consumed during construction, operation, rehabilitation, and eventually demolition, as well as the indirect energy required for manufacturing the building's materials and components [1–3]. From recent literature [4,5], it is estimated that building energy has been reported to occupy about 35% of total energy consumption worldwide. Additionally, carbon dioxide emission from the building industry is responsible for 40% of the total amount of carbon dioxide emitted worldwide [6]. In considering the energy challenges and environmental problems associated with building construction, it is essential to balance the advantages and disadvantages of using energy in buildings and to develop various schemes of achieving sustainability. Self-sustaining building systems thus seek to minimize their negative impacts on the environment through consuming fewer resources, such as materials, energy, water and so on. Among these resources, energy consumption is the primary concern, as it is associated with the entire building lifecycle and carbon dioxide emission. Building energy consumption can be compensated by on-site generation infrastructures or reduced by self-sustained building components.

Recently, timber has been increasingly recognized as an environmentally friendly resource and renewable building material. Construction of timber building is conducted within industry plants where little production and processing energy is required. Furthermore, timber buildings allow carbon dioxide storage, performance reproducibility and fast assembly, and their market trend is growing [7]. Timber building will be treated as one of the sustainable building styles, as stated in a recent ASCE report [8]. To promote the application of timber building as a robust alternative to traditional heavyweight infrastructure, acoustic and vibration emissions and management for timber building have recently been studied. Different prediction approaches, laboratory and field measurements, numerical analyses, and

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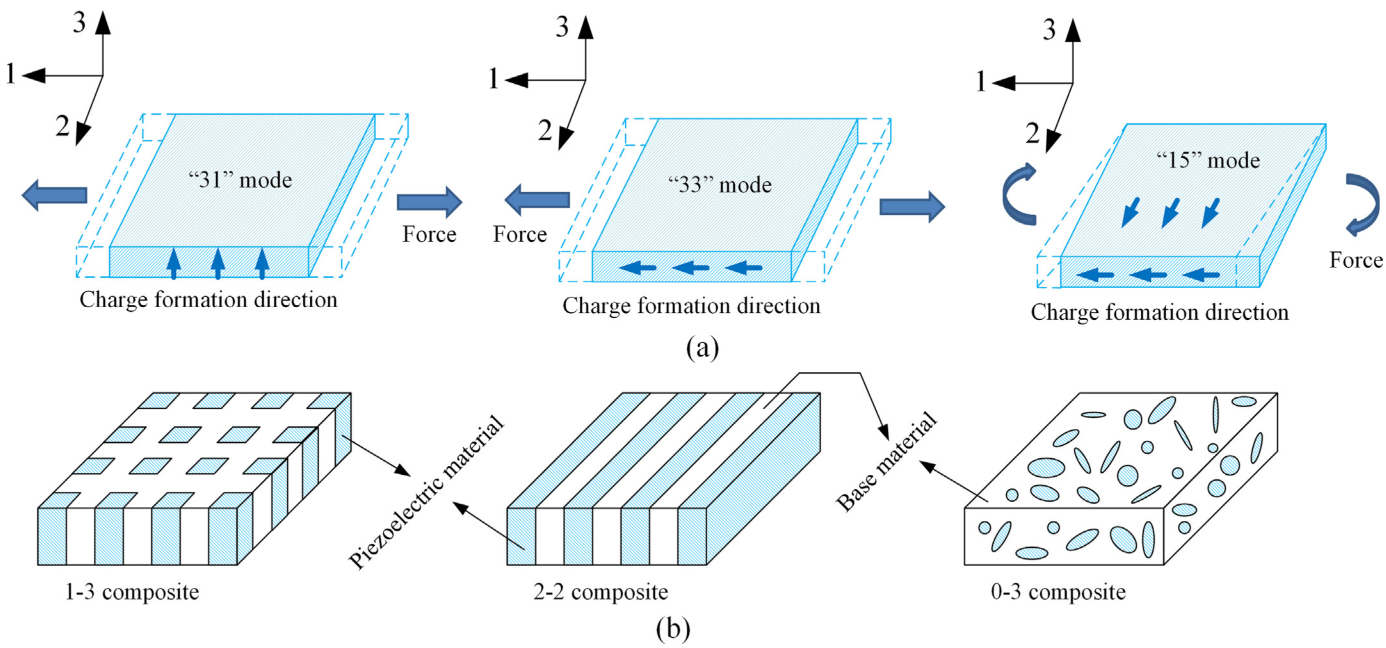

Fig. 1. Piezoelectric-based material system with (a) different modes of piezoelectric effect and (b) different configurations of piezoelectric-based composite. For "31" mode, the direction of mechanical force (axis 1) is perpendicular to that of the polarization axis (axis 3). For "33" mode, the direction of mechanical force ("3" axis) is parallel to that of the polarization axis (axis 3). For "15" mode, force moment is applied along axis 3 and the charge is formed in the direction of the arrows.

surveys assessing the response of large-scale wooden lightweight structures have been summarized and compared in the review article [9]. In order to deal with sound insulation and reduction, the vibration energy harvesting technique is recommended for diminishing the impact of noise in lightweight timber buildings [10]. Such technique can be implemented by using piezoelectric materials, further promoting the development of renewable and sustainable buildings. In addition to timber buildings, piezoelectric material provides motivation for scientists and engineers to develop a sustainable concrete structure with low life energy demand. This kind of material features the capacity to convert mechanical strain energy into electrical potential, and *vice versa*, in order to turn an applied electrical energy into mechanical strain. This physical behavior offers materials with high potential for use in the construction engineering field, helping to establish intelligent buildings with renewable and sustainable energy performance. On the one hand, piezoelectric materials can harvest mechanical energy (usually from ambient structural vibration) in the form of electrical energy which powers the associated electronic devices [11]. Many researchers have recognized that ambient vibration is a very attractive source of energy (with density estimated in the range from 50 to 250 $\mu W/cm^3$), and it is easily accessible and ubiquitous in structural fields at the micro-scale level [12–15]. Using piezoelectric material as a mechanical-to-electrical generator in building structures can save a portion of operating energy that is particularly used for indicator lighting, electrical heating for water, and ventilation. Compared with fuel-burning devices (*e.g.* microturbines), the use of energy technology from piezoelectric material can address issues related to noise, exhaust, and safety. On the other hand, piezoelectric material-based sensors can be inserted into construction material so that the smart building structures have the capacity for conducting real-time and on-line damage detection [16]. The smart sensing function is low-cost and energy-saving, and predicts the remaining useful life of a building structure.

