Construction and Building Materials 134 (2017) 585–593

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Performance investigation of cement-based laminated multifunctional magnetoelectric composites

Cuijuan Pang [a], Huafu Pei [b,*], Zongjin Li [a]

[a] Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[b] Department of Geotechnical Engineering, Dalian University of Technology, State Key Lab of Coastal and Offshore Engineering, Dalian, PR China

HIGHLIGHTS

- Cement-based magnetoelectric composite has been firstly successfully developed.
- Composite exhibits a brand new magnetoelectric coupling effect as expected.
- The best magnetoelectric performance ever found in the same category of composite.

ARTICLE INFO

Article history:
Received 7 September 2016
Received in revised form 29 November 2016
Accepted 29 December 2016
Available online 5 January 2017

Keywords:
Magnetoelectric
Composite
Cement
Magnetostrictive
Piezoelectric
FBG

ABSTRACT

In this paper, cement-based multifunctional magnetoelectric (ME) composite with the laminated structure of one lead zirconate titanate (PZT) layer sandwiched between two cement-based $Tb_{1-x}Dy_xFe_2$ alloy (Terfenol-D) layers has been successfully fabricated for the first time in the world. Furthermore, systematic investigation has been conducted on the overall performance of this newly developed composite. The dielectric and piezoelectric behaviors of this composite are equivalent to those of pure PZT, which dominates the ferroelectric properties of composite. A giant ME response is observed in the composite because of the strong mechanical coupling interaction among different phases detected by fiber Bragg grating sensing technique. The measured maximum ME sensitivity α_{E33} can reach up to 1.071 V/cm Oe under 3000 Oe H_{dc} field at low frequency with $f_v = 0.30$ of Terfenol-D in the composite, which is much superior to that of other polymer-based composites (just about 200–300 mV/cm·Oe) reported. Such great ME sensitivity can be attributed to that cement functions not only as particles binder, but also as the transmission medium with higher transfer efficiency. Such excellent performances make this novel ME composite be a strong potential candidate for engineering applications as sensors, actuators and other smart transducers.

1. Introduction

Functional composites, which have been utilized in intelligent devices applied in infrastructure and construction, have been studied and developed for a long time with worldwide considerations. From late of twentieth century, optimally synthesizing the desirable properties of different phases in a composite combining the most sensitive parameters in a form had become a superior for practical applications [1]. More and more attentions have been attracted in property research of piezoelectric and magnetostrictive techniques, and applied successfully and effectively in smart monitoring structure in the past decades. Therefore, it is very natural to consider mixing these two practical properties of materials to develop a multifunctional composite, which named the magnetoelectric (ME) composite, not only performing both of improved piezoelectric and magnetostrictive property of each phase, but also exhibiting a product ME property, which is not found in neither single phase [2–5].

The primary operation principle of this extrinsic ME property is based on the ME effect, which is manifested as the dielectric polarization response to an applied magnetic field or conversely an induced magnetization to an external electric field [6]. The polarized or magnetized reaction results from the mechanical coupling interaction between the piezoelectric and magnetostrictive phases (denoted as P and M phases): when the ME composite is subjected to a bias and an alternative magnetic field, which causes the mechanically strain in M phase, then this strain induces the stress passed along to the P phase, which generates the electric field as it is electrically polarized. The converse effect is also realized. ME

* Corresponding author.
E-mail address: huafupei@dlut.edu.cn (H. Pei).

http://dx.doi.org/10.1016/j.conbuildmat.2016.12.194
0950-0618/

effect has also been found as an intrinsic effect in single crystals (such as antiferromagnetic Cr_2O_3, $TbFeO_3$ and $Fe_xGa_{2-x}O_3$) [7,8], but few of them can be successfully applied in actual engineering fields due to several limitations: few categories discovered, weak ME response and rather low Curie temperatures much lower than room temperature [9]. As a workable solution, the ME composite is experimentally verified presenting far enhanced ME property by tens to a hundred orders of magnitude than the monophasic ME material [10].

In addition, it is reported that one piezoelectric ceramic smart composite integrating lead zirconate titanate (PZT) in cement matrix has been successfully processed and realizably applied in real civil engineering, which have been fabricated firstly and developed over the past ten years at HKUST [11–16]. This cement-based piezoelectric composite holds the special suitability of applications as actuators, sensors and transducers used in civil engineering because of its significant interface compatibility in acoustic impedance, temperature coefficient and volume stability with concrete, the most popular construction material [17]. The accurate and reliable monitoring output signals can be ensured by a good compatibility in acoustic and electric-mechanical properties. The higher stiffness of cement matrix compared with that of polymer materials makes it more beneficial for mechanical deformation transmission. Besides, this special cement-based composite shows outstanding durability with equivalent service life of that of concrete. Consequently, based on the previous experience of preparing cement-based composites, to explore a novel type of multifunctional ME composite incorporating functional material in cement matrix on purpose of utilizations in cement or concrete structures is the principal objective of this work. This cement-based ME composite is expected to be effective and applicable in piezoelectric, magnetostrictive, ME properties and compatibility for potential applications as transducers, sensors and smart components to monitor real-time strain and stress states, and degree of performance deterioration in construction materials and structures or corrosion situation of in-service reinforcements in concrete structures [18]. Furthermore, the responsivity, sensitivity and stability of composite also need to be achieved for more reliable applications.

