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Design, fabrication and properties of 1–3 piezoelectric ceramic composites with varied piezoelectric phase distribution

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Abstract

Here the 1–3 connectivity cement/polymer based piezoelectric composites with varied piezoelectric phase distribution were designed. The dielectric, piezoelectric and electromechanical properties of the composites were studied. The results indicate that the composite with varied distribution of piezoelectric ceramic has large relative permittivity, piezoelectric strain constant and electromechanical coupling coefficient at the thickness vibration mode. The composites with varied distribution of matrix phase have larger piezoelectric voltage constant, smaller mechanical quality factor and acoustic impedance value than those with varied distribution of piezoelectric ceramic phase. The electromechanical coupling property of the composites at the planar vibration mode shows obvious dependence on matrix phase distribution. The novel piezoelectric composites show potential applications in fabricating ultrasonic transducers with specific surface vibration amplitude.

Keywords: Smart composite; Cement based material; Piezoelectricity

1. Introduction

With increased number of engineering structures, the structural health monitoring and nondestructive evaluation employing intelligent materials system and structures are also gaining increasingly attention [1–4]. Among various intelligent materials, piezoelectric ceramics are widely used due to their simple structures, fast response speed and good sensing and actuating abilities. However, single phase piezoelectric ceramic materials have obvious problems of coupling compatibility when used in concrete structures, such as poor matching abilities of interface and acoustic impedance between piezoelectric ceramic and concrete materials.

In 2002, Li et al. first fabricated 0–3 piezoelectric composite by using PZT (Lead Zirconium Titanate) ceramic powder as piezoelectric component and cement as matrix [5]. Their research showed that the acoustic impedance of the piezoelectric composite could be compatible with that of concrete by adjusting the proportion of various components. In 2007–2009, Chaipanich et al. studied the influences of doping elements on properties of 0–3 cement based piezoelectric composites aiming to find a method to improve the comprehensive properties of this composite [6,7]. In 2009, Gong et al. fabricated 0–3 cement based piezoelectric composite by using carbon black as modifying component, and studied the piezoelectricity of the composites [8]. The fabrication technology of 0–3 cement based piezoelectric composites is simple, however, their piezoelectric properties are usually poor. Recently, new cement based piezoelectric composites have been developed based on the connectivity of two-phase piezoelectric composites [9]. In 2005, Dong et al. fabricated 2–2 cement based piezoelectric composite and demonstrated its good sensing and actuating capabilities as self-sensing actuator in civil engineering structures [10]. In 2005, Lam et al. fabricated 1–3 cement based piezoelectric composite of different piezoelectric ceramic volume fraction, and studied the electromechanical coupling properties of the composites [11]. In 2012, Xu et al. fabricated

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piezoelectric transducers by using 2–2 and 1–3 cement based piezoelectric composites as actuating elements, and studied their application in cement hydration reaction process monitoring [12].

Recently, many research activities focused on fabrication technology and property analysis of cement based piezoelectric composites have been conducted, however, there is few reports referring to the cement matrix modification, composite structural design and engineering applications etc. It is known that the acoustic impedance of cement based piezoelectric composite could be adjusted to match with that of concrete material, however, because the interfacial boding ability between piezoelectric ceramic and cement matrix is poor due to hydration effects of cement paste, the long-term reliability of cement based piezoelectric composites will inevitably be reduced. It is therefore important to enhance interfacial bonding ability between piezoelectric ceramic and cement matrix for improving the comprehensive properties of the composites. Additionally, it is also of great significance to design novel cement based piezoelectric composite to satisfy the desirable structural health monitoring application in civil engineering field.