The present article provides an overview of the fundamentals and applications of piezoelectric materials for building structures in an effort to achieve a renewable and sustainable energy concept towards the building industry. Two main focuses or timely questions are resolved in this review article, namely the improvement of the piezoelectric capacity of construction material and the utilization of piezoelectric material in structural elements for various applications. Before discussing the two key topics in depth, the fundamentals of the piezoelectric effect in the material system are briefly introduced in the next section. Then, the present review will discuss research findings on the piezoelectric properties of cementitious materials and current methods to enhance the piezoelectricity of cementitious materials along with efforts to develop new construction materials with high piezoelectricity. Afterwards, the paper outlines the applications of piezoelectric material in sustainable building systems, which are expected to provide the impetus for society to strengthen energy efficiency in buildings, maintain the ecological environment, and promote the sustainable development of buildings. After reviewing the literature on the above two aspects, future perspectives and insightful viewpoints on these subjects are provided in order to promote a more practical application for the use of piezoelectric material in sustainable buildings.

2. Fundamentals of piezoelectric material

From a theoretical point of view, the piezoelectric effect is a phenomenon involving electromechanical interconversion between the mechanical strain and the electrical charge in piezoelectric materials. Their relationship can be generally expressed on the basis of the linear coupling Eqs. (1) and (2) as shown below [17–19].

$$T = c_{ji} S - e_{jn} E \quad (1)$$

$$D = e_{mi} S + \varepsilon_{mn} E \quad (2)$$

where T refers to stress, S refers to strain, E refers to the electric field, c_{ji} refers to the elastic stiffness coefficient with a constant E, D refers to electrical displacement, e_{jn} together with e_{mi} refer to the piezoelectric stress coefficient, and ε_{mn} refers to the dielectric permittivity for constant stress. In the piezoelectric effect, the mechanical-electrical coupling has three principal modes (*i.e.* "31", "33", and "15" modes), as shown in Fig. 1. In order to evaluate the piezoelectric properties, piezoelectric charge coefficient (known as d_{33}), piezoelectric voltage factor (known as g_{33}) and electromechanical coupling coefficient (known as K_t) are the important parameters that should firstly be quantified [20–22]. In particular, when using piezoelectric material in a composite system, different forms of matrix can be fabricated.

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3. Advanced methods to improve the piezoelectricity of cement-based material

In view of the feature of the piezoelectric effect as mentioned in the above section, it is desirable to use piezoelectric material for developing a sustainable building system with low life cycle energy demand. Construction material with good piezoelectricity can benefit the implementation of a variety of applications such as energy harvesting and storage, self-powered sensing and structural control with actuators. Since cement-based material is one of the most common construction materials used in building structures [23,24], its piezoelectric capacity draws wide attention. Numerous investigations have been conducted to understand the piezoelectric properties of cement-based material as well as its potential to produce a sufficient and storable amount of energy. While a few experimental research studies have claimed that plain cement paste exhibits piezoelectric behavior, its piezoelectric capacity is not enough for energy harvesting, rendering it necessary to optimize the piezoelectricity. Resolving this key question, in this section, the piezoelectricity of cement paste is discussed and state-of-the-art approaches for enhancing cementitious piezoelectricity are reviewed.

3.1. Piezoelectricity of hardened cement paste

Previous researchers have regarded hardened cement paste as a kind of piezoelectric material [25]. Their investigations show that electrical current can be produced in cement to some extent once there is a compressive force being applied. Additionally, such electrical current is found to increase nonlinearly as compressive stress increases. It is also observed that the electrical current decreases gradually under sustained loading. Under cyclic loading, the largest intensity of the electrical current is found during the first loading cycle, while the current slightly reduces in the subsequent loading cycles. The generated electrical behavior above is explained by water redistribution in the cement system. Studies have demonstrated that the presence of piezoelectricity in hardened cement paste is associated with the movement of free ions and water molecules within the hydrated cement product under loading. To give evidence for this factor, the effect of water concentration on cementitious piezoelectricity has been investigated by the researchers as well. When hardened cement pastes are in dry condition, the specimens exhibit little piezoelectric effect. When dry hardened cement pastes are conditioned in an environment with increasing humidity, it is found that specimens under the same compressive stress show more electric current, as described in Table 1. Increasing water content in the hydrated cement paste benefits the activity of ionic movement under stress, resulting in an enhanced electrical current flow. Although some researchers have discovered the presence of piezoelectricity in hardened cement paste, the piezoelectric effect is still not strong enough because cement paste is not a completely crystalline material. Due to this limitation, numerous investigations have been conducted in the past decade to improve the piezoelectric properties of cementitious material through admixture additions and external conditioning.

3.2. Using carbon or steel fiber

In order to improve the piezoelectric effect of cement-based system, some researchers have explored the use of short carbon fibers in cement [26]. A study suggests that adding carbon fibers in cement paste can lead to a reduction in piezoelectric characteristics, given that the dosage of below the percolation threshold [27]. However, another study demonstrates that the piezoelectric effect can be significantly enhanced by using short carbon fibers when the dosage is above the percolation threshold (1% of the mass of cement). With a low percentage of carbon fiber, the progress of load-induced fiber is slow. Increasing the carbon fiber content from 1% allows the movement of charges to be more effective under the influence of mechanical loading, thus enhancing the piezoelectric effect [28].

Another experimental work has investigated the effect of short steel fibers on the piezoelectric properties of cementitious material system. In that study, the fiber diameter was 8 μm and the fiber length was 6 mm. The content of steel fiber in the cement paste was 0.18% by volume. Besides, the fibers contained 47% polyvinyl alcohol binder by volume. This was beneficial to disperse the fibers in the process of cement mixing and casting. The results show that the relative dielectric constant of the mixture (*i.e.* cement paste plus steel fibers) increases when compressive loading is applied, and the piezoelectric coupling coefficient is decreased by incorporating steel fibers [29]. In addition to the use of carbon and steel fibers, scientists have tried to enhance the piezoelectricity of cement paste through the addition of single-walled carbon nanotubes, as demonstrated by this literature [30].

Table 1
Variation of the water absorption and electric current of hardened cement paste in wet air environment with different periods [25].

Time (days)	0	1	2	3	4	8	12	100
Water absorption (%)	0	0.4	0.6	0.9	1.2	1.5	1.9	2.4
Electric current (10^{-8} A)	0	0.2	0.5	1.0	2.4	5.4	6.4	8.0

