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Effect of Pozzolanic Materials and Poling Field on Electromechanical Coupling Coefficient of Cement-Based Piezoelectric Composites

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Abstract. Electromechanical coupling coefficient of cement-based piezoelectric composites affected by pozzolanic materials and poling field are investigated. Specimens, through a pressure approach, are manufactured by combining PZT powders and cement-based binder with the same volume fraction. Pozzolanic materials including fly ash, slag and silica fume replace 20% cement in the binder. Three poling fields are considered to induce piezoelectricity of 0-3 cement-based composites. Results show that electromechanical coupling coefficients do not have many fluctuations in terms of material ages for any cement-pozzolanic piezoelectric composites. With the same volumetric substitutes of pozzolanic materials, the electromechanical coupling coefficient with pozzolanic materials except fly ash is lower than that with plain cement, especially for silica fume having a 7.9% decrease. Raising poling field can increase electromechanical coupling coefficients. Polarization of cement-based piezoelectric composites containing silica fume in low poling fields such as 0.5kV/mm and 1kV/mm is not easy to complete.

Introduction

Piezoelectric composites consisting of piezoelectric ceramics and cement have been attracted considerable attention more than ten years [1-6]. For applications of sensors and actuators in civil engineering structure, 0-3 cement-based piezoelectric composites developed to overcome the matching problem that traditional piezoelectric ceramics or polymers do not contact synchronously with concrete [7-9].

For 0-3 cement-based piezoelectric composites, most literatures have discussed the piezoelectric and dielectric properties affected by volume fraction and particle size of piezoelectric ceramics, poling time, poling temperature, poling field, curing time, the thickness and the forming of specimens [1,3,4,7-14]. For the properties of piezoelectricity, the thickness electromechanical coupling coefficient K_t on cement-based piezoelectric composites has less concerned.

Electromechanical coupling coefficient is a measure of the conversion efficiency between electrical and acoustic energy in piezoelectric materials. To enhance the electromechanical coupling coefficient of cement-based piezoelectric composites is important for the applications of engineering and energy. Researches [6,11] indicated that increasing volume fraction of piezoelectric ceramics in cement-based piezoelectric composites, such as lead zirconate titanate (PZT), can raise K_t. Electromechanical coupling coefficient also depends on forming pressure of specimens. While the applied forming pressure increases on the specimen, K_t will decrease [12]. In the polarization, high poling voltage, temperature and time applied to the composites are beneficial for K_t [8]. Chaipanich and Jaitanong [13] found that K_t approached to the optimum state at poling time of 45 minutes, and became lower for exceeding 45 minutes. Gong et al [15] pointed out that adding 0.4 vol % carbon black into 0-3 cement-based composites can obtain the maximum value of K_t.

Pozzolantic materials, such as silica fume, slag and fly ash, are commonly used in concrete to enhance the strength and durability. The dielectric and piezoelectric properties of cement-based piezoelectric composites containing pozzolantic materials are seldom studied [16]. It is interesting to investigate the effect of pozzolantic materials and poling voltage on electromechanical coupling coefficient of cement-based piezoelectric composites here. In this work, four cement-based binders of the composites containing 100% cement (PC), 20% replaced by silica fume (SF), 20% replaced by blast furnace slag (SL) and 20% replaced by fly ash (FA) in volume were investigated.

Experiments

The 0-3 cement-based piezoelectric composites consists of 50% PZT and 50% cement-based binder in volume. The particle diameter of PZT is 75~150 μm with specific gravity of 7.9. Cement is type I Portland cement with the fineness of 349m^2/kg and specific gravity of 3.16. The specific gravity, particle diameter and the fineness of silica fume are 2.2, 0.15 μm and 20,000m^2/kg, in turn. Blast furnace slag was produced from CHC Resources Corporation (Taiwan), where the fineness is 572m^2/kg and the specific gravity is 2.87, respectively. F type fly ash produced by Hsinta thermal power plant was also used, where the fineness is 326m^2/kg and the specific gravity is 2.11. The main chemical components are shown in Table 1.

