Chapter 77
Piezoelectric Properties of Cement-Based Piezoelectric Composites Containing Fly Ash

Huang Hsing Pan, Chang-Keng Chiang, Rui-Hao Yang and Neng-Huei Lee

Abstract Piezoelectric properties of 0–3 type cement-based piezoelectric composites with fly ash are investigated, where the piezoelectric inclusion is PZT, and the binder consists of cement and fly ash. Cement was replaced by fly ash from 10 % to 50 vol.% in the binder. Experimental results indicate that all fly ash/cement piezoelectric composites can be successfully polarized. Prior to polarization, relative dielectric constant ε_r increases with fly ash, but diminishes with curing time. Piezoelectric properties are stable at the 50th day after the polarization. Curing time is not sensitive to piezoelectric properties, but polarizing voltage is. A 20 vol.% replacement of cement by fly ash in cement-based piezoelectric composite with 50 vol.% PZT reaches a maximum value of 54 pC/N and 28×10^{-3} V-m/N for d_{33} and g_{33}, respectively.

Keywords Cement · Piezoelectricity · Fly ash · Curing · Polarization

77.1 Introduction

Sensors and actuators installed in civil engineering structure are usually made by piezoelectric ceramics and polymers. Among piezoelectric materials, lead zirconate titanate (PZT) is a ceramic with higher piezoelectric strain factor (d_{33}) that have been used in, such as, ceramic micro-electro-mechanical systems (C-MEMS), ultrasonic generators, ferroelectric thin films and small actuators.

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To overcome the matching problem in concrete structures that conventional sensors and actuators do not contact simultaneously with concrete, 0–3 type cement-based piezoelectric composites have been developed since last decade [1–7]. Common 0–3 type cement-based piezoelectric composites (PZT/cement composites) consist of cement binder as the matrix and randomly oriented PZT particles as the inclusion. To create piezoelectricity, we need to apply poling voltage to PZT/cement composites. No piezoelectric properties are found without the polarization.

Many factors affect the dielectric and piezoelectric properties of 0–3 type cement piezoelectric composites. Currently, PZT/cement composites containing PZT from 20 to 90 vol.% can be manufactured by pressure forming. The effect of volume fraction and particle size of piezoelectric ceramics was discussed [8–10]. The other factors such as poling time [11], poling temperature [12], poling field [13], the thickness and the forming of specimens [4, 14–16] were also investigated. To produce higher piezoelectric strain factor (d_{33}), adding carbon black into 0–3 type cement-based composites was reported [17], and adding 80 vol.% nano-PZT powder can obtain $d_{33} = 53.7$ pC/N [7].

Dielectric and piezoelectric properties of PZT/cement composites containing pozzolanic materials were rarely reported until a PZT-silica fume cement composite was conducted, where 5–10 wt.% silica fume were added [10]. Recently, d_{33} value up to 70 pC/N for 60 vol.% PZT and 20 wt.% silica-based replacement in cement was manufactured at 38 aging days [18]. No piezoelectric properties of PZT/cement composites containing fly as were investigated previously.

In this study, we focus on PZT/cement composites containing fly ash, and examine the influence of age effect including curing time and aging time after the polarization. Cement-based piezoelectric composites containing 50 vol.% PZT and partial cements were replaced by fly ash with 10–50 vol.% in the binder.

77.2 Materials and Experiments

PZT ceramics (piezoelectric inclusion) are randomly oriented in cement-based binders (matrix) to form a 0–3 type PZT/cement composite. The diameter of PZT particle is 75–150 μm, with a specific gravity of 7.9, $d_{33} = 470$ pC/N, piezoelectric voltage factor (g_{33}) of 24×10^{-3} V-m/N, and relative dielectric factor (ε_r) of 2100. Cement is type I Portland cement with the fineness of 349 m^2/kg and specific gravity of 3.16. Fly ash belongs to Class F produced by Hsinta thermal power plant (Taiwan) with a fineness of 326 m^2/kg and specific gravity of 2.11.

Six kinds of PZT/cement composites are made. The composite denoted by PP is a cement-based piezoelectric composite with 50 % PZT and 50 % cement by volume, and no PZT found in PP is named as PC (100 % cement). PP material containing fly ash is referred as FA groups. There are five replacements of cement by fly ash in PP material from 10 to 50 %, for example, FA10 represents 10 vol.% of cement replaced by fly ash in the binder, and FA50 is a 50 % replacement of fly ash.