3.3. Using lead zirconate titanate (PZT)

PZT can exhibit excellent pyroelectric and piezoelectric features, which are associated with its non-centrosymmetric crystalline structure [31]. It is recognized as smart material in numerous applications (*e.g.* sensors) [32]. In general, this material is fabricated by calcining lead titanate and lead zirconate at around 800 °C [33]. In recent years, PZT has attracted worldwide attention since it can be incorporated into cement to form a new composite (*i.e.* a cement-based piezoelectric ceramic composite) that can be used in building construction. This composite shows a good interface compatibility, especially in temperature coefficient and volume stability. In particular, another good interface compatibility in acoustic impedance between such composite and concrete has been reported, as acoustic energy sources (from both airborne and structure-borne sound, arising from vehicles, aircrafts, power plants and machinery [34]) often act on the composite system. The cement-based piezoelectric ceramic composite can show strong piezoelectric properties, given that it is well polarized by an external electric field. It is noted that the electrical response of the piezoelectric ceramic-cement composite is rather large and can be readily detected by an ordinary voltmeter. Cement-based piezoelectric ceramic composite can be developed into different forms, for instance, 0–3, 1–3 and 2–2 modes, as illustrated in Fig. 1. 1–3 and 2–2 PZT-cement composites exhibit a larger d_{33} and K_t than the 0–3 PZT-cement composites [35–38], but the 0–3 PZT-cement composite can be more easily fabricated than the 1–3 and 2–2 composites. According to the literature, the d_{33} values of 0–3 PZT-cement composites are within 2–15 pC/N [39,40]. The d_{33} value depends on many factors such as fabricating, polarizing, and heating conditions. Generally, a piezoelectric cement sample with higher PZT content is shown to have a larger d_{33} value. Moreover, the d_{33} value of PZT-cement composites can be increased along with the polarizing age and temperature. Some researchers have figured out that the optimum polarizing time is around 45 min [41,42]. It has been reported that the 0–3 PZT-cement composite containing 50% PZT by volume, polarized with appropriate poling conditions (*e.g.* time and temperature), exhibits d_{33} value of 13 pC/N and K_t value of 19.39% [43].

Although studies of PZT-cement composite are extensive with great progress, a lot of problems still remain unsolved. As stated in the literature [42], the degree of polarization and the piezoelectric properties of the PZT-cement composite can be influenced by pore structure and internal pore solution. During polarization, it can be observed that the direction of the applied electric field is parallel to ferroelectric domain alignment. However, when the polarizing process is stopped, the piezoelectric values of this composite are found to drop with an increase of time. This may be attributed to parts of the diverted 90° ferroelectric domains being converted back to a disorder condition. To improve the polarization level, PZT-cement composites with carbon or silica particles incorporated as a new material phase in the system were recently investigated [44–46]. The researchers found that the d_{33} value of the composite increases after polarizing for 10 days to reach saturation level. However, a recent article indicates that the energy loss through ferroelectric hysteresis loops and the reduction in dielectric properties can be escalated for such a composite, given that the proportion of conducting material is increased [46,47]. In reviewing this issue, current research work has investigated the application of polyvinylidene fluoride (PVDF) as a new material phase with PZT and cement to produce a novel composite (*i.e.* a cement/PZT/PVDF combination) [46]. Due to its relatively low dissipation factor and high permittivity, the incorporation of PVDF can effectively decrease the dielectric permittivity (ε_{33}) with 5% PVDF content. This PVDF concentration also leads to the highest d_{33} value in the composite system, which can be regarded as the percolation threshold. Also, the PVDF addition in the composite system is found to reduce poling time during the polarizing process, as a result of which the interfacial bonding between PZT particles and cement is improved by the filling effect of PVDF [46]. Furthermore, numerous studies have reported the incorporation of other phases (*e.g.* sulfoaluminate, carbon nanotubes (CNTs), carbon black, silica fume and aluminum) into PZT and Portland cement to improve their piezoelectric properties. Table 2 summarizes the d_{33}, g_{33}, and K_t values for different forms of cement-based piezoelectric composite, based on data from many recent articles. Although PZT-cement composites have been extensively investigated and developed, their long-term aging issue should be considered. A comprehensive understanding of the long-term aging of newly developed cement-based piezoelectric composites is still limited, and more future studies are needed. Besides, most of the research studies focus on using the PZT in a cement matrix, while concrete material consists of not only cement but also sand and gravel. In the presence of aggregate, the efficiency of polarizing the PZT particles may be reduced due to the more complicated interfacial situation among various constituents inside the composite. Hence, more studies should be conducted to evaluate the performance of cement-sand-based piezoelectric composite in terms of its piezoelectric and dielectric properties. Solutions to improve the poling efficiency for such piezoelectric composites are essential.

3.4. Lead-free barium zirconate titanate-Portland cement composites

Lead-based piezoelectric ceramics used with Portland cement to fabricate PZT-cement composites have attracted widespread attention in terms of designing renewable and sustainable building systems. However, the satisfactory application of this composite not only depends on the good piezoelectric properties of the ceramic, its compatibility with concrete, and the volume change in response to temperature variation, but also relies on other factors such as environmentally friendly chemistry. In fact, using lead-based piezoelectric ceramics can lead to negative environmental issues due to the toxicity associated with lead oxide and the high vapor pressure during the process of sintering [64,67–69]. In view of this, it is valuable to develop lead-free piezoelectric ceramics with equivalent piezoelectric properties, which can be regarded as an alternative (or even substitution) to a lead-based PZT-cement composite. In recent years, barium zirconate titanate (BZT) ceramics ($BaTi_{1-x}Zr_xO_3$) have been considered as promising candidates for fabricating lead-free piezoelectric ceramics owing to several merits including high dielectric constant, low loss tangent, and excellent piezoelectric/electrostrictive properties [63,70,71]. This type of material can be produced by substituting Zr ions at the Ti site in the $BaTiO_3$ lattice [72]. A study has discovered that $BaTi_{1-x}Zr_xO_3$ features remarkable piezoelectric properties and low-temperature poling [69]. These properties are beneficial to PZT-cement composites for the application in smart and green concrete structures. Another study demonstrates that K_t can be effectively enhanced with an increase of the BZT content in the PZT-cement composite [63]. Table 2 summarizes the piezoelectric properties of the BZT-cement composite. Also, composites at approximately 30–50% BZT content show a suitable interfacial compatibility in terms of acoustic impedance between composite and concrete. Additionally, the effect of temperature condition on thermal behavior of 0–3 BZT- cement composites has been studied [73]. It has been found that the thermal expansion coefficient of 0–3 BZT- cement composites can be well matched with concrete components. In particular, it is clarified that there is no chemical interaction between the ceramic and cement in the BZT-cement composite.

Table 2
Piezoelectric properties of plain cement paste, PZT, and different forms of cement-based piezoelectric composite.

Material type	d_{33}	g_{33}	K_t
Plain cement paste	0 [39]	0 [39]	0 [39]
PZT	215 [48]	15.9 [39,52]	40 [48]
	350–390 [49–51]	19.3 [44]	58 [49,50]
	400 [40]	23–25 [49–51]	60–67 [39,40,44,51,52]
	513 [39,52]		
PZT-cement composite	2–53.7 [39,42,43,49,50,53–57]	8–15 [49]	9.47 [44]
	29.3–77.2 [51]		10.1–18.1 [53]
	18–85 [41,52,58]	15.0–22.1 [39]	11.6–20.7 [39,41,57]
	18–197 [33]		14.7–20.8 [33]
	112–213 [48]		39–55 [48]
Sulfoaluminate-PZT-cement composite	2–16 [40]	22.94 [40]	11.57–28.19 [40]
CNTs-PZT-cement composite	35–62 [45]	29–47 [45]	/
Carbon black-PZT-cement composite	2.5–28 [44]	1.4–17 [44]	10.51–12.16 [44]
PVDF-PZT-cement composite	16–24 [46]	12–15 [46]	/
Silica fume-PZT-cement composite	18–20 [59]	/	/
Aluminum-PZT-cement composite	4.9 [60]	/	/
	0.5–8 [61]		
BZT-cement composite	7 [62]	20–25 [63]	10.6–16.6 [66]
	68–137 [63]	19 [64]	13.2–17.7 [67]
	80–133 [64]	24.5 [65]	18.8–22.3 [63]

Notes: / means not available.