Table 1. Main chemical components of materials.

chemical components	cement	silica fume	slag	fly ash
SiO_2 (S)	21.24	95.01	33.36	46.26
Al_2O_3 (A)	4.44	-	14.19	19.47
Fe_2O_3 (F)	3.44	-	0.37	5.72
CaO	64.51	-	42.63	4.90
MgO	2.35	-	5.80	1.53

PZT power was drily mixed with four binders to produce mixed materials. Then the mixed materials were pressed into disks of 15mm diameter and 10mm thickness under 80 MPa for 3minutes. The specimens were put in a curing room with a temperature of 90˚C and relative humidity of 100% for 7 days before polarizations. After curing, the surfaces of the disks were polished to 2mm ± 0.05mm thickness, and coated with silver paint baked 30 minutes at 150˚C. The poling was carried out three poling voltages of 0.5, 1 and 1.5kV/mm each, in a stirred silicone oil bath. The poling temperature and time are 150˚C and 45 minutes respectively. During the polarization, voltage increase was applied stably to prevent from current breakdown of the specimens.

After poling, the composites were aged for 24 h prior to the measurements. We use impedance analyzer to measure frequency at minimum impedance f_m and frequency at maximum impedance f_n, and follow [11]

$$K_t^2 = \frac{\pi}{2}\frac{f_m}{f_n}\tan\left(\frac{\pi}{2}\frac{f_n - f_m}{f_n}\right) \tag{1}$$

to calculate the thickness electromechanical coupling coefficient K_t.

Results and Discussion

Material Age Effect. We measured the impedance spectra of the composites subjected to 1.5kV/mm at the 0 day, 10th, 14th and 28th days for four kinds of composites, shown in Figs. 1 ~ 4. The results on the impedance of four cement-based piezoelectric composites show that the measured values of impedance decrease with the material ages. Obviously, the impedances after 10 days become stable because the hydration products gradually complete filling the pore in the composites.

