



# Epoxy-cement composite packaging for KNN piezoelectric sensors

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## ABSTRACT

Durable and high-performance piezoelectric sensors are critical for long-term infrastructure monitoring, especially under harsh mechanical and environmental conditions. The choice of encapsulation materials plays a decisive role in determining their stability, sensitivity, and service life. This study evaluates solvent-based and waterborne epoxy resins, with/without cement, for potassium sodium niobate (KNN)-based sensors. Cement addition in solvent-based epoxy reduced compressive strength and signal stability, yet maintained high sensitivity and good linearity under loading. Waterborne epoxy-cement composites achieved higher strength ( $\leq 57.8$  MPa) and 2–4 times greater voltage output. However, these composites failed structurally at loads exceeding 600 N, limiting their use in environments with heavy loads. Fatigue tests showed that solvent-based epoxy encapsulation had excellent durability, with only a 4.4 % voltage drop after 100,000 loading cycles. This indicates superior robustness for long-term deployment. The results reveal a trade-off between sensitivity and robustness in packaging strategies. Waterborne systems are suitable for low-to-moderate load conditions where sensitivity is prioritized, while solvent-based epoxies offer long-term reliability under repetitive and higher mechanical stresses. These findings provide important material selection guidelines for the development of reliable, lead-free piezoelectric sensors tailored to the specific demands of infrastructure health monitoring applications.

## 1. Introduction

The development and sustainability of urban infrastructure are intrinsically linked to the quality and longevity of road networks [1]. Ensuring the safety and structural integrity of pavements requires continuous monitoring, for which embedded sensor technology has emerged as a promising solution [2]. Among the various sensing technologies, piezoelectric sensors have been widely applied due to their high sensitivity, fast response, and robustness. In particular, embedded piezoelectric sensors allow for real-time monitoring of internal stress evolution and damage progression in cementitious materials, offering critical data to guide maintenance and extend service life [3,4].

Indeed, lead zirconate titanate (PZT) piezoelectric ceramics have become the de facto standard for embedded sensors in structural health monitoring of infrastructure [5]. Extensive research demonstrates their successful deployment within various cement-based and cement-polymer composite packaging systems, including cement-epoxy "smart aggregates" for hydration monitoring, grooved-interface sensors for enhanced coupling [6,7], and dedicated packages for impact damage

detection and non-destructive stress/strain evaluation [8,9]. These PZT-based sensors, embedded within the concrete matrix, exhibit proven capabilities such as high sensitivity to internal damage, effective filtering of external noise, and stable signal acquisition during critical processes like curing, establishing their functional efficacy for in-situ monitoring applications. However, a significant and growing concern overshadows this technological maturity: the high lead content intrinsic to PZT ceramics presents substantial environmental and toxicity risks, particularly concerning leaching during end-of-life disposal or structural demolition [10]. This critical drawback fundamentally contradicts the principles of sustainable infrastructure development. This has created a pressing demand for high-performance, lead-free piezoelectric alternatives [11].

Potassium sodium niobate (KNN)-based ceramics present a highly promising, environmentally benign alternative to lead-based PZT. Typical piezoelectric charge constants ( $d_{33}$ ) of 80–160 pC/N, and Curie temperatures of 380–420 °C make KNN competitive with certain PZT formulations, particularly where high-temperature operation and lead-free compliance are required. [12–14]. However, compared with PZT,

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KNN's lower relative permittivity, distinct electromechanical coupling behaviour, and differences in mechanical stiffness can reduce charge accumulation and dielectric displacement under identical loading. This often results in lower voltage output and narrower signal bandwidth in embedded applications. Furthermore, the multiphase interphase zone (PZT/KNN sensor/packaging material/pavement matrix) governs the system's efficacy and longevity [15]. The adhesion between the sensor and the surrounding road surface can significantly impact the sensor's ability to accurately detect and transmit data, potentially leading to signal delays or disruptions and making it challenging to comprehensively understand the real-time situation [8,16]. The direct substitution of PZT with KNN ceramics in embedded sensors is fundamentally impeded by mismatches in dielectric coupling efficiency and interfacial compatibility, which critically govern electromechanical energy transfer and stress wave propagation within matrices. Thus, research focusing predominantly on bulk KNN properties [17] or employing packaging paradigms optimized for PZT [18,19] overlooks these KNN-specific interfacial complexities. A critical knowledge gap persists in understanding the evolution of interfacial bonding under cyclic loading, associated stress transfer mechanisms, and their effects on electromechanical response and cohesive/adhesive failure within the KNN-package-pavement system. Therefore, merely substituting PZT elements with KNN ceramics within existing packaging architectures represents an inadequate strategy, likely leading to suboptimal performance and premature failure. Fundamental investigation into tailoring interface engineering and packaging design specifically for KNN's material characteristics is imperative to achieve robust interfacial bonding, maximize electromechanical coupling efficiency, ensure signal stability, and guarantee compatibility over decades of service.

To address the dual requirements of environmental compatibility and mechanical durability in embedded pavement sensors, this study adopts potassium sodium niobate (KNN) ceramics as the piezoelectric sensing unit, combined with cement/solvent-based epoxy and cement/waterborne epoxy composites as encapsulation materials. These systems were selected to represent a balance between long-term bonding stability and reduced environmental impact, both being representative in pavement sensor integration. Appropriate packaging is critical for maintaining measurement accuracy and extending service life, as mechanical mismatches at the sensor-matrix interface can induce stress concentrations and lead to premature failure [20,21].

Previous studies have shown that PZT-based sensors can be effectively packaged using either solvent-based epoxy or cement-based materials [22–24]. Solvent-based epoxy offers strong bonding and stable output in concrete, while cement-based encapsulation may improve strain transmission and measurement accuracy [7,25]. In addition, several studies have demonstrated that the combination of solvent-based epoxy and cement is also an option to enhance the durability of the sensors by reducing the aging of the epoxy when exposed to UV light [26]. While these findings confirm that both epoxy and cementitious materials are feasible for packaging PZT piezoelectric devices [7,27,28], two main knowledge gaps need to be bridged for exploring environmentally friendly piezoelectric sensors. First, while waterborne epoxy is a more sustainable alternative, its compatibility with cementitious matrices has not been fully explored. Second, most existing studies focus on PZT-based systems; the interaction between lead-free ceramics such as KNN and epoxy/cement packaging remains unclear.

In response to these gaps, this work develops a KNN-based piezoelectric sensor encapsulated with waterborne epoxy and cement composites, aiming to evaluate their mechanical compatibility and sensing performance. The mechanical behavior of the packaging layers was characterized at both macro and micro scales, while the sensitivity, stability, and repeatability of the KNN-based sensor were evaluated in a similar testing environment. This work provides a fundamental basis for the development of low-cost, lead-free, high-performance embedded sensors tailored for structural health monitoring in concrete pavements.

By targeting both the lack of systematic application of KNN in cementitious environments and the insufficient understanding of sensor-matrix mechanisms, the findings contribute to the advancement of smart, sustainable, and resilient infrastructure systems.

## 2. Materials and characterization methods

### 2.1. Materials preparation

In this study, lead-free piezoelectric ceramics, epoxy-based packaging composites, and embedded sensor prototypes were prepared for experimental evaluation. The preparation procedures for each component are described below.

#### 2.1.1. Synthesis of KNN ceramics

Potassium sodium niobate-based ceramics with the nominal composition  $0.95 \text{ K}_{0.5}\text{Na}_{0.5}\text{NbO}_3-0.02(\text{Bi}_{0.5}\text{Na}_{0.5})\text{ZrO}_3-0.03\text{CaHfO}_3$  (KNN-BNZ-0.03CHO) ceramics were synthesized via the solid-state reaction method. The starting materials included  $\text{K}_2\text{CO}_3$  (99 %),  $\text{Na}_2\text{CO}_3$  (99.8 %),  $\text{Nb}_2\text{O}_5$  (99.5 %),  $\text{Bi}_2\text{O}_3$  (99.999 %),  $\text{CaCO}_3$  (99.9 %),  $\text{ZrO}_2$  (99.5 %), and  $\text{HfO}_2$  (99.5 %), were supplied by Sino-pharm Chemical Reagent Co., Ltd, China. All starting powders were oven-dried and weighed according to the designed stoichiometric composition, then wet-milled in absolute ethanol for 24 h. The dried slurry was pressed into thin compacts and calcined in a corundum crucible at  $860^\circ\text{C}$  for 5 h. The pre-sintered bodies were crushed in an agate mortar, re-milled in a planetary ball mill with ethanol for 4 h, dried, and pressed again into compacts for a second calcination at  $860^\circ\text{C}$  for 2 h. A final milling step in ethanol was performed, and the calcined powder was sieved through a 60-mesh screen to ensure uniform particle size. The powder was then mixed with 8 wt% polyvinyl alcohol (PVA) binder and uniaxially pressed into 15 mm diameter discs.

Sintering was conducted under a controlled schedule: the temperature was ramped from  $50^\circ\text{C}$  to  $1090^\circ\text{C}$  over 240 min, lowered to  $1060^\circ\text{C}$  within 10 min, and held for 2 h, then reduced to  $800^\circ\text{C}$  over 80 min before furnace cooling to room temperature. All samples were processed under identical conditions to minimise preparation-induced variability [29].