3.5. Electrical treatment

Although the piezoelectricity of cement material can be improved by admixture additions, such additives can largely decrease the hydration degree due to the partial replacement of cement [74]. With the presence of carbon fibers or PZT components, the mechanical properties (*e.g.* load bearing capacity) of this blended cement can be significantly reduced in comparison to plain cement paste. To avoid this issue, recent studies have considered and explored the application of external treatments to modify the piezoelectricity of cement material. Some researchers have conducted special studies on using thermal treatment to enhance cement piezoelectricity [75–78]. However, the thermal treatment of cement material may encounter problems in real application owing to the difficulty of consistently controlling the thermal condition on a large scale and the limitation of polarizing only the small portions of the material system. In recent years, an innovative method has been employed with an aim to increase the piezoelectric capacity of cement paste based on altering the atomic/molecular alignments in the material [79]. The idea is to apply the external electrical treatment (*i.e.* the static electric potential field) to the cement paste during the curing process. Prior to the exposure of the electric field, dipoles exist with random orientations at the beginning of curing, as depicted in Fig. 2(a). In the case that a strong direct-current electric field is applied, the cement paste begins to polarize, and its dipoles almost align with the electric field, as illustrated in Fig. 2(b). The electrical treatment is performed until the cement paste is hardened. At this stage, the polarization remains in the cement paste after the electric field is removed. Fig. 2(c) illustrates the polarization state after electrical treatment. Every electric dipole has roughly the same direction, forming a more aligned structure.

Based on this principle, a study has investigated the mechanical-electrical response of cement paste cured with electrical treatment [79]. Fig. 3 illustrates the electrical treatment for improving cement piezoelectricity. The study demonstrates that the piezoelectric coefficient g_{33} of the polarized cement specimen is about 2.4 times as large as that of the non-polarized cement, which indicates that applying the electric field in the curing process of cement paste can effectively improve the cement piezoelectricity. To understand further piezoelectricity at the nano scale, atomic force microscopy (AFM) has been adopted to explore the surface charge aspect and morphology characteristics of the cement specimens. Obviously, the polarized cement specimen reveals a more aligned structure than the specimen without electrical treatment. Under the influence of an electric field, the hydration product calcium-silicate-hydrate (C-S-H) can form more aligned nano-scale morphology during the process of precipitation. It has been recognized that the density of surface charge on C-S-H products is large [80–82], and the interfacial interactions between C-S-H and surface change can decline the ion mobility in the pore solution. Thus, a significant imbalance in charge distributions can result, improving the piezoelectricity of cement paste.

Although electrical treatment to enhance the piezoelectricity of cement is attractive, several concerns are being taken into consideration in order to optimize this electrically-induced polarized cement paste. The following points of future research aspects are discussed:

The mechanical strength of the electrically-induced polarized cement paste should be examined before utilization in building structures. With an electric field, the special pore structure of cement paste can be formed, resulting in the variation of strength development. Mechanical properties including the compressive strength, Young's modulus, as well as density need to be evaluated, as they are the essential parameters in the safe design of concrete structures in building construction.

Durability performance of the electrically-induced polarized cement paste is also a concern requiring further investigation. Poor durability performance of building materials can lead to high maintenance cost and high energy consumption. Compared with ordinary Portland cement paste, the electrochemical system of electrically-induced polarized cement paste is altered due to the electrical treatment. Many studies have reported that electrochemical properties are closely related to ion transfer and diffusion which determines the degree of carbonation and chloride ingress [83–86]. Therefore, the degradation resistance of this type of cement paste should be evaluated when using as a construction material.

The balance between the energy consumed for electrical treatment and the energy harvested by this cement composite should be compared and assessed. Using this curing process requires electric potential and its power generation. After being applied to building structures, polarized cement paste can be used as smart sensors and as an energy harvester. This is a positive aspect for saving energy. Methods should be developed to reduce energy consumption in the curing process and improve the efficiency of energy storage.

On the whole, the electrical treatment provides a novel approach for functionalizing cement paste's piezoelectricity, which is promising for further developments in self-sensing or energy harvesting construction materials.

4. Applications of piezoelectric material in sustainable building structures

The concept of sustainability incorporates interconnected domains,

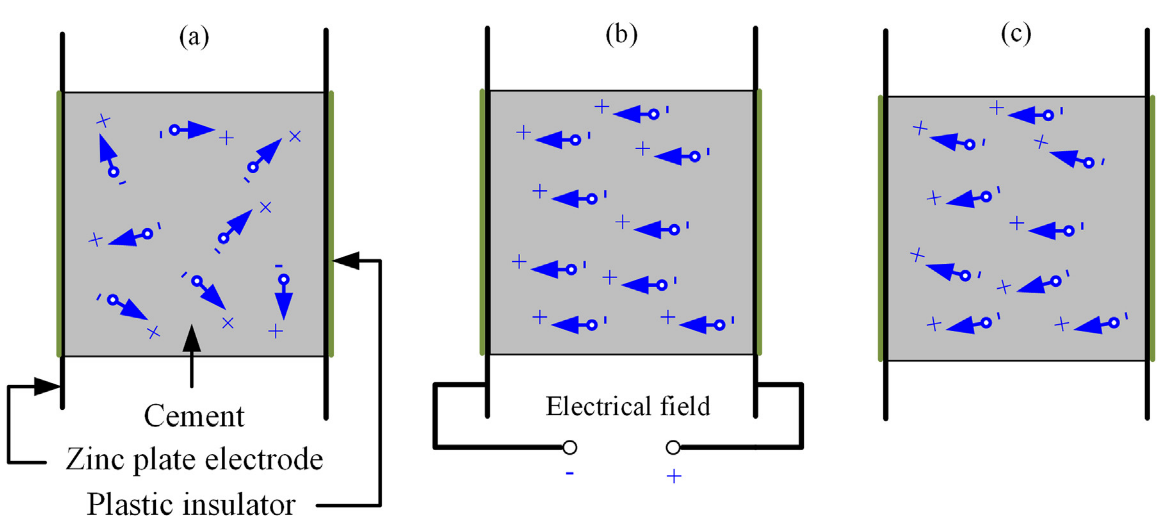

Fig. 2. Electrical treatment to improve cement piezoelectricity: (a) random orientation of electric dipoles prior to electric field exposure; (b) cement curing under the electric field treatment; (c) polarization in the cement paste remains after removing the electric field when the cement is hardened.