Our present work focuses on the investigation of 2-2 type cement-based laminated ME composites, where both the cement-based M and P phases are two dimensionally connected. In this paper, the fabrication process of ME composite composed of the sandwich structure of two cement-based magnetostrictive rare-earth-iron alloy $Tb_{1-x}Dy_xFe_2$ (Terfenol-D) layers and one PZT layer in the middle with simple bonding is provided in detail, and the corresponding microstructure, dielectric, piezoelectric, magnetic, magnetostrictive and direct ME properties are investigated. A full evaluation of the overall performance of such a ME composite can validate the feasibility and efficiency of potential applications in practical civil engineering.

2. Materials and experiment

In the cement-based laminated ME composites, the commercial P-5H lead zirconate titanate (PZT) ceramic plates (Hong Kong Functional Ceramic Co. Ltd.) were chosen as the P phase since the desirable piezoelectric property. The size of PZT plates remained 20 mm × 25 mm × 0.35 mm. Silver paint was coated over the side surfaces of plates to form smooth electrodes, and the polarization orientation was along the thickness direction (denoted as the 3-axis of the plate). Considering the excellent magnetostriction, rare-earth-iron alloy (Terfenol-D) with giant magnetostrictive effect (GME) was one of the most ideal choice for M phase because of its high magnetostriction and coupling factor. The $Tb_{0.3}Dy_{0.7}Fe_{1.92}$ powders (ETREMA Products, Inc.) with the average particle size of 38–106 μm and Portland cement (H.S.L. Enterprises Co. Ltd.) were used to fabricate the cement-based magnetostrictive layers (C-M layers). In the C-M layer, cement just acted as the inactive matrix binder and connected with Terfenol-D particles. The basic properties of the PZT layer, Terfenol-D and cement are listed in Table 1.

Firstly, Terfenol-D powders and cement with certain volume fractions were well mixed using a normal mixing method (mixing duration is about 10 min) until the mixture became sufficiently uniform without any agglomeration found. After mixing, the weighted mixture (approximately 1 g per sample, increasing a little with the increase of M phase fraction to ensure the same thickness of every sample) was molded in a stainless steel mould under high pressure (maximum load is 40 kN holding for 1 min, controlled by 810 Material Testing System) to form a consolidated disk with 14 mm in diameter and around 1 mm in thickness. Then the disk casts needed to be steam cured in the standard curing room at a temperature of 60 °C for 24 h to accelerate the hydration process of cement matrix. There were total five groups of mixing proportion prepared, in which the fraction of Terfenol-D gradually increased, meanwhile the cement decreased, while the PZT layers were kept the same for performance comparison. The mixing proportions of each group of cement-based ME composites are listed in Table 2. Following, two machined C-M layers of each group with the same PZT layer in the middle (M-P-M structure) were laminated and simply bonded together using conductive silver epoxy. Finally, the positive and negative poles of intertwined electric wires were directly connected to the corresponding electrodes of PZT layer for measurement, which is more benefit for output signal collection, avoiding considerable signal transmission loss happened through other phases or boundaries of different layers. The schematically illustration of this sandwich structured cement-based ME composites can be seen in Fig. 1.

For microscopic analysis, the particles distribution as well as interface between Terfenol-D and cement of the prepared C-M layer were measured by scanning electron microscopy (SEM, JSM 6300F, JEOL). For dielectric property, capacitance of the cement-based ME composite was measured by an impedance/gain-phase analyzer (Model 4294A, Hewlett Packard, Tokyo, Japan) to calculate dielectric constant. The piezoelectric strain factor d_{33} of the composites was measured by using a d_{33} meter (Model ZJ-3B, Institute of Acoustics Academia Sinica, China). The magnetic hysteresis loops of C-M layers were measured by vibrating sample magnetometer (VSM, Model 7307 American Lakeshore Co.) to probe the magnetic saturation situations. A special fiber Bragg grating (SM125 Micron Optics Inc.) sensing technology was applied to monitor the magnetostrictive strains in C-M layers transferred to

Table 1
Basic properties of phase materials.

Parameters	PZT	Terfenol-D	Cement paste
Piezoelectric strain factor, d_{33} (10^{-12} C/N)	600	–	–
Piezoelectric voltage factor, g_{33} (10^{-3} Vm/N)	30.8	–	–
Dielectric constant, ε_r (at 1 kHz)	2200	10	56
Electromechanical coupling factor, K_p	0.63	0.75	–
Mechanical quality Q_m	46	–	–
Elastic compliance s_{33} (10^{-12} m^2/N)	16.7	40	72
Density, ρ (10^3 kg/m^3)	8.46	9.17	2.00
Acoustic velocity V (10^3 m/s)	2.66	1.94	2.64
Acoustic impedance $Z = \rho V$ (10^6 kg/m^2 s)	22.50	17.79	5.3
Curie Temperature T (°C)	200	380	–
Magnetostrictive Strain λ (με)	–	800–1200	–
Energy Density w (kJ/m^3)	–	14–25	–
Resistivity ρ (Ohm·m)	6400	58 × 10^{-8}	20