PZT powders, cement and fly ash were pre-mixed without adding water. The mixture was placed in a cylindrical steel mold of 15 mm in diameter, and then applied by a compressive stress of 80 MPa for 5 min to form a disk-like shape. Before the polarization, specimens were cured in 90 °C and relative humidity of 100 % for 7, 28 and 56 days (curing time), respectively. After curing, specimens were polished to 2 mm in thickness, coated by silver paint as an electrode, and then, baked at 150 °C for 30 min in oven. During the polarization, the specimen was subjected to three poling voltages, 0.5, 1.0 and 1.5 kV/mm, respectively, in a 150 °C silicone oil bath for 30 min (polarizing time).

After the polarization, specimens were placed in the air for 24 h and measured piezoelectric and dielectric properties based on aging time. Piezoelectric strain factor d_{33} was directly measured by d_{33} Piezometer, and other piezoelectric properties were captured by Impedance Phase Analyzer. Each experimental value shown as follows is an average of three specimens, and was measured at 24 °C and 50 % humidity condition.

77.3 Results and Discussion

77.3.1 Properties Before Polarization

Cement-based composites do not have piezoelectric properties unless the addition of piezoelectric inclusions and a successful polarization [1, 4, 11, 16]. Prior to the polarization, electric properties including capacitance (C), dielectric loss (D) and relative dielectric factor ε_r were measured and calculated.

Table 77.1 displays the capacitance of PC, PP and FA-group materials. Capacitance gradually decreases as curing time increases. FA-group materials with increasing fly ash always have a higher capacitance, compared with PP material. While the content of fly ash greater than 30 vol.% in the binder, the capacitance of PZT/cement composites raises tremendously.

Materials with high dielectric loss are difficult to be polarized, and easy to induce current breakdown in the specimen during the polarization. Table 77.2 indicates that cement-based materials at longer curing time own the lower dielectric loss. PC materials (pure cement) cannot be polarized due to a higher D, and lead to no piezoelectric properties. Compared with PC material, dielectric loss of PP and FA-group materials is lower.

Before the polarization, relative dielectric factor ε_r of cement-based composites is shown in Table 77.3. The development of ε_r is similar to the capacitance in Table 77.1, so that increasing curing time will reduce ε_r. Cement containing PZT (PP material) has the lowest ε_r, and continues to develop with increasing fly ash. Obviously, relative dielectric factors of FA40 and FA50 material are dramatically high, compared with the others materials.

Table 77.1 Capacitance before the polarization (unit: pF)

Curing time	PC	PP	FA10	FA20	FA30	FA40	FA50
7 days	108	75	84	95	165	644	742
28 days	80	70	78	87	158	466	552
56 days	56	68	74	71	121	285	398

Table 77.2 Dielectric loss before the polarization

Curing time	PC	PP	FA10	FA20	FA30	FA40	FA50
7 days	0.94	0.21	0.31	0.39	0.49	0.68	0.73
28 days	0.85	0.20	0.27	0.37	0.43	0.62	0.71
56 days	0.76	0.19	0.25	0.34	0.39	0.51	0.69

Table 77.3 Relative dielectric factor before the polarization

Curing time	PC	PP	FA10	FA20	FA30	FA40	FA50
7 days	138	96	107	121	165	824	949
28 days	102	90	100	111	158	596	706
56 days	72	86	95	91	121	365	508

77.3.2 Piezoelectric Properties

Polarizing voltages applied to PZT/cement composites to create piezoelectric properties as the curing time reached. After the polarization, specimens were measured daily until 60 days. To discuss aging effect (the time after polarization), results of piezoelectric properties are shown in Figs. 77.1, 77.2, 77.3, 74.4, 75.5, 77.6 for the material undergone 1.5 kV/mm at 7 and 56 curing days.

Figures 77.1 and 77.2 show relative dielectric factor of PP and FA-group materials at 7 and 56 curing days respectively. Relative dielectric factors increase with aging time, and the growth of ε_r displays less fluctuant after the polarization of 50 days, where ε_r values are between 150 and 200. From Figs. 77.1 and 77.2, choosing the day after the polarization of 24 h to determine ε_r is not adequate because of rapid variations of the property at early age. After the polarization of 50 days, increasing fly ash to PP material will diminish ε_r no matter what curing day is, and this trend is different from that prior to polarization in Table 77.1.