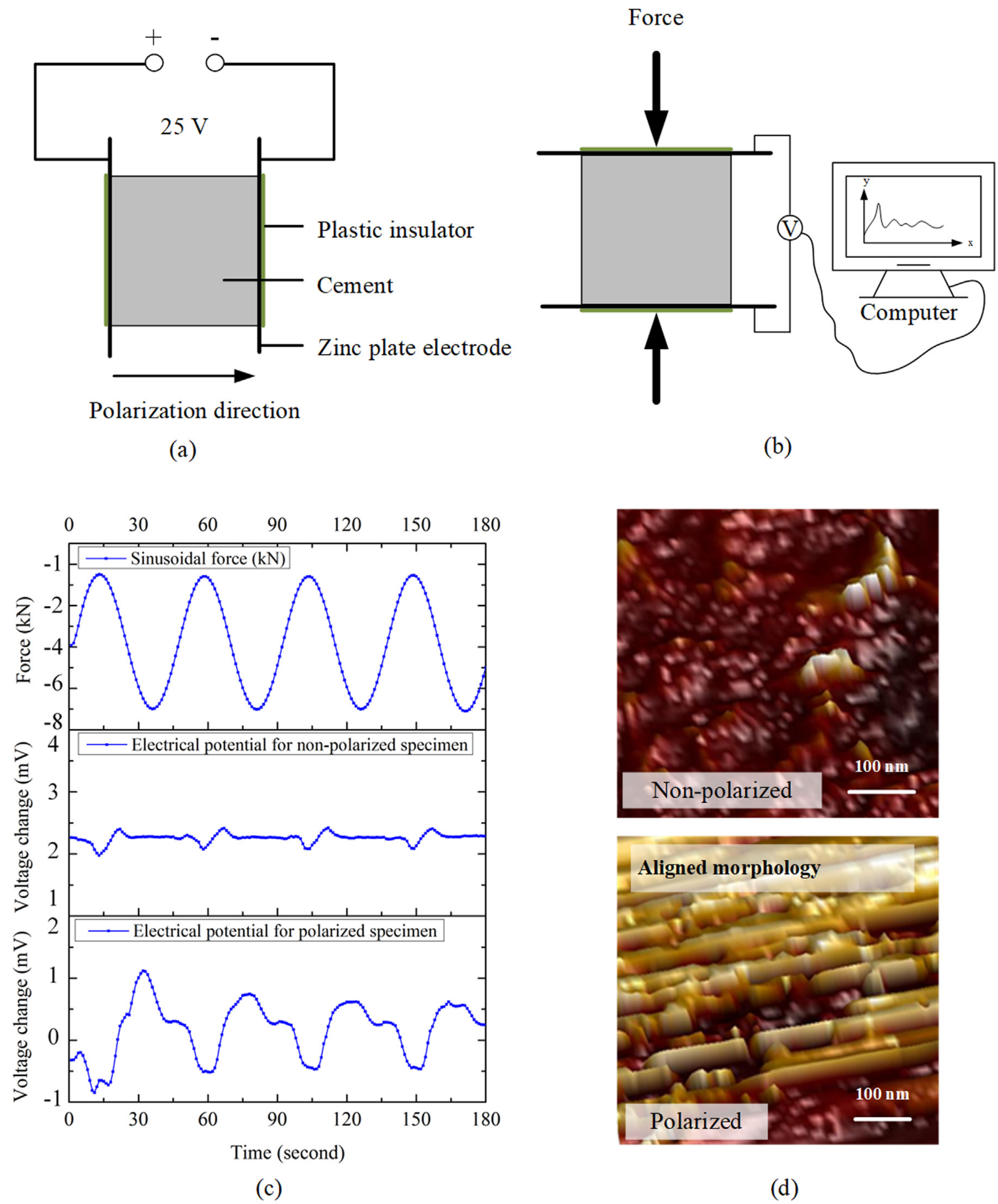

Fig. 3. Electrical treatment to improve cement piezoelectricity: (a) curing of cement paste under the electric field with the potential of 25 V, (b) polarized cement paste under compressive loading and measurement of the electrical signal, (c) the mechanical force and electrical signals between plain cement and polarized cement, and (d) the AFM result of plain cement and polarized cement.

including environment, economic and social areas [87]. Sustainable building systems have a narrower definition, which mainly focuses on the process of design, construction, and maintenance of building structures [88]. As discussed in the previous section, energy consumption is the primary concern of designing renewable building systems [89]. Building components can significantly reduce their energy consumption through implementing energy harvesting, self-sustained sensing and actuating devices with piezoelectric materials. This section reviews recent applications of piezoelectric material in various construction materials and building structures. Cement-based material is commonly used in building structures, and its piezoelectric properties can be improved from the perspective of the material level for better application in power harvesting and smart sensing in buildings. In addition, timber buildings represent a robust and sustainable alternative construction type for low-rise buildings [7]. As acoustic and sound insulation is one of the most significant concerns for inhabitants [9], using piezoelectric material to harvest this acoustic and vibrations energy not only improves lightweight timber buildings' insulation but also provides an additional energy source for daily use. For these buildings, advanced techniques for energy harvesting, smart sensing, and actuators are being developed, promoting the application of cement-based material and timbers with high piezoelectricity and other piezoelectric materials in renewable and sustainable building systems. Among these applications, power harvesting is key to converting unused and wasted energy resources into electric energy to allow self-sustained wireless electronics. In Section 4.1, a number of the current studies on designing piezoelectric power harvesting devices and improving the power harvesting efficiency through various geometrical and physical configurations are first and foremost summarized. In addition, applying the piezoelectric material for the purpose of energy harvesting also associates with the development of self-sustained wireless sensing technologies. As such, in Section 4.2, we focus on the research on exploring the possibility of implementing piezoelectric material in supplying energy to various types of sensors and fabricating self-powered sensors, either directly with piezoelectric materials or by utilizing the piezoelectric properties in existing construction materials. Through the application of a piezoelectric sensor, smart and advanced structures with integrated self-monitoring can be established that instantaneously provide reliable and quantitative structural health data. This can minimize energy requirements in structural inspection and maintenance. In addition to structural health monitoring, the application of a piezoelectric actuator attracts interest in structural vibration control. Power harvesting and storage of piezoelectric material can sustain the application of the piezoelectric actuator, which converts the electrical energy into a precisely controlled physical displacement (stroke) to minimize the dynamic or seismic responses of a building system. In Section 4.3, research investigations into the applications of a piezoelectric actuator are outlined.