#### 2.1.2. Preparation of packaging materials

Packaging materials: The study selected solvent-based epoxy and waterborne epoxy as matrix materials, which were compounded with cement (Portland cement P-O 42.5 with a density of  $3200 \text{ kg/m}^3$ ) in varying ratios to prepare composite slurries (see Table 1). The solvent-based epoxy employed in this study is diglycidyl ether of bisphenol A, with a molecular formula of  $\text{C}_{21}\text{H}_{24}\text{O}_4$  and a density of  $1.17 \text{ g/cm}^3$ . The curing agent used has a molecular formula of  $\text{C}_5\text{H}_{12}\text{FNO}$ , a density of  $0.957 \text{ g/cm}^3$ , and a viscosity of 6 Pa·s. A commercially available waterborne epoxy resin (60 % solids by weight) was procured from Shandong Jiaziyu Lakeside New Materials Science & Technology Co.,

**Table 1**  
Mix composition of the packaging materials.

|                     |         | Matrix materials/g | Cement/g | Additional solvents (deionized water and defoamer)/g |
|---------------------|---------|--------------------|----------|------------------------------------------------------|
| Solvent-based epoxy | 100:0   | 100                | 0        | 0                                                    |
|                     | 100:50  | 67                 | 33       | 0                                                    |
|                     | 100:100 | 50                 | 50       | 0                                                    |
|                     | 0:100   | 0                  | 100      | 0                                                    |
| Waterborne epoxy    | 100:0   | 100                | 0        | 1                                                    |
|                     | 1:100   | 1                  | 100      | 42.61                                                |
|                     | 5:100   | 5                  | 100      | 41.05                                                |
|                     | 10:100  | 10                 | 100      | 39.1                                                 |
|                     | 50:100  | 50                 | 100      | 23.5                                                 |
|                     | 100:100 | 100                | 100      | 4                                                    |
|                     | 0:100   | 0                  | 100      | 43                                                   |

Ltd., and utilized as the base resin in the formulation.

Epoxy resin and curing agent were premixed at a mass ratio of 100:10 for 3 min, followed by the gradual addition of cement powder under mechanical stirring (800 rpm) to prevent local agglomeration and ensure uniform dispersion. For the waterborne epoxy-cement system, waterborne epoxy resin emulsion, curing agent, and a defoamer (added at 1 wt% of the total mass of the premixed waterborne epoxy resin) were first premixed for 3 min. Cement powder was then added gradually under mechanical stirring at 800 rpm to ensure uniform dispersion. The effective water-to-cement ratio ( $w/c = 0.43$ ) was maintained for all mixtures, where the total water content included both the intrinsic water in the waterborne epoxy resin and the externally added water, which was adjusted accordingly. After mixing, the slurry was gently vibrated to remove air and cast into  $20 \times 20 \times 20$  mm cube molds for curing.

### 2.1.3. Fabrication of embedded sensors

The resultant ceramic disc was then polished to a thickness of 0.8–1 mm, with silver electrodes printed on the surface, and subsequently sintered at 600 °C for 30 min. The samples were then polarized in an electric field of 3 kV/mm at 80 °C for 0.5 h.

To construct the piezoelectric sensor unit, five silver-electrode-coated ceramic discs were stacked and bonded to form a cylindrical element with dimensions of approximately  $15 \text{ mm} \times 5 \text{ mm}$  (see Fig. 1). Copper wires were soldered onto the top and bottom surfaces as electrical leads. Finally, the assembled structures were packaged using different packaging materials, resulting in a rectangular sensor with an average length and width of  $19 \pm 1 \text{ mm}$  and  $9 \pm 1 \text{ mm}$  in height (with

slight dimensional variations due to the fabrication process).

The piezoelectric coefficient ( $d_{33}$ ) of the unpackaged KNN ceramic element was measured to be 321 pC/N. After packaging, the  $d_{33}$  values decreased slightly to 317 pC/N for the solvent-based epoxy and 309 pC/N for the waterborne epoxy, indicating that the poling state of the ceramic element was well preserved and that the packaging layer caused negligible degradation in the intrinsic piezoelectric properties.

### 2.2. Characterization methods

The slurry was prepared by mixing epoxy resin and cement in different ratios and cast into  $20 \text{ mm} \times 20 \text{ mm} \times 20 \text{ mm}$  standard cube specimens. The specimens were cured in a constant temperature environment at 60 °C for 24 h, after which compressive strength tests were conducted following ASTM C109/C109M standards using a universal testing machine (Instron 5967, USA) [30]. The compressive load was applied under displacement control at 0.5 mm/min until failure. Given the chemical reaction between waterborne epoxy and cement, a series of specimens with varying ratios was prepared in this study. These specimens were cured in a standard curing chamber (temperature  $20 \pm 2$  °C, relative humidity  $\geq 95\%$ ) for 3 days, 7 days, and 28 days, respectively. Following this, compressive strength tests were performed to investigate the influence of material ratios and curing ages on the mechanical properties of the composite materials.

For scanning electron microscopy (SEM) analysis, specimens were extracted from the crushed mortar samples obtained from the compressive strength tests. The fragmented specimens were cut into cubes with dimensions of less than 5 mm. These cubes were immersed in

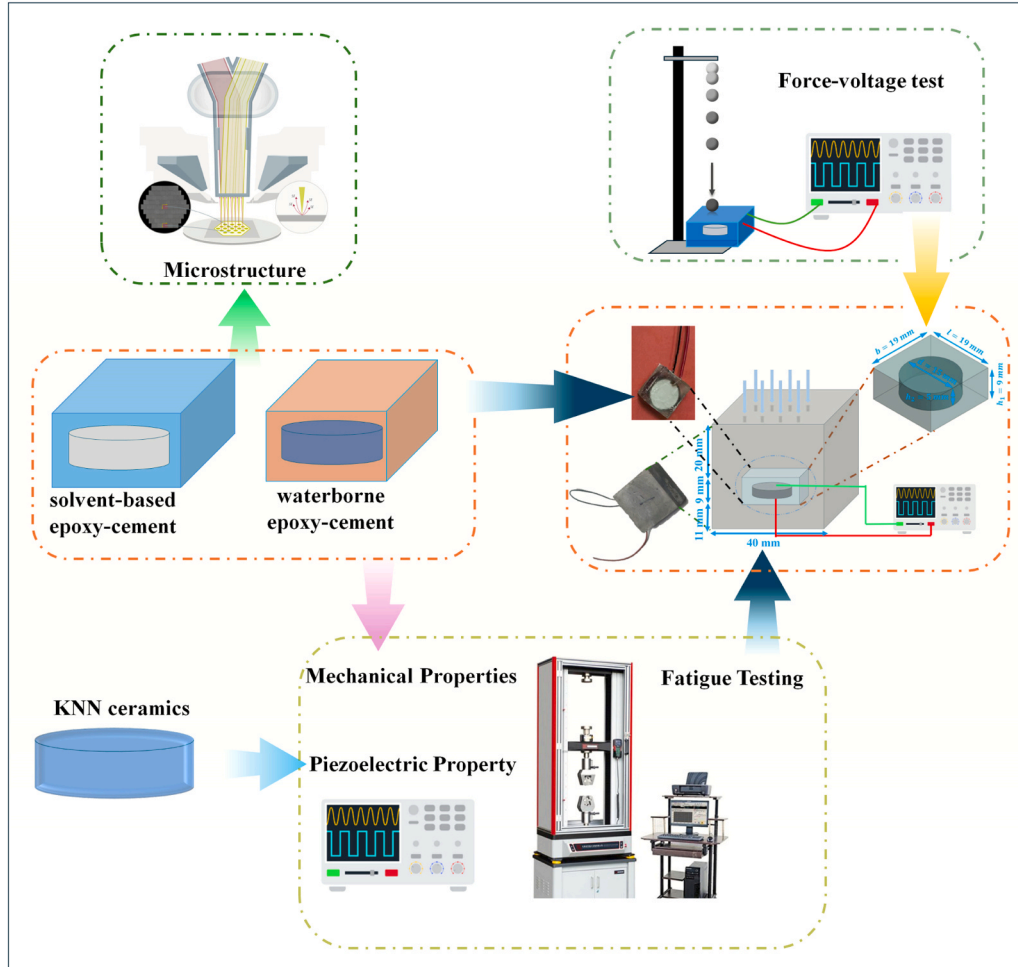


Fig. 1. Schematic workflow of sensor encapsulation, characterization, and performance evaluation.

isopropanol for 24 h and subsequently dried in a vacuum oven at 42 °C for an additional 24 h. The SEM analyses were conducted using a JSM-IT800 field emission scanning electron microscope (FE-SEM) system manufactured by JEOL Ltd., Japan, at an accelerating voltage of 15.0 kV.

Sensitivity testing of the packaged sensing unit was performed based on the principle of momentum conservation. The sensor leads were connected to an oscilloscope (Tek MSO-3014), and small spheres of varying masses were dropped from a fixed height of 30 cm through a guiding frame to ensure consistent alignment and minimize human error during manual release, as illustrated in Fig. 1. Each impact test was repeated ten times for every specimen, and the average voltage responses were used for analysis. In total, ten independent specimens were tested for each packaging material, resulting in 1000 voltage measurements per group. The coefficient of variation of the output voltage was below 5 %, demonstrating satisfactory repeatability. The corresponding force-voltage relationship was then derived to evaluate the sensor's force-to-electric conversion characteristics and sensitivity. All voltage data were processed using identical filtering, normalization, and statistical methods to ensure consistent comparison among different material systems.

To evaluate the long-term durability of the piezoelectric sensor, a fatigue test was conducted by embedding the sensor within a 40 mm × 40 mm cement paste specimen. To simulate realistic compressive load transfer, the sensor was embedded at a depth of 20 mm from the specimen surface, as illustrated in Fig. 1. The fatigue test was carried out using a hydraulic-servo universal testing machine (COOPER HYD25). The specimens were subjected to a constant axial load of 5 kN at a loading frequency of 10 Hz, with the ambient temperature maintained at 20 ± 5 °C, relative humidity 40–50 %. Three independent specimens were used for this test. A total of 100,000 loading cycles was applied. The open-circuit voltage output of the sensor was continuously monitored using an oscilloscope. Peak voltage values were recorded at intervals of every 10,000 cycles to assess signal variation over time. Additionally, full waveform snapshots were captured after the first loading cycle and upon completion of 100,000 cycles to evaluate waveform consistency and quantify any signal attenuation by the oscilloscope.