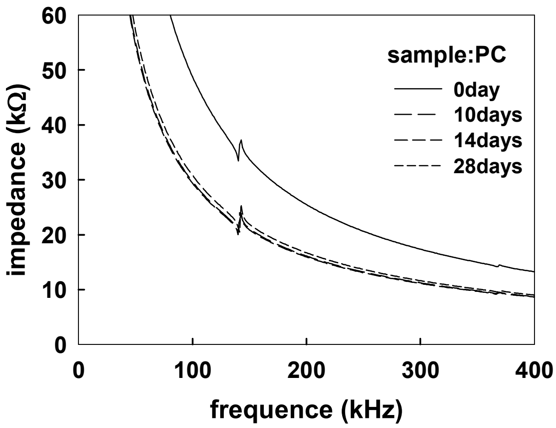

Fig. 1 Age effect for PC materials

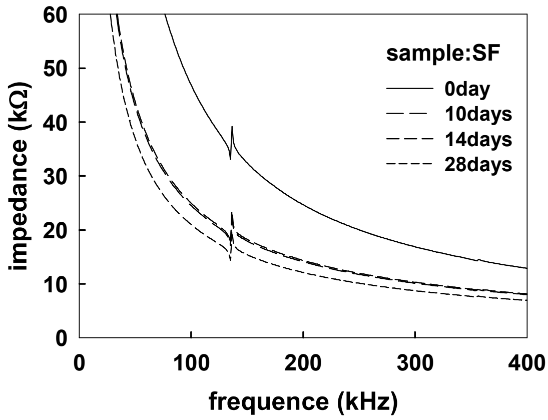

Fig. 2 Age effect for SF materials

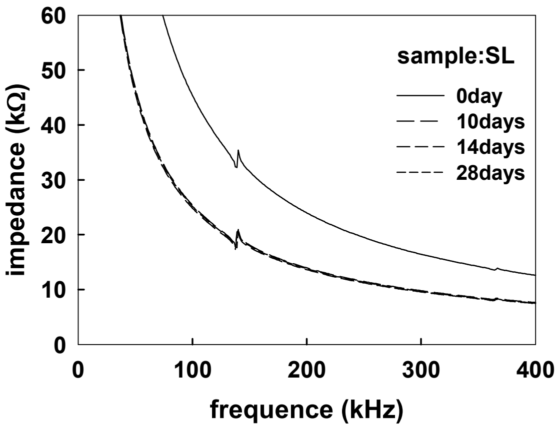

Fig. 3 Age effect for SL materials

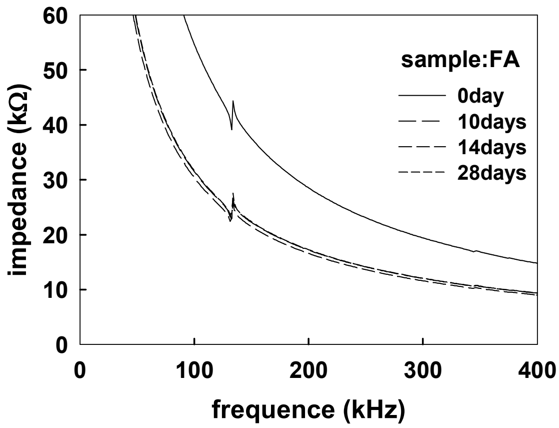

Fig. 4 Age effect for FA materials

From the impedance spectra and Eq. (1), we calculated the electromechanical coupling coefficient for four composites, shown in Fig. 5. Although the impedance spectra alter with the materials ages, the fluctuations of K_t are small. The electromechanical coupling coefficient is independent of the material age.

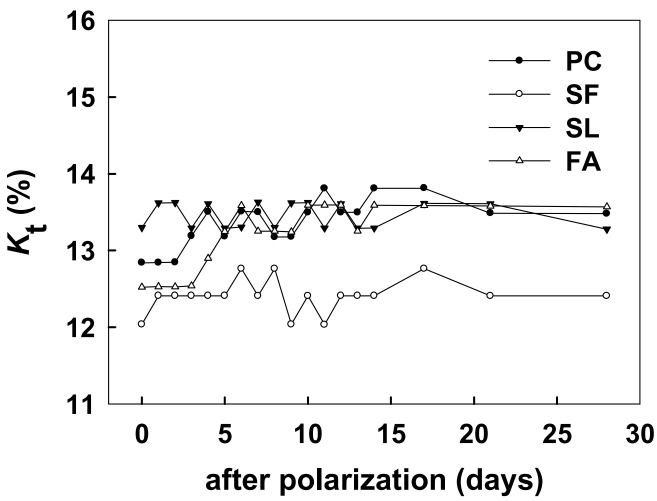

Fig. 5 Electromechanical coupling coefficient vs. material ages

Pozzolanic Materials Effect. To compare the effect of pozzolanic materials, we applied the poling voltage of 1.5kV/mm to the composites and calculated K_t at 28 days, shown in Table 2. The electromechanical coupling coefficient of FA (fly ash inside the composite) is 13.58%, higher than the others materials. However, the K_t values of the composites containing slag (SL) and silica fume (SF) are both lower compared with PC (without any pozzolanic materials), especially for silica fume-cement piezoelectric composite with 7.9% reduction.

Table 2. Electromechanical coupling coefficient at 1.5kV/mm.

coefficient	PC	SF	SL	FA
K_t (%)	13.48	12.41	13.27	13.58

Poling Field Effect. Three poling voltages, 0.5kV/mm, 1.0 kV/mm and 1.5kV/mm, were applied to the composites. Results of K_t after the polarization of 24 hours (0 day) are shown in Table 3, where PZT is the 100% piezoelectric ceramic. The K_t values for all materials shown in Table 3 increase with increasing poling voltages. This result coincides with Dong et al [8].

Table 3. Electromechanical coupling coefficients for 24 hours after the polarization [%].

poling voltage	PC	SF	SL	FA	PZT
0.5 kV/mm	12.77	10.89	12.53	12.47	18.26
1.0 kV/mm	13.40	12.5	13.17	12.9	54.05
1.5 kV/mm	13.65	12.5	13.45	13.58	55.81

From the relation between impedance spectra and poling fields shown in Figs. 6~9, the resonant frequency and anti-resonance frequency of the composites become obvious if the poling voltages increase. Table 4 is the frequency at the minimum and maximum impedances of four piezoelectric composites under different poling voltages. The composites containing silica fume (SF) show no obvious the resonant frequency and anti-resonance frequency under 0.5kV/mm and 1kV/mm, shown in Fig. 7 or Table 4. The polarization for the composites with silica fume is not completed when the lower poling voltages are applied. Therefore, the minimum poling fields to successfully achieve the polarization will not be the same for the cement-based piezoelectric composites containing pozzolanic materials. The poling field and the additions control the electromechanical coupling coefficient of cement-based piezoelectric composites, but the material ages do not.