4.1. Piezoelectric energy harvesting

Energy harvesting aims at converting unused and wasted energy resources into electricities. Given their high power density, architectural simplicity, and scalability, piezoelectric materials have been identified as the preferable choice among all smart materials with energy harvesting potential [90]. Since the material scale significantly constrains the implementation of energy harvesting, Toprak and Tigli classified piezoelectric energy harvesters into three scale groups: macro and meso-scale, micro-electromechanical systems (MEMS) scale, and nano-scale [90]. As illustrated in Fig. 4, macro and meso-scale harvesters usually provide power to small electric devices such as wireless network transmitters and sensor nodes. MEMS scale harvesters can power sub-cm sized chips and structural components. Nanometer scale harvesters collect energy through synthesized nanowires and can be fabricated as self-sustained sensors [91,92], as shown in Fig. 4. When applied in building structures, piezoelectric technology transforms mechanical strain into electrical charge and converts applied electrical potential into elastic potential [93]. Therefore, buildings exposed to drastic vibration and huge dynamic loads from winds, earthquakes, traffic, and human activities are considered the most suitable candidates for implementing piezoelectric energy harvesters and sensors [94,95]. For example, Hu et al. proposed self-powered sensing and data transmission systems in buildings [96]. For low-rise lightweight timber buildings, which are exposed to drastic vibration and acoustic environment, energy harvesting shows an inconvenient potential [10].

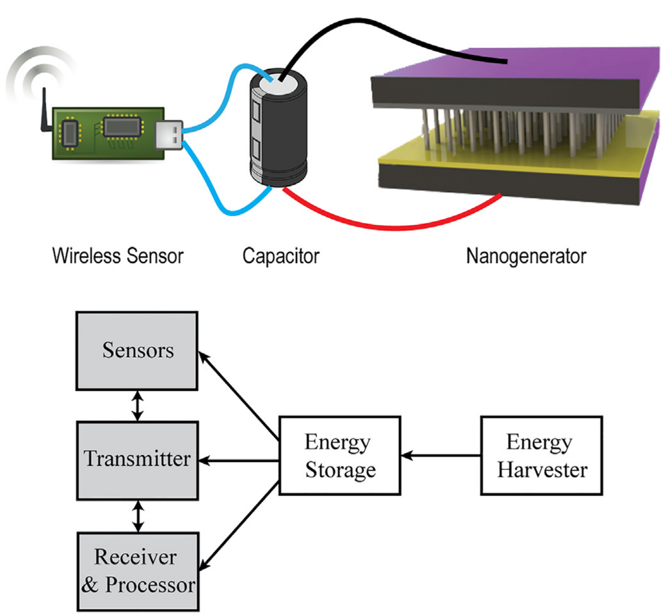

Fig. 4. Energy harvesting from piezoelectric generators and self-sustained sensors.

4.1.1. Energy harvesting in vertical building structures

In conventional vibration control design, tuned mass damper is a widely utilized devices to absorb and mitigate vibration energy. Since piezoelectric materials can convert ambient vibration into energy, researchers in recent studies have proposed the concept of incorporating energy harvesting with vibration control [97]. For example, piezoelectric coupled cantilever structures have been used not only to realize energy harvesting but also to help dissipate the vibration of buildings as tuned mass dampers [98], as illustrated in Fig. 5(a). Xie et al. investigated these building structures under harmonic motions and loads [99]. Xie et al. also proposed a piezoelectric generator design for high-rise buildings, which has two sets of piezoelectric patches that connected in series with a shared shaft [93], as shown in Fig. 5(b). The piezoelectric harvesters also can be arranged in a ring, which is compatible with high excitation frequencies and suitable for varying radius sizes [100], as Fig. 5(c) illustrates. In their research, Xie et al. reported a harvested power of up to 5274.8 W in such harvester designs for vertical buildings [100].

In addition to absorbing vibration energy, the piezoelectric materials can directly capture renewable and sustainable wind energy. Compared to traditional wind turbines, current piezoelectric devices have advantages in compactness, robustness, and simple installation [101]. For example, Priya et al. developed and demonstrated a piezoelectric windmill technology based on bimorph actuators [102], as depicted in Fig. 5(d). The prototype piezoelectric windmill with ten piezoelectric bimorph transducers is able to generate 7.5 mW power at a wind speed of 10 mph [103]. Li et al. developed a set of bio-inspired piezo-leaf that efficiently recovered electrical power through a wind-induced fluttering [104] and flapping motion [105]. The piezo-leaf can be fabricated into numerous shapes with flexible piezoelectric material, and the power density can reach as high as 2 mW/cm^3 per single leaf [104]. Hobeck and Inman introduced a novel bio-inspired piezoelectric grass to harvest energy in highly turbulent fluid flow environments such as rooftops [106]. The preliminary results suggest that a small pack of such artificial grasses can produce up to 10 mW per cantilever from high-intensity air turbulence. Based on previous studies, Akaydin et al. proposed numerical and empirical models to investigate the design and implementation of piezoelectric generators in harvesting energy from unsteady and turbulent fluid flow [107].

In low-rise households and office buildings, piezoelectric building components are also viable power sources. Both residential and commercial buildings have many sources of low magnitude and low-frequency vibrations from facilities and equipment, such as car engines, compartments, clothes dryers, door frames, and HVAC vents [100]. These sources of vibration can be categorized as structure-borne and airborne vibration based on their transmission medium. As the vibration energy is usually captured by the piezoelectric structural elements, the major source of energy is structure-borne vibration. For example, Aminzahed et al. proposed energy harvesting floors to generate electricity from occupants' activities [108]. Elhalwagy et al. also introduced piezoelectric floors to recover energy from pedestrians walking in the interior spaces of buildings [109]. Similarly, Li and Strezov proposed