Piezoelectric strain factor d_{33} and piezoelectric voltage factor g_{33} are important piezoelectric properties for sensors and actuators. Aging effect for d_{33} and g_{33} are shown in Figs. 77.3, 77.4, 77.5, 77.6, where d_{33} and g_{33} are on the increase with aging time. Figure 77.3 shows d_{33} at 7 curing days, and d_{33} values of PP (with 50 % PZT) are 18, 40, 43 and 44 pC/N at aging time of 0, 21, 28 and 60 days respectively. It seems that adding fly ash to PP material does not increase d_{33} except for FA10 and FA20 material after 40 days. d_{33} values of FA20 material are

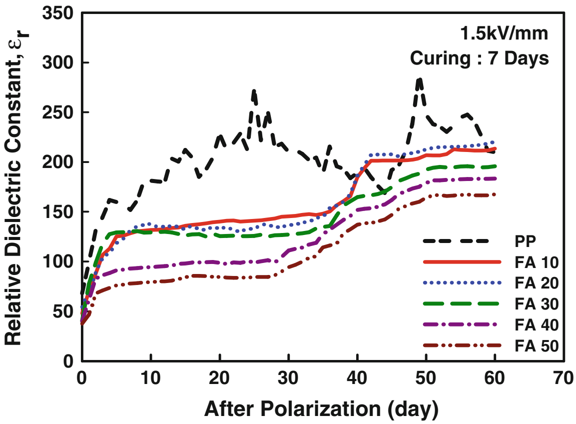


Fig. 77.1 Aging effect of ε_r at 7 curing days

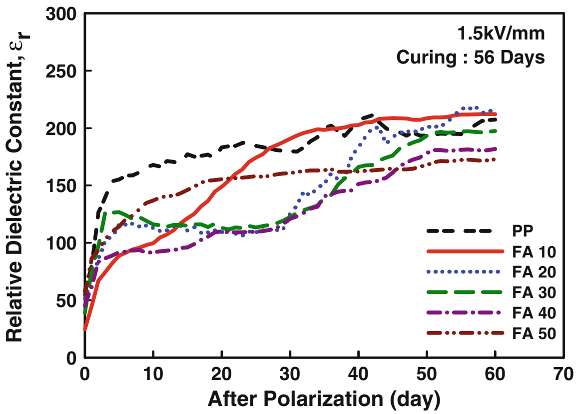


Fig. 77.2 Aging effect of ε_r at 56 curing days

23, 42, 45 and 54 pC/N for aging time of 0, 21, 28 and 60 days respectively. In Fig. 77.4, the trend of d_{33} at 56 curing days is similar to Fig. 77.3.

Figure 77.5 shows experimental results for g_{33} at 7 curing days, and indicates that g_{33} reduces tremendously at early aging time. g_{33} values for FA10 and FA20 at the 28th day of aging time are 30.6 and 37.4 mV-m/N respectively, those even greater than that for PZT ceramic (g_{33} = 24 mV-m/N). The replacement (fly ash) less 30 vol.% is a better choice to increase g_{33}. In Fig. 77.6, the trend of g_{33} with the aging day is also similar to Fig. 77.5.

Experimental results display that all FA-group materials can be successfully polarized. Now, we select the experimental data at the 60th day after the polarization to show the effect of curing time and fly ash contents. In Fig. 77.7, curing time shows less effective to enhance ε_r, and increasing poling voltage will reduce ε_r. A 20 % replacement by fly ash is the most effective to improve the dielectric constant.