### 3. Results and discussion

#### 3.1. Characterization of packaging materials

##### 3.1.1. Mechanical properties

Before evaluating the compatibility between the KNN and the epoxy/

cement packaging materials, the essential factor is to explore the mechanical properties of the packaging materials. As a result, we tested the compressive strengths of the solvent-based epoxy and the waterborne epoxy, along with cement with various cement/epoxy ratios. The results are plotted in Fig. 2. As can be seen from Fig. 2a, the compressive strength of the traditional solvent-based epoxy decreases with increasing cement content from zero to 100 %. The neat solvent-based epoxy resin demonstrates a compressive strength of approximately 110 MPa, and remains relatively constant at around 90 MPa for epoxy: cement = 100: 50 and epoxy: cement = 100: 100 by mass. This phenomenon can be ascribed to the fact that the addition of cement primarily serves as a filler material embedded in the solvent-based epoxy matrix. Without the hydration process, the reinforcement effect of the cement in the solvent-based epoxy is quite limited because the addition of the cement particles brings more cement/epoxy interfaces, leading to extra defects that weaken the mechanical properties. Meanwhile, as demonstrated in Fig. 2b, the compressive strength as a function of the cement/epoxy ratio of the waterborne epoxy shows a “bell” trend. The maximum 28-day compressive strength (55 MPa) appears at the waterborne epoxy: cement = 5:100. Although the compressive strength is not as high as that of the solvent-based epoxy, the merits of using the neat waterborne epoxy are acceptable. First, the manufacturing cost will be significantly saved by using the waterborne epoxy due to the solid content of the epoxy has been considerably reduced. Second, as can be observed in Fig. 2b, with the increasing cement content, the compressive strength boosts from 35 MPa to over 55 MPa, due to the hydration of the cement particles. In addition, for the health monitoring application of the cement concrete structures, provided with cement packaging, the compatibility between the sensing device and the cement structure can be significantly improved, which is beneficial to enhance the accuracy of the output data [8,20].

##### 3.1.2. Interactions between the cement and epoxy resins

To understand the interaction mechanism between the epoxy and the cement fillers, the fracture surfaces of the solvent-based epoxy and waterborne epoxy mixed with cement particles are compared through SEM images. As can be observed from Fig. 3a, the fracture surface of the neat solvent-based epoxy resin is smooth without any apparent micro-cracks. However, with the addition of cement particles, the fracture surfaces have become typical brittle fracture modes (Fig. 3b). The cracks are propagated along the interfaces between the cement particles and the solvent-based epoxy matrix. Most importantly, barely hydration products can be observed even with mixing high-weight content of cement. It is well agreement with the results of the compressive strength testing, shown in Fig. 2a.

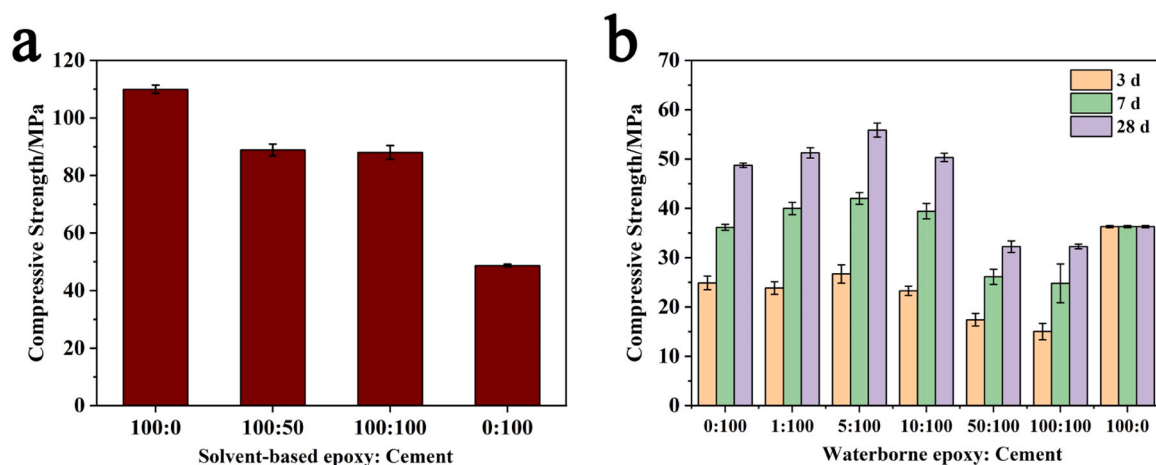
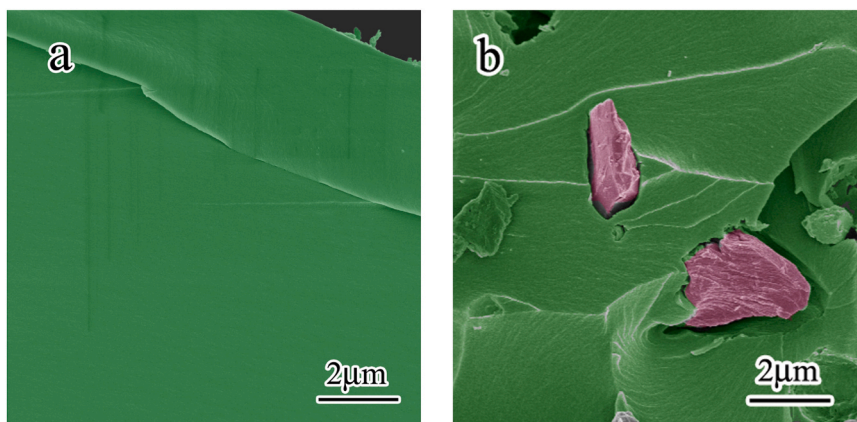


Fig. 2. The compressive strength of packaging materials with the variation of cement dosage, a) solvent-based epoxy packaging material, b) waterborne epoxy packaging material.



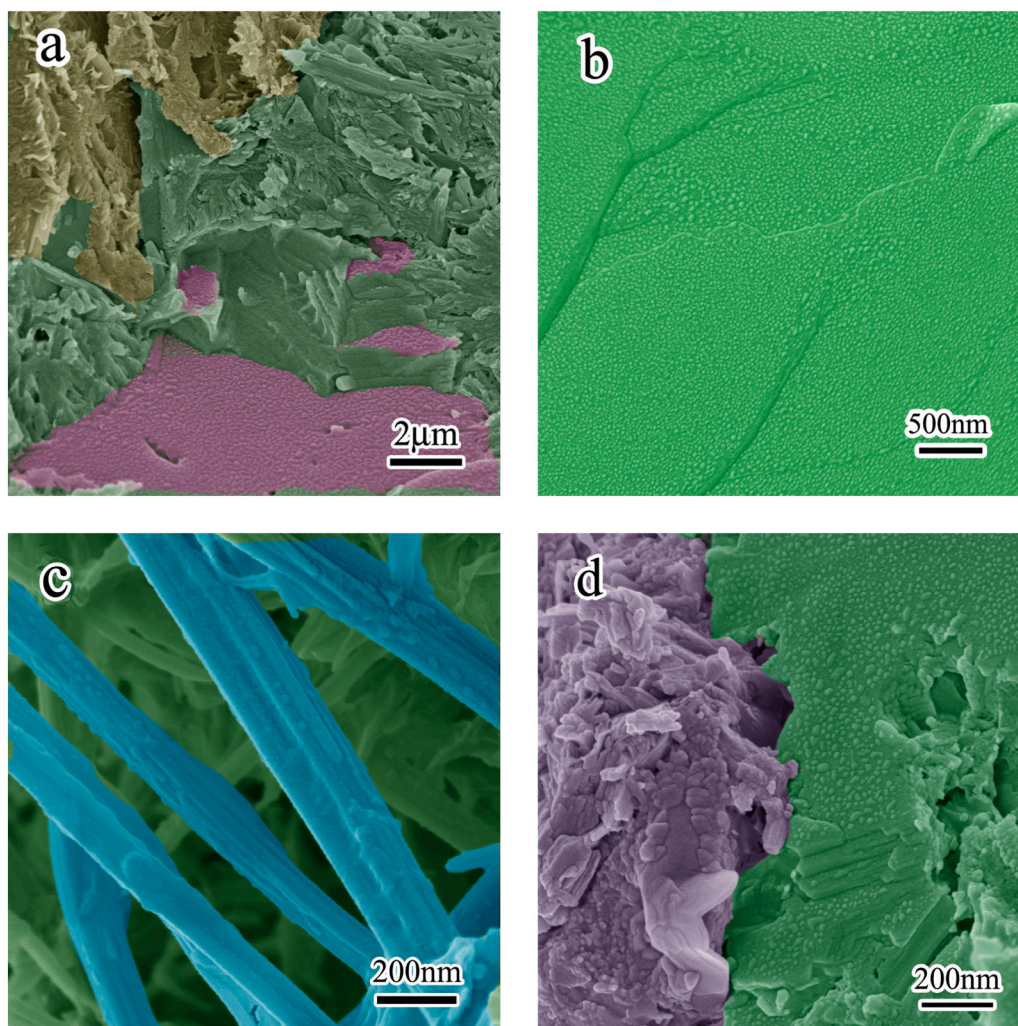


**Fig. 3.** Fracture surfaces SEM morphologies of a) neat solvent-based epoxy and b) solvent-based epoxy/cement.

Unlike the solvent-based epoxy, the fracture surfaces of the waterborne epoxy are more complicated. As depicted in Fig. 4a, with the addition of cement particles, the hydration production of the cement is observable. In contrast to the unreacted cement particles in the solvent-based epoxy matrix, which cause the interfacial defects (Fig. 3b), typical C-S-H hydration products can be identified. In addition, the fracture surface of the waterborne epoxy is not as smooth as the solvent-based

epoxy. A distinctive texture of densely packed protrusions can be observed. These nano-sized protrusions are the waterborne epoxy emulsion particles, which are stuck on the surface of the hydration products. It can be detected on the flat surfaces (Fig. 4b) and other forms (Fig. 4c and d) of the cement hydration products.