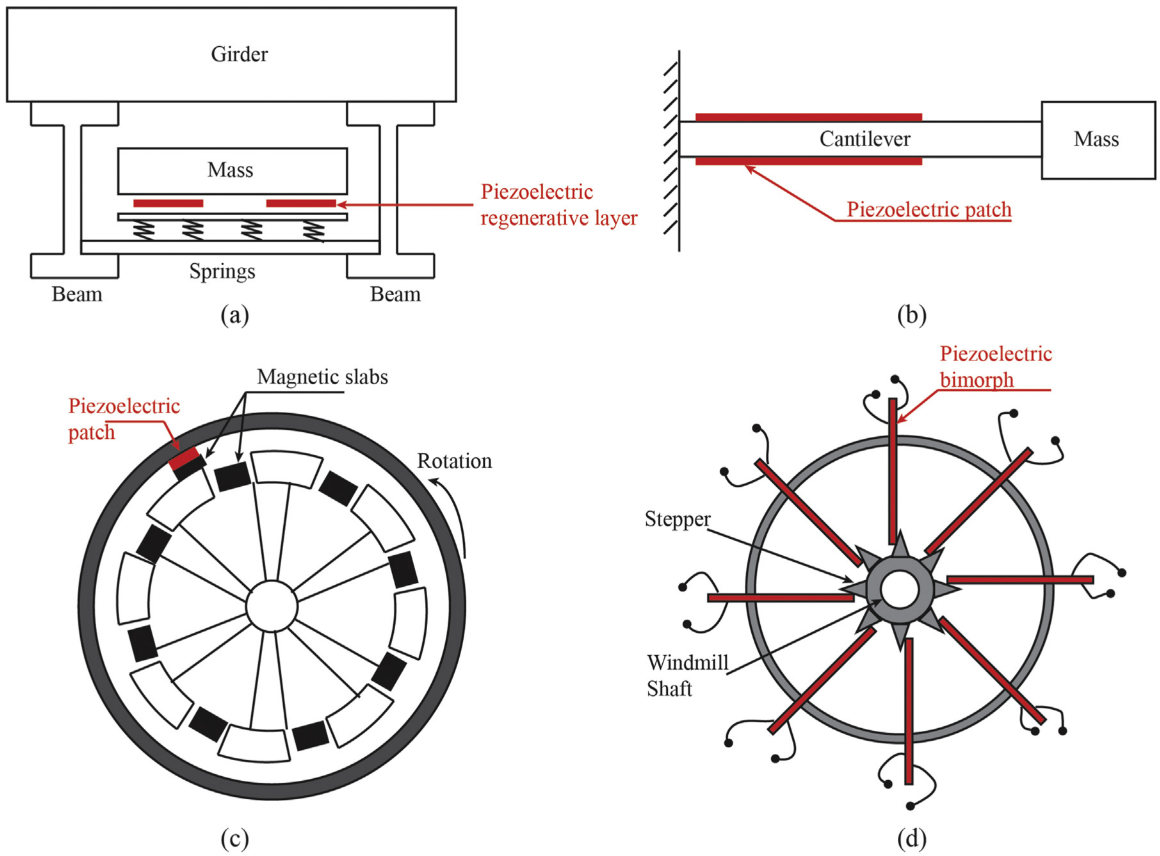

Fig. 5. Piezoelectric structural elements: (a) piezoelectric damper, (b) piezoelectric cantilever, (c) piezoelectric harvester, and (d) piezoelectric windmill.

commercialized piezoelectric tiles to harvest occupants' walking energy [110]. Additionally, recovered vibration power is sufficient to sustain low power wireless sensors and networks in building monitoring [96].

4.1.2. Energy harvesting in horizontal building structures

Energy harvesting is also viable in horizontal infrastructure systems, such as railways, highways, and bridges, given that a huge amount of energy is transferred to and consumed by infrastructure pavement [111]. Xiong and Wang developed large-scale piezoelectric energy harvesters for public roadways in Virginia, USA. The harvesting system was composed of six prototype harvesters to harness the deformation energy from road pavement [112]. Based on the measured voltage outputs, they revealed the corrections between the efficiency of different scales of piezoelectric energy harvesters and the road axle configuration and the density of moving vehicles [112]. Jiang et al. also developed a compression-based harvester that integrates multiple embedded piezoelectric units to recover electricity from traffic-induced vibrations on the roadway [113]. Ali et al. installed energy harvesters in highway bridges to absorb the structural vibration caused by moving vehicle loads [114]. Erturk concluded that bridge-based vibration energy harvesters could mitigate both the moving load excitation and surface strain fluctuation, which could be extremely efficient if combined with cantilevered piezoelectric harvesters [115]. Yuan et al. installed piezoelectric drum transducers on railroad tracks to recover the dissipated vibration by trains [116], and the system showed a peak open-circuit voltage of around 50–70 V under a full train load. Zhang et al. investigated instantaneous power outputs for single concentrate loads and four-wheel distributed loads, and reported that the maximum power outputs were 41.2 mW and 47.3 mW, respectively [117]. In the same study, they also found a non-linear relationship between wheel number and energy efficiency. Xiang et al. investigated the power outputs for all types of piezoelectric harvesters under different damping effects, the Winker modulus, and the traffic velocity when the road pavement was modeled as an infinite Bernoulli-Euler beam [118]. In addition, piezoelectric materials can be used in other infrastructure functions. For example, Faisal et al. designed a piezoelectric composite plate to melt ice on roads and sidewalks. The study reported that the energy collected from the piezoelectric composite was sufficient to raise the temperature of ice-covered sidewalks by 20 °C within 2.5 h [119]. Xiong et al. also utilized lead zirconate titanate materials to build a piezoelectric micro power generator for LED traffic lights [112].

4.2. Piezoelectric sensors

Due to dynamic environments and drastic weather, buildings and infrastructures suffer from erosion, aging, fatigue, and other negative environmental impacts. Therefore, the performance and health conditions of buildings require close long-term monitoring [120–122]. For this purpose, sensors and network components are often embedded into building structures to ensure building functionality and elongate a building's service life with proper maintenance. These health monitoring sensors, such as accelerometers, strain gauges, and force sensors, are subjected to a limited lifespan, complicated battery replacement, and interrupted functionality. The interference of the structural component could result in deteriorated strength and high replacement costs. As discussed previously, piezoelectric material features the application of energy harvesting, and thus many researchers recommend directly fabricating sensors with piezoelectric materials or utilizing piezoelectric properties in existing construction materials.

Due to distinctive and nonuniform expansion rate, normal polymer-based piezoelectric composites are seldomly used in civil structures. For building structures, researchers developed the 0–3 (0 dimension for ceramic phase and 3 dimensions for cement phase) cement-based piezoelectric ceramic composite [39,50]. Sensors made of such composite can be embedded and casted into concrete to collect responses from various frequency bands [123]. In the study, a concrete beam was examined in a four-point bending test and the sensors shown high sensitivity and excellent abilities in detecting acoustic emission activity. Han and Ou also developed similar cement-based strain sensors to monitor compressive strength of concrete structures [124]. Kuo et al. employed the volumetric method to investigate the mechanical and electrical properties of piezoelectric powder replacements in creating cement mortar [125]. Song et al. utilized 3D printing to design and fabricate a novel aggregate-shape embedded piezoelectric sensor system that uses piezoelectric ceramic chips [126]. They also empirically tested the frequency independence, sensitivity, and response rate of the sensor system and found a good mechanical-electrical coupling performance.

When monitoring structural health, the major issue is detecting corrosion and cracks. The corrosion of reinforcement can weaken the load-carrying capacity, while cracks intensify corrosion and stress concentration. Lu et al. used piezoelectric composite sensors and the intensity of acoustic emission intensity to assess the corrosion rate of concrete beams reinforcement [127]. Their experiments demonstrated that those sensors, characterized by high sensitivity, long duration, and broadband and flat frequency domain response, are highly suitable for monitoring the corrosion process of reinforcement in concrete structures [127]. Lu and Li developed a DEcLIN monitoring system to monitor the acoustic emission on mortar specimens under different static loading patterns in a laboratory [128]. Such a system can explore the severity of the behavior of concrete cracks of cement-based composites. Structural overload is another health indicator for horizontal infrastructures. For example, vehicle overload can cause traffic accidents and serious pavement damage on highway infrastructures. Cement-based piezoelectric composites can be employed in smart traffic-monitoring systems to obtain real-time traffic information, including flow volume, vehicle speed, and vehicle weight [129]. Zhang et al. established an integrated mechanical-electrical traffic flow monitoring system to measure the weight-in-motion of vehicles and harvest the pressure and friction energy [129].