It is known that piezoelectric composite can usually be classified into 10 categories based on the connectivity of piezoelectric phase and matrix phase [9], such as 0–3, 1–3 and 2–2. Usually, 1–3 connectivity piezoelectric composite means that one-dimensional piezoelectric ceramic rods arrange uniformly in three-dimensional matrix. Here, novel 1–3 connectivity cement/polymer based piezoelectric composites with varied distribution of piezoelectric phase were designed and fabricated based on the dimensional variations of piezoelectric ceramic and cement/polymer matrix. The epoxy resin which has superior binding characteristic and low acoustic impedance value was especially considered to improve the interfacial bonding ability and acoustic impedance compatibility between cement matrix and piezoelectric ceramic. The composites were fabricated by using PZT ceramic as piezoelectric phase and mixture of cement powder and epoxy resin as matrix phase. The dielectric, piezoelectric and electromechanical coupling properties of the composites were mainly discussed in this research.

2. Experiments

It is known that the piezoelectric transducers made of 1–3 connectivity piezoelectric composite which has uniform distribution of piezoelectric phase and matrix phase will also produce uniform amplitude of surface vibration [13]. Nevertheless, the piezoelectric composite which has varied distribution of piezoelectric phase or matrix phase can be designed based on their dimensional variations in the composites. Therefore, the piezoelectric, dielectric and electromechanical coupling properties of the composites will correspondingly take specific distribution due to the varied distribution of piezoelectric phase in the composites. It is known that piezoelectric composites of large piezoelectric ceramic volume fraction have stronger piezoelectric effects than those of small piezoelectric ceramic volume fraction, thus the piezoelectric transducers with specific distribution of surface vibration amplitude could be tailored by using the piezoelectric composites of varied distribution of piezoelectric ceramic volume fraction.

2.1. Design of the piezoelectric composites

The 1–3 connectivity piezoelectric composites with piezoelectric ceramic rods of varied dimension were designed. Fig. 1(a) is the composite with piezoelectric ceramic rods of homogeneous distribution, and Fig. 1(b)–(d) are the composites which have the varied dimension of piezoelectric ceramic rods. The unit cell of the piezoelectric composites is illustrated as Fig. 2, nevertheless, all the piezoelectric composites finally end up with the piezoelectric phase rather than matrix phase due to the practical fabrication factors, as shown in Fig. 1.

Assuming that the spacing between the piezoelectric ceramic rod, which is denoted as the symbol d, is the same in the x-y plane. The general formula of the dimension of all piezoelectric ceramic rods along x and y direction of the composites can be expressed as matrix $\boldsymbol{X}$ and $\boldsymbol{Y}$, respectively.

$$\boldsymbol{X}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}, \boldsymbol{Y}=\begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix}$$

where m and n represent the line and column number of the piezoelectric ceramic elements along y and x direction of the composite, respectively. Additionally, the piezoelectric ceramic elements in each column of matrix $\boldsymbol{X}$ are the same, and those in each line of matrix $\boldsymbol{Y}$ are the same.

As for the composite of Fig. 1(a), because all piezoelectric ceramic rods have the same cross-section dimension, the

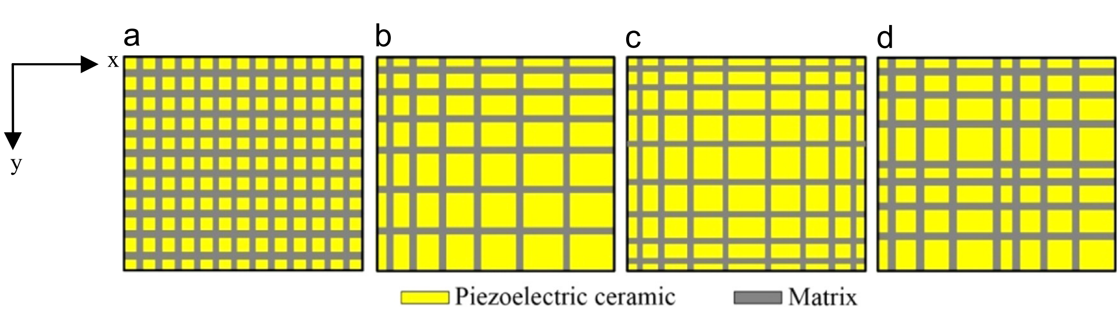

Fig. 1. Schematic of the 1–3 piezoelectric composite with different distribution of piezoelectric ceramic rods.