However, with the increase of cement content in the waterborne epoxy, due to the boost of the hydration degree of the cement, the rising



**Fig. 4.** Fracture surface SEM morphologies of waterborne epoxy/cement, a) low-magnification image, and high-magnification images of b) hydration product with flat surface, and c) and d) other forms of surface of C-S-H hydration products.

pH value will break the emulsion of the waterborne epoxy, and form large size epoxy spheres, which weaken the mechanical properties of the waterborne epoxy/cement system due to the new formed weak interfaces. As can be seen from Fig. 5a, numerous epoxy spheres of various sizes can be observed, and the cracks propagate along the interfaces of these spheres. Meanwhile, the amount of the nano-sized protrusions stuck on the flat surfaces of the hydration products is significantly reduced due to the breaking of the epoxy emulsions and forming the large-sized epoxy spheres, as demonstrated in Fig. 5b (the purple area). These underlying mechanisms confirm the “bell” structure alteration trend of the mechanical properties, as shown in Fig. 2.

### 3.2. Force-voltage generation

#### 3.2.1. Voltage collection

Since the mechanical properties and the compatibility between the epoxy and the cement have been investigated, the following challenge is to find out the feasibility of using them as the packaging materials for the KNN-based piezoelectric ceramics. To evaluate the force-voltage responsive sensitivity of the KNN/epoxy/cement systems, we compared the voltage signal output of the KNN plates embedded in the waterborne-based epoxy/cement and solvent-based epoxy/cement materials, by using the strategy of free-falling ball test with different masses (2 g, 5 g, 20 g, and 30 g) and a falling height of 30 cm. To ensure statistical reliability and minimize experimental errors, the free-fall impact tests for each ball mass were repeated 1000 times under identical conditions. The corresponding time-voltage signals generated by the sensor were subsequently captured and analyzed using a digital oscilloscope, enabling precise characterization of the sensor's dynamic response to impact forces. This rigorous experimental protocol enhances the validity and reproducibility of the obtained results.

The sensitivity of force-voltage response of the solvent-based and waterborne epoxy mixed with cement as packaging materials for KNN piezoelectric sensors is evaluated through a radar graph (Fig. 7, Fig. 8, and Fig. 9) and their corresponding voltage distribution. Each radar plot consists of 100 equally spaced radial lines, where the radii do not correspond to physical directions but to individual groups of 10 repeated measurements. For each group, the plotted point represents the logarithm of the average output voltage, which was applied to normalize the large dynamic range and to ensure consistent scaling among different samples. Therefore, the radial scaling is log-transformed and normalized rather than arbitrary. Because all radii are equivalent, the overall circularity of the graph reflects the uniformity of the voltage responses across repeated experiments. A smoother, more symmetric shape indicates better repeatability, while irregularities suggest greater variation between tests. In the distribution graph,  $\Delta R$  is the difference between the highest and the lowest electric voltage located in the corresponding

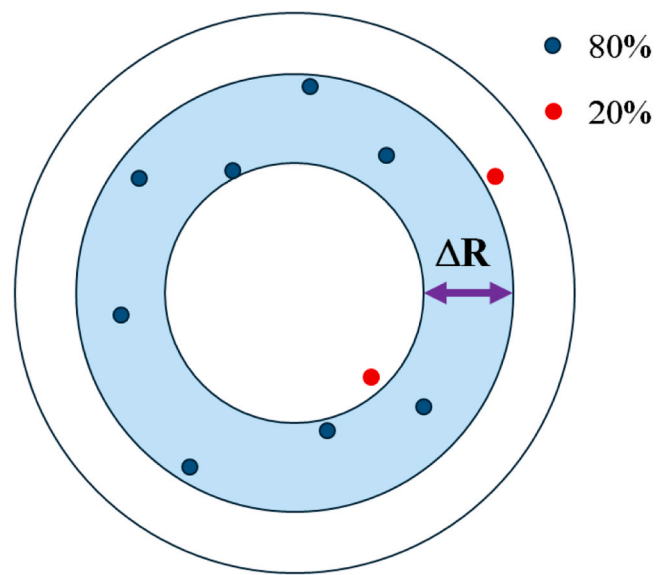


Fig. 6. Schematic illustration of how the radar graphs and  $\Delta R$  are derived from repeated measurements to assess voltage response repeatability.

proportion of the tested sample numbers. For instance, “ $80 \pm 2\%$ :  $\Delta R = 0.558\text{ V}$ ” indicates that 80 % of the test data fall within a voltage window of 0.558 V. A schematic of this calculation is provided in Fig. 6.

As illustrated in Fig. 7, given that the weight of the free-falling ball of 2 g, from the stability perspective, the performance of the solvent-based epoxy/cement packaging materials with the solvent-based epoxy: cement = 5:100 is the best. Compared with the other three, the values of the  $\Delta R$  corresponding to the 60 %, 70 %, and 80 % are all the lowest, with values of 0.096 V, 0.192 V, and 0.288 V, respectively. However, from a sensitivity perspective, the highest voltages can reach 4.41 V and 6.93 V, corresponding to the waterborne epoxy/cement system with the waterborne/cement ratio of 5:100 and 100:100, respectively. In addition, the average force-responsive voltage of the waterborne epoxy/cement system is higher than that of the solvent-based epoxy/cement system.

When the weight of the free-falling ball increases to 5 g, the generated voltage has significantly risen in contrast to the ones that were generated by 2 g balls. Unlike the samples obtained from the 2 g group, the voltage distribution data show that the waterborne epoxy/cement group with a ratio of 5:100 has the highest stability. In this group, most of the data were located in a narrow range with  $\Delta R$  values of 1.363 V and 2.726 V corresponding to 80 % and 90 %, respectively.

According to the 2 g and 5 g free-falling ball testing results, it seems

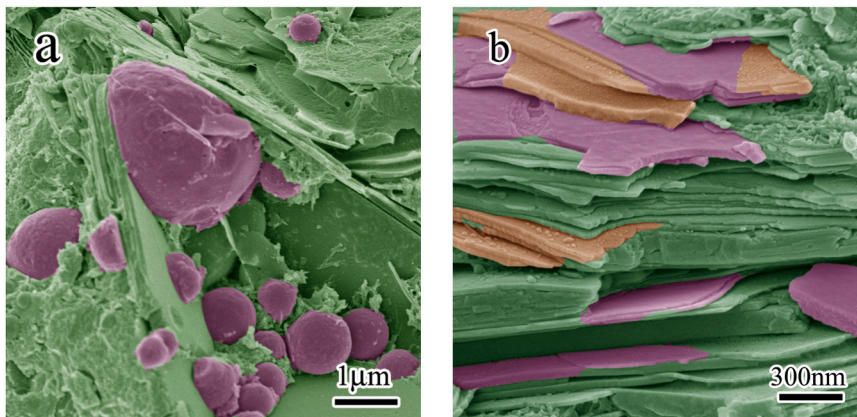


Fig. 5. Fracture surface SEM morphologies of waterborne epoxy/cement with a) low-magnification image, and b) high-magnification images.