4.3. Piezoelectric actuators

Similar to piezoelectric sensors, the power harvesting and storage of piezoelectric material also motivates and realizes the application of piezoelectric actuators. Over the last decade, extensive research has been conducted using piezoelectric actuators to eliminate building element vibration for their quick response and high adaptability [130]. The controllers have been intensively studied for various building elements, such as cantilever beams [131], sandwich beams [132], flexible truss structures [133], and grid structures [134]. Meressi and Paden implemented piezoelectric actuators and strain sensors and concluded that the actuators can postpone the buckling effect beyond the first critical load of a flexible beam with proper feedback control [135]. Thompson and Loughlan examined piezoelectric actuators with the active buckling control on smart composite column strips and found that imperfection in the system can results in premature deformation of the piezolaminated struts [136]. Kamada et al. also found the actuator can properly control the vibration of frame structures and the bending movement of columns [137]. Later, they looked into utilizing flexural-shear type frame structures with the same piezoelectric actuator [138]. To enable active control in actuators, Mukherjee and Chaudhuri derived analytical solutions to the piezolaminated columns' response to axial forces [139]. Xu and Koko proposed a scheme to analyze the design of piezoelectric sensors and actuators with a piezoelectric finite element code and a user-selected feedback control mechanism [140]. Their studies revealed the importance of installation locations on system integration and control performance. Sethi and Song conducted an empirical study to demonstrate the control efficiency of surface-bonded PZT type piezoceramic patches and proposed a multimodal active control and placement algorithm [141]. In a more recent study, Fallah and Ebrahimnejad evaluated the seismic response of tall buildings with piezoelectric actuators [130]. In that study, they compared three control schemes: the linear quadratic regulator, the regular fuzzy logic controller, and the supervisory fuzzy controller. They found that piezoelectric actuators considerably reduce a building's seismic response and that supervisory fuzzy control is the best strategy to command the actuators.

5. Performance of piezoelectric materials and THeir future development

As discussed previously, numerous approaches have been demonstrated that effectively improve the piezoelectric properties of cement-based material. This promotes the application of construction material with high piezoelectricity in building systems. Utilizing piezoelectric materials can harvest vibration energy from various sources. This not only recovers energy for various purposes but also reconciles the potential damage caused by vibrations. In addition, sustainable buildings should have less impact on the environment and require fewer resources to maintain their functionality. Therefore, piezoelectric materials show significant potential in the next generation of building development. Compared to other energy harvesting and self-sustaining technologies, such as electromagnetic and electrostatic harvesters, piezoelectric materials have impressive advantages.

First, piezoelectric harvesters have higher power efficiency. Roundy et al. compared all three types of vibration energy harvesting approaches: piezoelectric, electromagnetic, and electrostatic generators. They concluded that piezoelectric converters produce higher power outputs than electrostatic converters and also have a higher power density ($250\,\mu W/cm^3$) [12]. In a later study, Roundy compared the efficiency of harvesters again and concluded that electromagnetic generators tend to produce very low voltage, while piezoelectric generators produce higher voltages and lower currents [142]. Wang et al. conducted a similar comparison study, and found that under various dimensionless force factors, the its electric resistance is consistent and less than 1, and the piezoelectric harvester generates higher power than electromagnetic harvesters. On the country, when the change of dimensionless resistance is greater than 1.5 under same dimensionless force factor, electromagnetic harvesters produce more electricity than that of piezoelectric harvesters [143].

Second, implementation of a piezoelectric harvester is more flexible. Sterken et al. compared the implementation conditions and circumstances of each generating technology [144] and concluded that the electromagnetic conversion is preferable for large and centralized equipment, electrostatic generators is suitable for very small systems, and Piezoelectric converters is applicable for all equipment sizes [144]. Also, given that piezoelectric materials have higher power density and can be produced as thin films, they can be utilized in almost all types of device, even wearable devices [11,145]. Piezoelectric nanowire can be used to enhance the piezoelectric effects, mechanical properties, and sensitivity to small forces of existing materials [146]. In addition, piezoelectric generators require no voltage input and also have lower maintenance and replacement costs [147].

Third, the piezoelectric solution is exceptionally suitable for building structures. To provide reliable energy outputs, harvesters need to capture and convert available environmental energy sources. Nechibvute et al. identified and compared potential ambient sources for energy harvesting, including light energy, mechanical vibrations, thermal energy, and radio frequency [146]. Many mechanical vibrations have a high energy density, the vibration-based generating system may outperform the solar harvesting system for indoor spaces. Buildings have the richest vibration sources, such as structural vibrations (bridges, floors, rails, and stations), appliance vibrations (washing machines, refrigerators, and microwave ovens), system vibrations (compressors, pumps, chillers, and motors), and natural vibrations (windows, walls). Piezoelectric materials mainly rely on converting vibrations to usable energy, making them exceptionally suitable for implementation in buildings.

Although the fabrication, performance, and application of piezoelectric materials have been thoroughly studied, several crucial issues still need to be further improved to allow more practical applications in sustainable buildings:

(1) Increasing the output power density. Thus far, the generated voltage of piezoelectric harvesters has been sufficient for sensor nodes and low power lights. However, larger building facilities require higher outputs.
(2) Distinguishing mechanical energy from various working conditions. Buildings have distinctive geographic, thermal, and functional conditions. This results in the diversity of energy sources. Therefore, it is necessary to optimize piezoelectric materials and harvester designs so that they will be best suited for their specific environmental conditions.
(3) Improving the long-term stability, mechanical strength, and chemical stability of nano-generators. The service life of buildings often lasts for decades, and the strength of materials can deteriorate due to weathering, creep, aging, and/or chemical reactions. Therefore, further investigations are suggested in order to help understand the long-term performance of piezoelectric building components.
(4) Optimizing building structural designs for more efficient electromechanical conversion. Compatible building structures could provide a feasible platform and improve energy conversion efficiency. Further studies from the perspective of building designers are also suggested.

6. Conclusions

Sustainable buildings should be environmentally responsible and resource-efficient throughout their life cycle. Piezoelectric materials allow more sustainable building components due to harvesting energy from structural strain and vibrations, less consumption of energy, and fewer carbon dioxide emissions. Compared to other materials, piezoelectric materials are more easily incorporated into construction materials and building systems. This paper systematically reviews a wide band of studies on mechanisms and applications of piezoelectric materials in the building industry. These advanced studies have introduced methods that can enhance the piezoelectric and energy storage capacity of building materials, such as cement and ceramics. Having a profound understanding of these methods and their applications in various building components and systems can inspire more insightful research and encourage more practical applications. With those methods, more self-sustained building structures can be integrated into renewable and sustainable building systems. It also can be concluded from the existing literature that although the application of piezoelectric materials has proved promising, future research is still urged to improve the power efficiency, structural reliability, durability, and economic feasibility of piezoelectric materials in various environmental conditions.

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