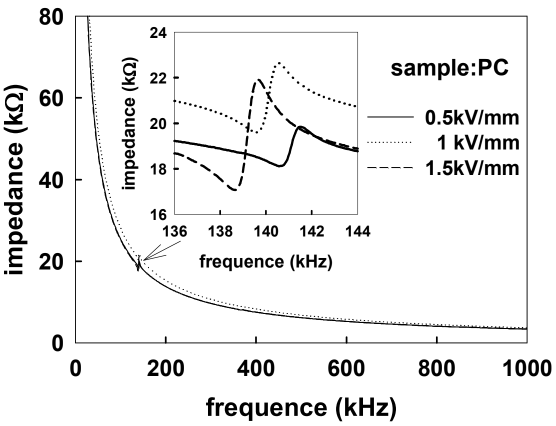

Fig. 6 Poling effect for PC materials

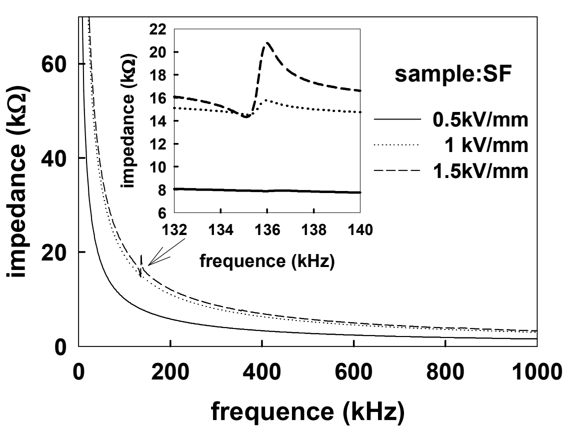

Fig. 7 Poling effect for SF materials

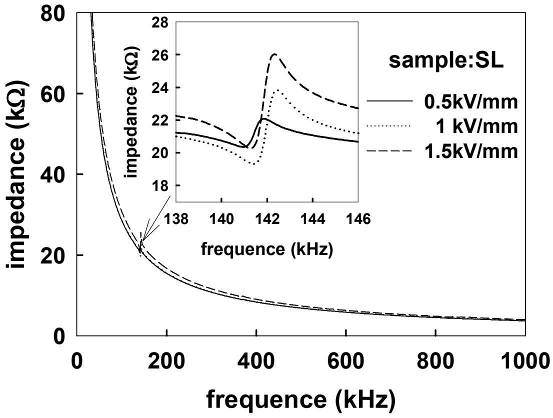

Fig. 8 Poling effect for SL materials

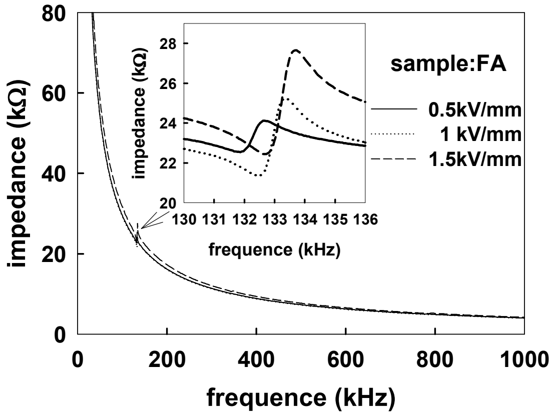

Fig. 9 Poling effect for FA materials

Table 4. Frequency at minimum and maximum impedance [kHz].

poling voltage	frequency	PC	SF	SL	FA
0.5 kV/mm	f_m	140.573	135.980	140.975	131.869
	f_n	141.477	136.583	141.829	132.623
1.0 kV/mm	f_m	139.578	135.176	141.427	132.472
	f_n	140.533	135.980	142.432	133.377
1.5 kV/mm	f_m	138.623	135.126	141.276	132.673
	f_n	139.628	135.980	142.332	133.678

Conclusions

We considered the effect of pozzolanic materials and poling fields to the electromechanical coupling coefficient of the 0-3 cement-based piezoelectric composites by the pressure method. After the tests, we conclude the results as follows.

(1) The fluctuations of the electromechanical coupling coefficient are pretty small with increasing the material ages for the cement piezoelectric composites with or without pozzolanic materials.
(2) The electromechanical coupling coefficients of cement piezoelectric composites containing pozzolanic materials except fly ash are less compared with the PC composite. The reduction of K_t for adding slag and silica fume is 1.6% and 7.9%, respectively.
(3) Increasing poling field is effective to the electromechanical coupling coefficient.
(4) The cement-based piezoelectric composites containing silica fume need higher poling voltages to induce the piezoelectric properties.

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