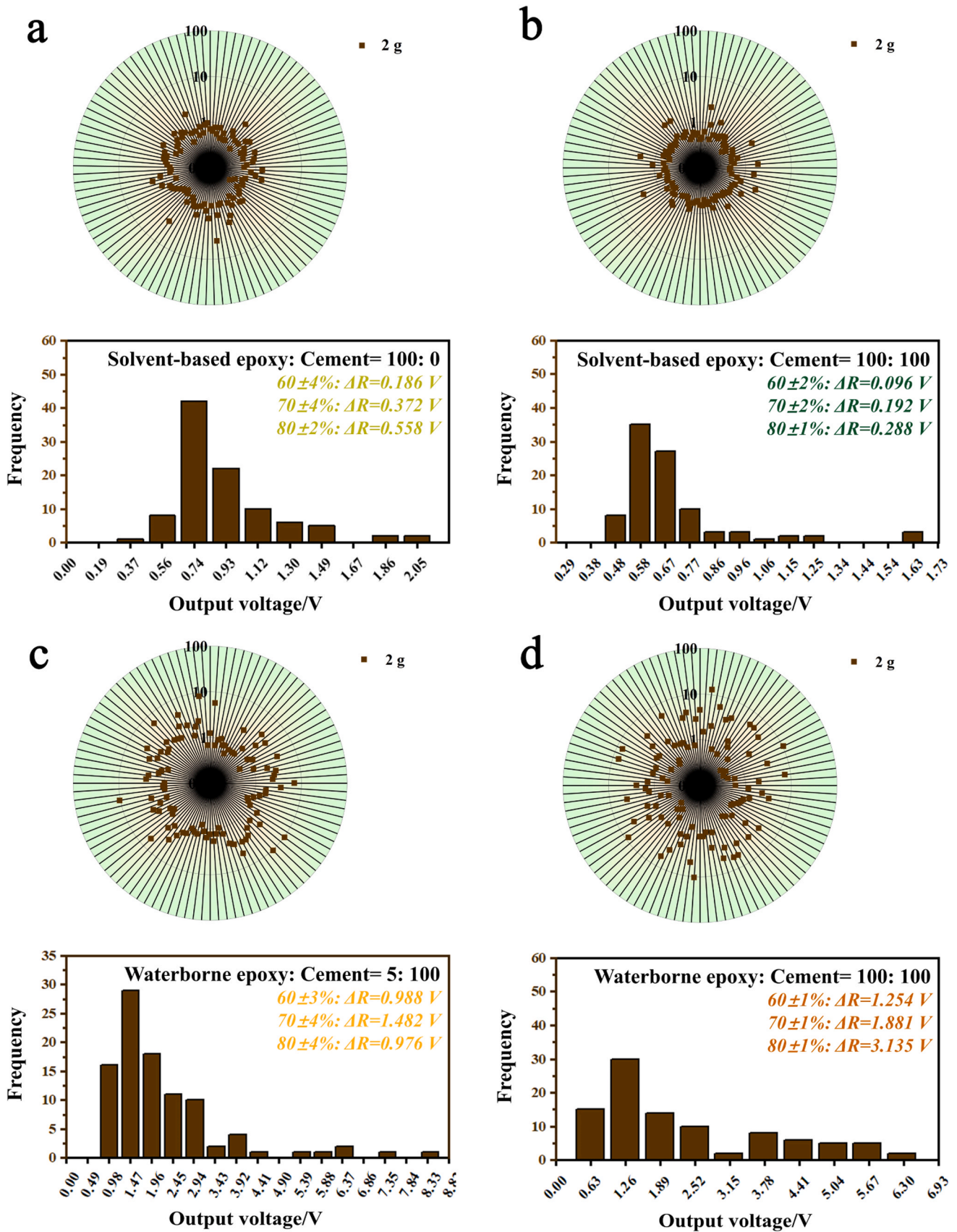
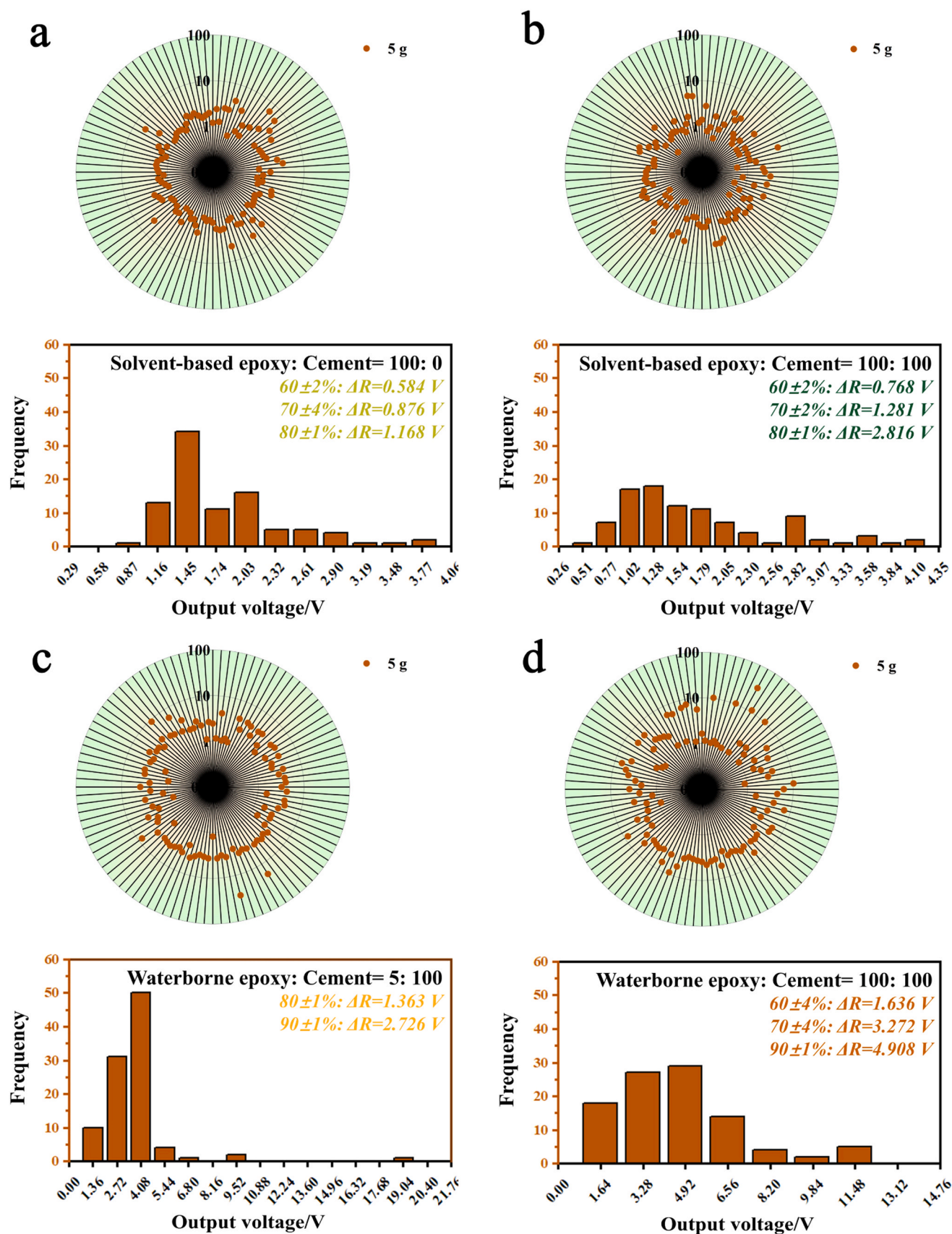
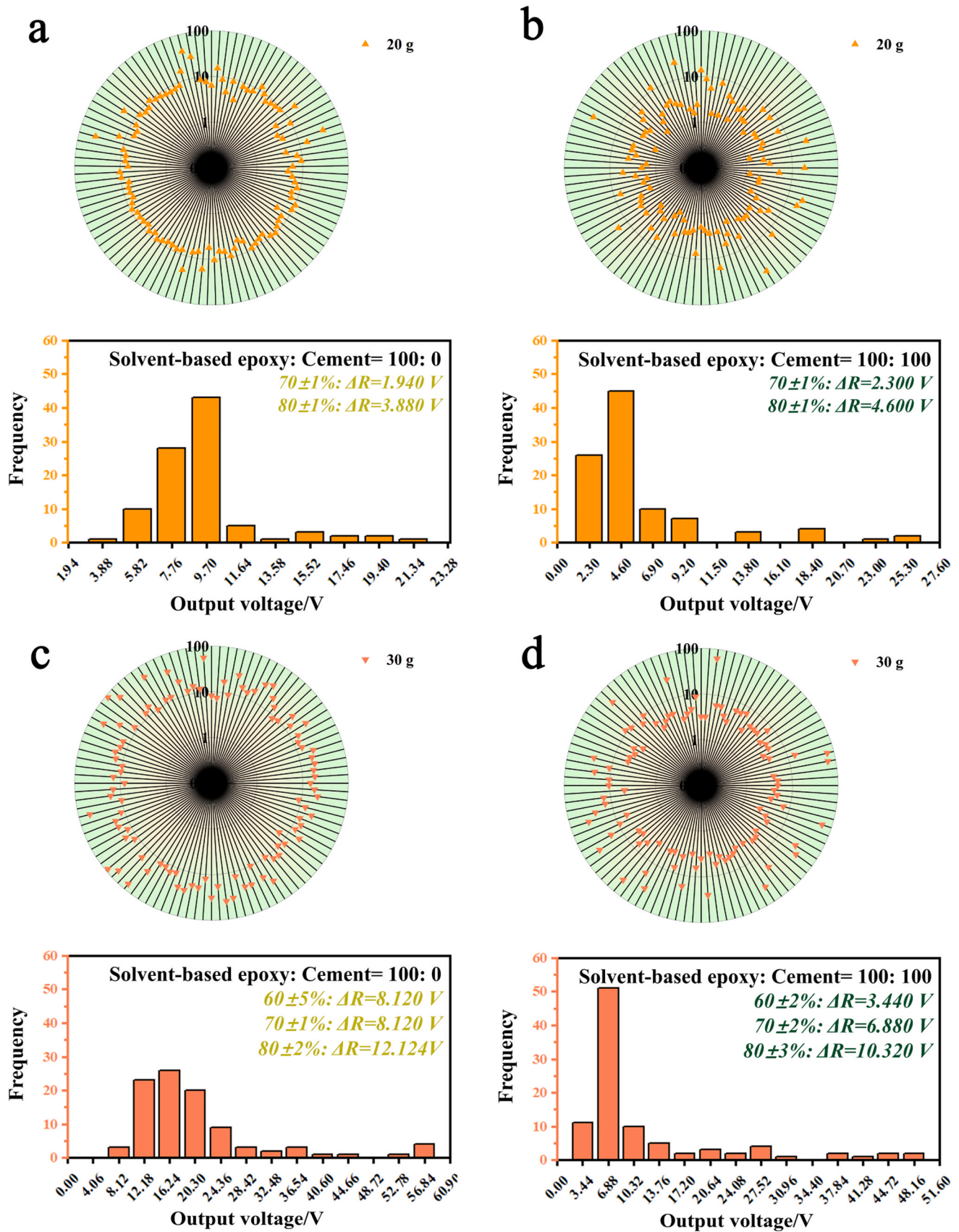


Fig. 7. Radar graphs and the corresponding voltage distribution sensitivity of force-voltage response of the waterborne and solvent-based epoxy mixed with cement as packaging materials for KNN piezoelectric sensors under a 2 g falling ball, a) solvent-based epoxy: cement = 100:0; b) solvent-based epoxy: cement = 100:100; c) waterborne epoxy: cement = 5:100, and d) waterborne epoxy: cement = 100:100.



**Fig. 8.** Radar graphs and the corresponding voltage distribution sensitivity of force-voltage response of the waterborne and solvent-based epoxy mixed with cement as packaging materials for KNN piezoelectric sensors under a 5 g falling ball, a) solvent-based epoxy: cement = 100:0; b) solvent-based epoxy: cement = 100:100; c) waterborne epoxy: cement = 5:100, and d) waterborne epoxy: cement = 100:100.





**Fig. 9.** Radar graphs and the corresponding voltage distribution sensitivity of force-voltage response of the solvent-based epoxy mixed with cement as packaging materials for KNN piezoelectric sensors under 20 g and 30 g falling balls, a) solvent-based epoxy: cement = 100:0; b) solvent-based epoxy: cement = 100:100; c) solvent-based epoxy: cement = 100:0; d) solvent-based epoxy: cement = 100:100.

that the waterborne epoxy/cement packaging materials have a better performance compared with the solvent-based epoxy/cement system. However, provided with the weight of the falling ball rising to 20 g and 30 g (as shown in Fig. 9), the waterborne epoxy/cement system does not work very well in contrast to the solvent-based epoxy/cement system. All waterborne epoxy/cement samples have broken, and thus, no data can be obtained. For the solvent-based epoxy/cement system, from both stability and sensitivity perspectives, the neat solvent-based epoxy demonstrates a better performance than the solvent-based epoxy/cement composites.

### 3.2.2. Linearity of force vs. voltage signal

The impact forces generated by balls of different masses were calculated based on the principle of momentum conservation, expressed as:

$$mgh = E_k = \frac{1}{2}mv^2 \quad (1)$$

$$m v = F\Delta t \quad (2)$$

where  $m$  is the mass of the ball,  $g$  is the gravitational acceleration,  $h$  is the drop height,  $v$  is the impact velocity,  $F$  is the peak impact force, and  $\Delta t$  is the impact duration extracted from the recorded waveform.

The impact duration and maximum output voltage corresponding to each impactor acting on the KNN sensor surface were determined from the waveform diagrams obtained using an oscilloscope. As a representative example, Fig. 10 illustrates the waveform generated by a 2 g ball impact on the surface of a sensor packaged with solvent-based epoxy (solvent-based epoxy: cement = 100:0). The analysis reveals a total impact duration of 0.0202 s and a corresponding voltage output of 0.88 V. For higher impact masses (5 g, 20 g, and 30 g), the recorded voltage signals showed similar temporal shapes with proportionally increased peak amplitudes. Using the measured values of  $\Delta t$  and calculated  $v$ , the corresponding peak dynamic impact forces were derived from Eq. (2). The resulting forces and durations for each impactor mass are summarized in Table 2. The short contact durations on the order of tens of milliseconds lead to transient high peak forces even for small impact masses, consistent with typical dynamic impact behavior.

The radar plots (Fig. 7, Fig. 8, and Fig. 9) revealed significant data dispersion for certain materials, indicating inconsistencies in sensor response. Additionally, the sensor encapsulated with waterborne epoxy resin experienced structural failure after 1000 impact cycles with 20 g spheres, suggesting limited durability under high-load conditions. To enhance the reliability of the comparative analysis, data points exhibiting a coefficient of variation exceeding 10 % were excluded, and the

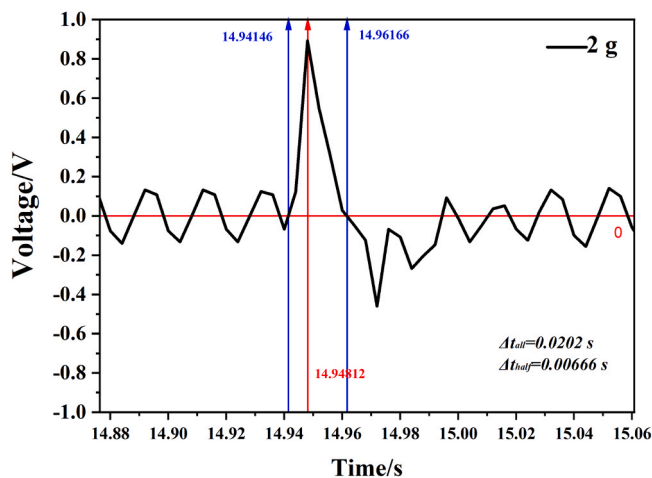


Fig. 10. The oscillogram of a 2-gram ball in free fall on the surface of the sensor.

Table 2

The force and time of action corresponding to different balls.

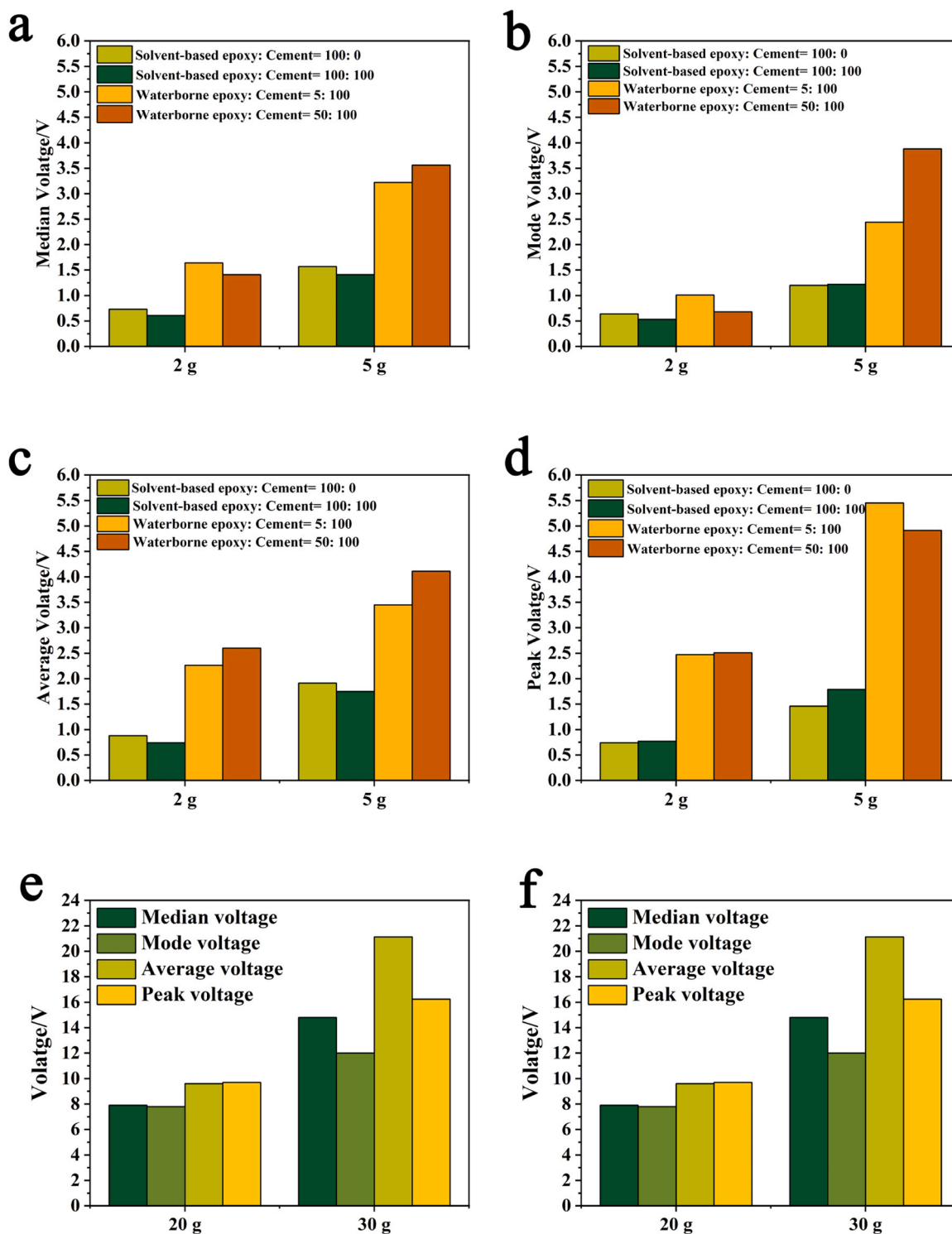
|              | 2 g    | 5 g    | 20 g   | 30 g   |
|--------------|--------|--------|--------|--------|
| F/N          | 240    | 647    | 3491   | 6367   |
| $\Delta t/s$ | 0.0202 | 0.0187 | 0.0139 | 0.0114 |

remaining voltage data (the voltage responses under 2 g and 5 g impact conditions) were analyzed to determine the median, mode, average, and peak values (from normal distribution statistics), as illustrated in Fig. 11. Under impact by 2 g and 5 g falling balls (corresponding to approximately 240 N and 647 N, respectively), the sensor packaged with waterborne epoxy resin generated output voltages that were 2–4 times higher than those packaged with solvent-based epoxy. Under identical impact conditions, the sensor packaged with a waterborne epoxy: cement = 5:100 yielded higher voltage outputs compared to the 100:100 formulation, suggesting that a moderate incorporation of cement can enhance the piezoelectric sensitivity of the composite. The sensor packaged with solvent-based epoxy resin combined with cement exhibited a significantly reduced voltage response, approximately half compared to the pure solvent-based epoxy, indicating a detrimental effect of cement addition on sensitivity in this particular matrix. These observations are illustrated in Fig. 11(a, b, c, d). For the pure solvent-based epoxy resin (Fig. 11e and f), a notable increase in output voltage was observed under 20 g and 30 g impacts, highlighting its superior performance under higher loading conditions. Furthermore, the four voltage parameters exhibited considerable variation under identical impact forces, consistent with the findings in Fig. 9, which indicates increased signal output dispersion due to potential inhomogeneity introduced by cement incorporation.

Apart from the absolute values of the force-generated voltage, the relative voltage values, which were calculated according to  $\Delta R/V_{max}$ , where  $V_{max}$  is the maximum voltage, are also another important criterion to evaluate the overall performance of the packaged sensors. The relative voltage values are listed in Table 3. As can be detected from this table, for the 2 g free-falling ball group, the highest absolute voltage was obtained in the waterborne epoxy/cement system with the W/C ratio of 5:100. However, the lowest relative voltage is observed in the S/C<sub>100/100-2g</sub> group with a value of 0.17, which is far less than the other three. For the 5 g free-falling ball group, the W/C<sub>100/100-5g</sub> group reaches the highest absolute voltage with a value of 4.92, while the W/C<sub>5/100-5g</sub> group has the lowest relative voltage of 0.50. In this group, the waterborne epoxy/cement system performs better than the solvent-based epoxy/cement system. Finally, when the weight of the free-falling ball increased to over 20 g, due to the breakage of the waterborne epoxy/cement samples, the results had to be compared between the neat solvent-based epoxy and the solvent-based epoxy/cement composites. As illustrated by the results, the neat solvent-based epoxy shows a better general performance than the solvent-based epoxy: cement = 100:100.

Sensors fabricated with waterborne epoxy resin exhibited substantially lower voltage outputs across all impact forces compared to those with solvent-based epoxy (Fig. 11). Despite the significant difference in compressive strength between the waterborne epoxy: cement = 5:100 and waterborne epoxy: cement = 50:100, their output voltages were remarkably similar. The gradual increase in peak and median voltage values suggests limited sensor sensitivity, rendering these materials unsuitable for high-load applications. These findings provide critical insights into the relationship between packaging material composition and sensor performance under varying mechanical loads.

Through data processing, four typical voltage parameters were obtained to investigate the influence of different packaging materials on sensor performance. This study particularly focused on the relationship between force and voltage output for two material formulations: solvent-based epoxy to cement ratios of 100:0 and 100:100. The forces and corresponding voltages listed in Table 3 were analyzed, and linear fitting methods were applied to examine the trends of median voltage,



**Fig. 11.** Force-voltage response of the waterborne and solvent-based epoxy mixed with cement as packaging materials for KNN piezoelectric sensors, a) median voltage; b) mode voltage; c) average voltage; d) peak voltage; e) solvent-based epoxy: cement = 100:0 under 20 g falling ball; f) solvent-based epoxy: cement = 100:100 under 30 g falling ball.

mode voltage, average voltage, and peak voltage. For sensors packaged with the solvent-based epoxy: cement = 100:0, as shown in Fig. 12a, the experimental results demonstrate a highly linear response under varying force conditions. The linear fitting correlation coefficients for median voltage, mode voltage, average voltage, and peak voltage are 0.99932, 0.98278, 0.98498, and 0.99511, respectively. This strong linear relationship indicates that sensors packaged with pure epoxy resin exhibit highly stable voltage output and are exceptionally sensitive to changes

in applied force. Notably, under higher force conditions, the voltage output increases significantly, further validating the superior performance of this material in high-load environments. These findings underscore the potential of pure epoxy resin as an effective packaging material for sensors requiring precise and reliable force detection capabilities. Fig. 12b shows that the solvent-based epoxy with a cement ratio of 100:100 exhibits inferior performance in terms of voltage output. Experimental data revealed that the voltage output of this



**Table 3**  
V<sub>max</sub> and ΔR/V<sub>max</sub> of different falling balls.

|                                     | S/C <sub>100</sub> /0-2g  | S/C <sub>100</sub> /100-2g  | W/C <sub>5</sub> /100-2g  | W/C <sub>100</sub> /100-2g  |
|-------------------------------------|---------------------------|-----------------------------|---------------------------|-----------------------------|
| V <sub>max</sub> /V                 | 0.74                      | 0.58                        | 1.47                      | 1.26                        |
| ΔR <sub>80</sub> %                  | 0.558                     | 0.288                       | 0.976                     | 3.135                       |
| ΔR <sub>70</sub> %                  | 0.372                     | 0.192                       | 1.482                     | 1.881                       |
| ΔR <sub>60</sub> %                  | 0.186                     | 0.096                       | 0.988                     | 1.254                       |
| ΔR <sub>80</sub> %/V <sub>max</sub> | 0.75                      | 0.50                        | 0.66                      | 2.49                        |
| ΔR <sub>70</sub> %/V <sub>max</sub> | 0.50                      | 0.33                        | 1.00                      | 1.49                        |
| ΔR <sub>60</sub> %/V <sub>max</sub> | 0.25                      | 0.17                        | 0.67                      | 1.00                        |
|                                     | S/C <sub>100</sub> /0-5g  | S/C <sub>100</sub> /100-5g  | W/C <sub>5</sub> /100-5g  | W/C <sub>100</sub> /100-5g  |
| V <sub>max</sub> /V                 | 1.45                      | 1.28                        | 4.08                      | 4.92                        |
| ΔR <sub>90</sub> %                  | /                         | /                           | 2.726                     | 4.908                       |
| ΔR <sub>80</sub> %                  | 1.168                     | 2.816                       | 1.363                     | /                           |
| ΔR <sub>70</sub> %                  | 0.876                     | 1.281                       | /                         | 3.272                       |
| ΔR <sub>60</sub> %                  | 0.584                     | 0.768                       | /                         | 1.636                       |
| ΔR <sub>90</sub> %/V <sub>max</sub> | /                         | /                           | 0.67                      | 1.00                        |
| ΔR <sub>80</sub> %/V <sub>max</sub> | 0.81                      | 2.20                        | 0.50                      | /                           |
| ΔR <sub>70</sub> %/V <sub>max</sub> | 0.60                      | 1.00                        | /                         | 0.67                        |
| ΔR <sub>60</sub> %/V <sub>max</sub> | 0.40                      | 0.60                        | /                         | /                           |
|                                     | S/C <sub>100</sub> /0-20g | S/C <sub>100</sub> /100-20g | S/C <sub>100</sub> /0-30g | S/C <sub>100</sub> /100-30g |
| V <sub>max</sub> /V                 | 9.70                      | 4.60                        | 16.24                     | 6.88                        |
| ΔR <sub>80</sub> %                  | 3.880                     | 4.600                       | 12.124                    | 10.320                      |
| ΔR <sub>70</sub> %                  | 1.940                     | 2.300                       | 8.120                     | 6.880                       |
| ΔR <sub>60</sub> %                  | /                         | /                           | 8.120                     | 3.440                       |
| ΔR <sub>80</sub> %/V <sub>max</sub> | 0.40                      | 1.00                        | 0.75                      | 1.50                        |
| ΔR <sub>70</sub> %/V <sub>max</sub> | 0.20                      | 0.50                        | 0.50                      | 1.00                        |
| ΔR <sub>60</sub> %/V <sub>max</sub> | /                         | /                           | 0.50                      | 0.50                        |

material was significantly lower than that of pure epoxy resin, particularly under higher force conditions. The linear fitting correlation coefficients were as follows: median voltage ( $r^2=0.9765$ ), mode voltage ( $r^2=0.9578$ ), average voltage ( $r^2=0.97489$ ), and peak voltage ( $r^2=0.96269$ ). The relatively low correlation coefficient for peak voltage suggests that the incorporation of cement substantially reduced the material's sensitivity, resulting in unstable voltage output under high force conditions. This instability may be attributed to the inhomogeneity introduced by the cement, which increased the dispersion of signal output. These findings highlight the detrimental effects of cement addition on the material's performance, particularly in applications requiring high sensitivity and stability under varying force conditions.

The comparative analysis of different epoxy-cement formulations revealed crucial insights into how packaging materials affect sensor sensitivity and signal stability under mechanical loading. Notably, sensors encapsulated with pure solvent-based epoxy demonstrated outstanding linearity and high voltage outputs across varying force levels. In contrast, the significant reduction in output voltage and correlation coefficients observed in the solvent-based epoxy: cement = 100:100 configuration indicates that the addition of cement compromises the homogeneity of the matrix. Cement particles introduce

interfacial defects and microvoids, which can act as charge traps or scattering centers, thereby reducing piezoelectric efficiency and overall signal stability [31,32]. These findings align with previous studies on composite-based sensors, where increased filler content often leads to performance trade-offs between mechanical robustness and signal fidelity [33].

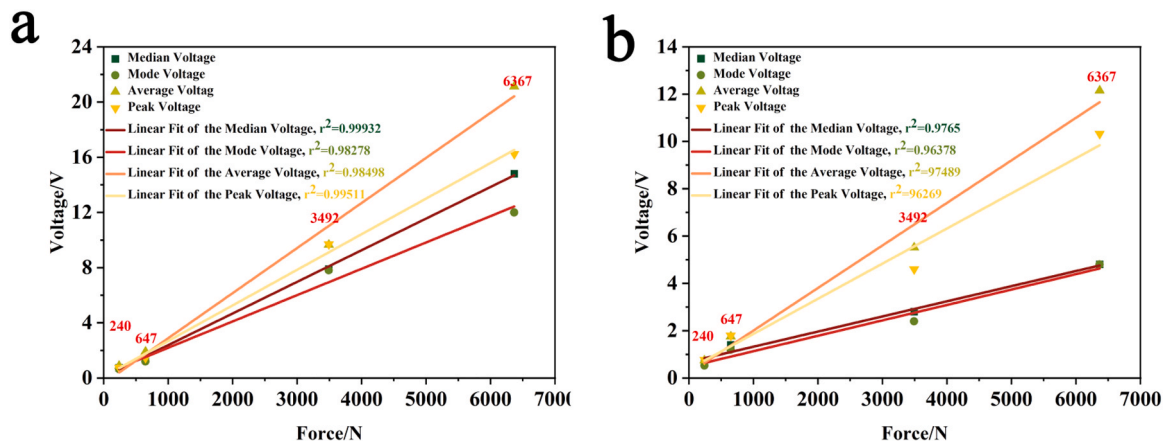
Interestingly, waterborne epoxy systems exhibited different trends: the inclusion of cement enhanced voltage output, despite the formulation's inherently lower performance compared to solvent-based systems. This suggests a fundamentally different interaction mechanism between waterborne epoxy and cement. One possibility is that the cement particles in the waterborne matrix promote a more conductive or stress-sensitive microenvironment, potentially improving stress transfer or local polarization effects. However, the overall sensitivity remained low, indicating limitations in load-bearing applications.

These contrasting behaviors underscore the importance of matrix-filler compatibility and interfacial interactions in sensor packaging materials. While pure solvent-based epoxy offers superior sensitivity and linearity, its brittleness and environmental concerns limit its broader application. On the other hand, waterborne systems are more eco-friendly and compatible with cement, but currently lack sufficient sensitivity. Future research should focus on exploring hybrid formulations, such as incorporating conductive nanoparticles or using modified resins, to enhance both mechanical resilience and signal performance without sacrificing sensitivity [34,35].

The porosity of the encapsulation layer also plays an important role in determining the sensor's output characteristics. Increased porosity within the epoxy-cement composites can reduce the effective stiffness and mechanical impedance of the encapsulating matrix, leading to partial attenuation of the transmitted stress and consequently lower voltage amplitudes. The presence of pores and interfacial voids may also induce local stress scattering and time delays, slightly broadening the response waveform and reducing high-frequency components. On the other hand, moderate porosity can improve strain accommodation and relieve local stress concentrations, which contribute to the stable and repeatable signal generation observed in highly porous waterborne epoxy systems. This balance between stress transfer efficiency and damping explains the observed trade-off between sensitivity and stability across different formulations.

### 3.3. Evaluation of sensor fatigue behavior

To evaluate the long-term electrical stability of sensors under cyclic loading conditions, solvent-based epoxy packaged sensors were embedded within silicate cementitious matrix specimens at a depth of 2 cm from the surface for fatigue testing. A comparative analysis of the



**Fig. 12.** Plot of force versus output voltage converted by the momentum conservation theorem, a) solvent-based epoxy: cement=100:0, b) solvent-based epoxy: cement=100:100.

open-circuit voltage response was conducted during 100,000 loading cycles, as depicted in Fig. 13. Oscilloscope measurements revealed an initial 10,000-cycle peak output voltage of approximately 4.50 V. Following high-cycle fatigue, this peak value exhibited a slight reduction to 4.30 V. Although the oscilloscope exported the voltage waveforms as processed image data rather than uniformly sampled raw signals, the time-domain waveforms exhibited highly stable amplitudes and oscillation periods throughout the fatigue cycles. This consistency strongly indicates that no resonance drift or waveform distortion occurred during

testing. This represents a marginal 4.4 % reduction in peak voltage amplitude, indicating sustained stability and reproducible electrical signal generation. The observed performance demonstrates exceptional fatigue tolerance, with minimal attenuation of the piezoelectric response, thereby satisfying the reliability requirements for high-durability sensors in practical applications.

Furthermore, the fundamental waveform morphology remained consistent before and after cyclic loading, with no discernible waveform distortion or significant increase in electrical signal noise. This

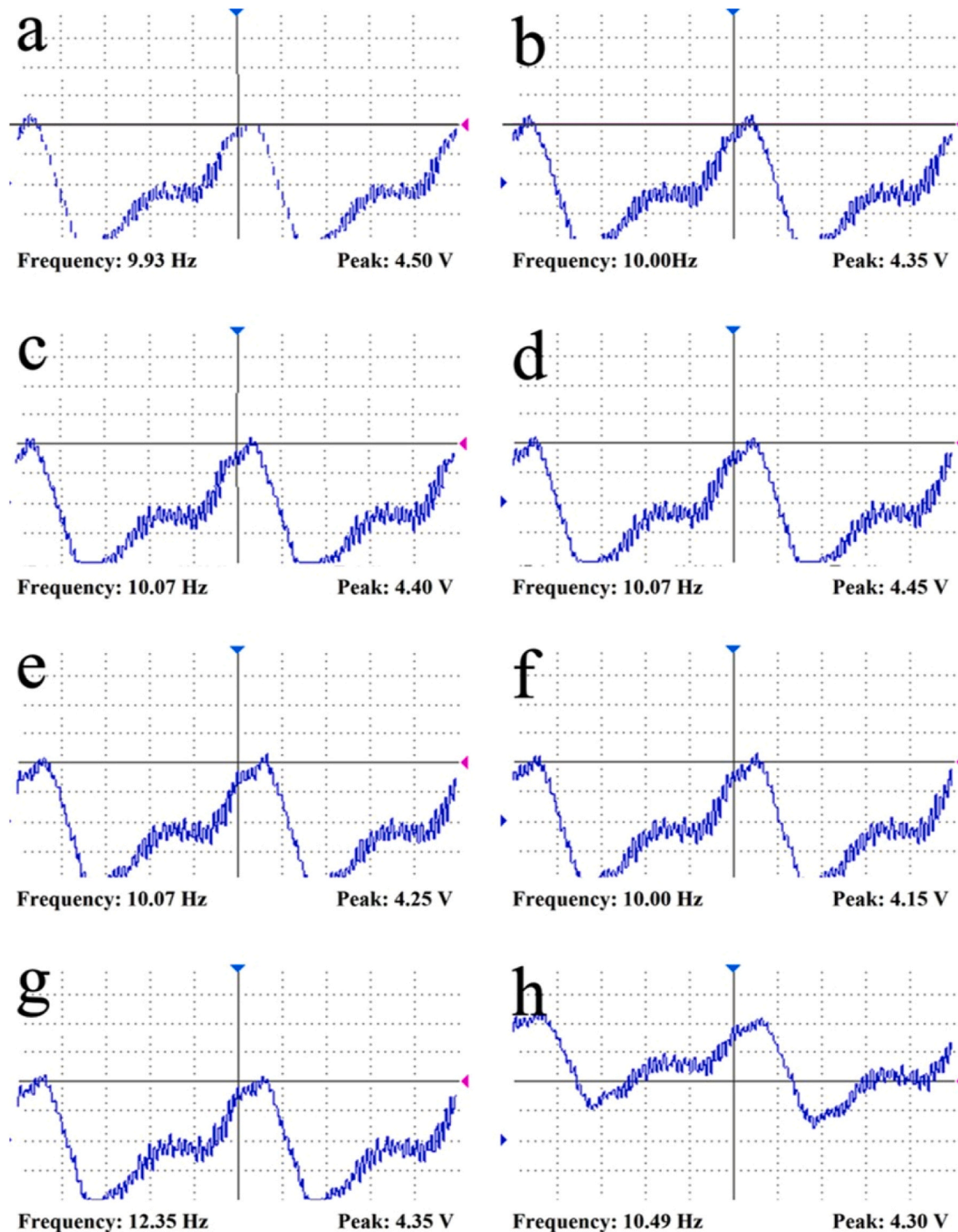


Fig. 13. Waveforms of sensors packaged with solvent-based epoxy embedded in roadbed material with a load of 5 kN, a) 1 cycle; b) 10,000 cycles; c) 20,000 cycles; d) 30,000 cycles; e) 40,000 cycles; f) 60,000 cycles; g) 80,000 cycles; h) 100,000 cycles.

observation further corroborates the structural integrity of the sensor and the stability of its electrode connections under prolonged operational conditions. This robust performance is essential for real-world applications, such as pavements or bridge decks, where sensors are exposed to millions of repetitive stress events over time. A packaging system that maintains signal fidelity under fatigue not only enhances monitoring accuracy but also reduces maintenance frequency, thus lowering lifecycle costs in structural health monitoring systems.

In contrast, although waterborne epoxy resins demonstrated structural vulnerability under high-load conditions, their voltage output was 2–4 times higher than that of solvent-based epoxy formulations. This significant signal enhancement suggests that waterborne systems have great potential in low-to-moderate load environments where sensitivity is prioritized over mechanical robustness. However, their long-term durability under cyclic loading remains underexplored. As such, targeted fatigue studies under appropriate loading conditions are critical to unlocking their full application potential, particularly in smart pavement surfaces or wearable sensing platforms where high sensitivity and environmental compatibility are essential.

The contrasting behaviors of these two resin systems underscore the importance of tailoring sensor encapsulation materials not only for their mechanical resistance but also for electrical performance within specific operational contexts. Future work should expand fatigue testing to include variable load amplitudes, environmental stressors, and multi-material hybridization strategies, such as combining waterborne epoxy with nanofillers or flexible reinforcement phases, to achieve a balanced performance profile.

#### 4. Conclusions and outlook

This study bridges a critical research gap by conducting the first systematic investigation into the packaging of KNN piezoelectric sensors for pavement monitoring applications. Comprehensive evaluation of solvent-based epoxy and waterborne epoxy resin composites incorporating cement revealed fundamentally divergent behaviors. The incorporation of cement into solvent-based epoxy significantly reduces compressive strength, and due to particle agglomeration, the packaged sensors exhibit poor signal reproducibility, with output voltages approximately half those of pure resin under the same applied forces. However, sensitivity and linearity remain unaffected. When waterborne epoxy resin is mixed with cement, the compressive strength exceeds that of both pure cement and pure waterborne epoxy resin at ratios of 1:100, 5:100, and 10:100, reaching a maximum value of 57.8 MPa at a ratio of 5:100. This enhancement is attributed to the waterborne epoxy resin promoting hydration and filling voids. Despite this material system demonstrating high signal output voltage responsiveness, generating 2–4 times higher output voltages than solvent-based epoxy systems, there is a risk of rupture after direct action above 600 N, which limits applications.

In the next stage of research, more attention could be given to adjusting the material composition to better balance mechanical properties and electrical output. For example, adding small amounts of nanomaterials like carbon nanotubes or graphene oxide might help improve particle distribution and make the signal more stable. Since the waterborne epoxy systems responded well at lower loads, it would be worthwhile to test how they perform under repeated stress or long-term loading. At the same time, it's important to observe how the materials behave in outdoor conditions, including temperature changes, moisture, and freezing cycles. These steps could help determine whether the sensors are reliable for long-term use in practical environments.

#### CRediT authorship contribution statement

**Pengfei Liu:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Ning Xie:** Writing – review & editing, Methodology, Investigation. **Kai Zheng:** Writing – review & editing, Writing –

original draft, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Data availability

Data will be made available on request.

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