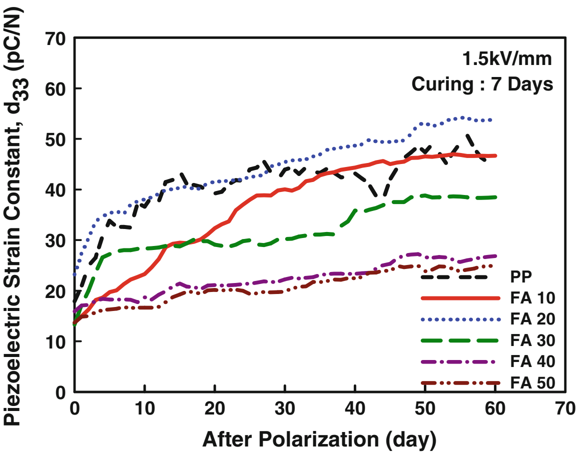


Fig. 77.3 Aging effect of d_{33} at 7 curing days

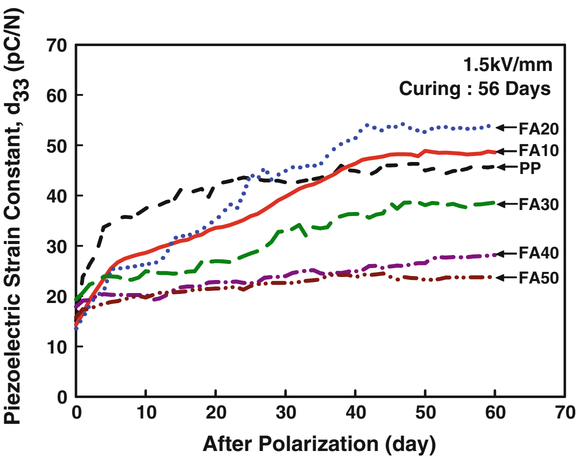


Fig. 77.4 Aging effect of d_{33} at 56 curing days

The results for d_{33} and g_{33} at 60 days are shown in Figs. 77.8 and 77.9 respectively. d_{33} and g_{33} have a less fluctuation for different curing times at the constant poling voltage, but increase with poling voltages. Both figures indicate that a 20 % replacement by fly ash is the best choice to promote piezoelectric properties. d_{33} values for PZT/cement piezoelectric composites with fly ash from 0 to 50 % at 56 curing days and 1.5 kV/mm are 46, 49, 54, 39, 28 and 24 pC/N respectively, and g_{33} are 24.9, 25.9, 28.0, 22.1, 17.5 and 15.6 mV-m/N in turn. Hence, d_{33} and g_{33} of FA20 material reaches a maximum value, where $d_{33} = 54$ pC/N and $g_{33} = 28.0$ mV-m/N.

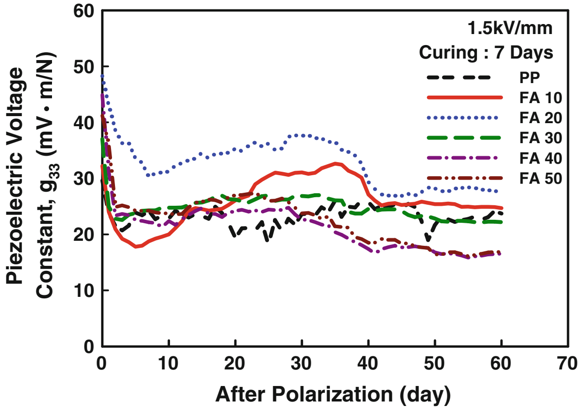


Fig. 77.5 Aging effect of g_{33} at 7 curing days

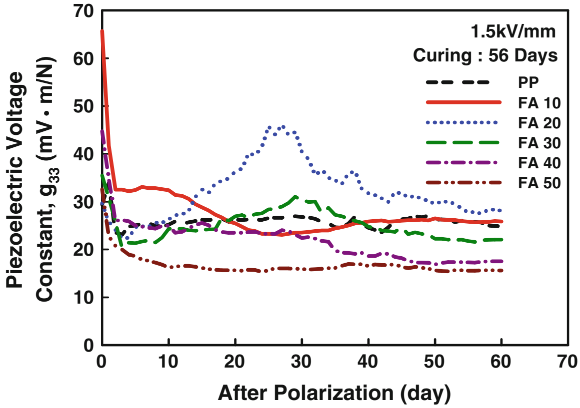


Fig. 77.6 Aging effect of g_{33} at 56 curing days

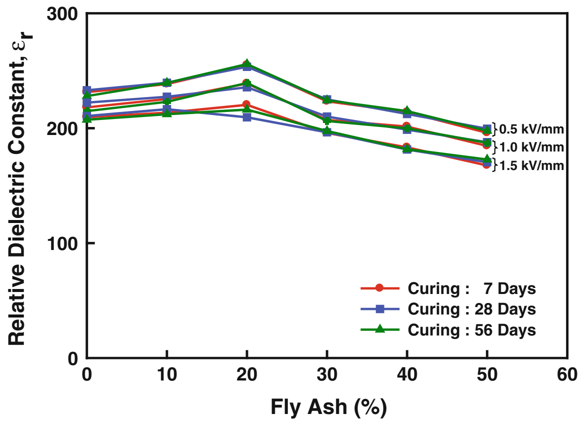


Fig. 77.7 Volume fraction of fly ash and ε_r

Fig. 77.8 Volume fraction of fly ash and d_{33}

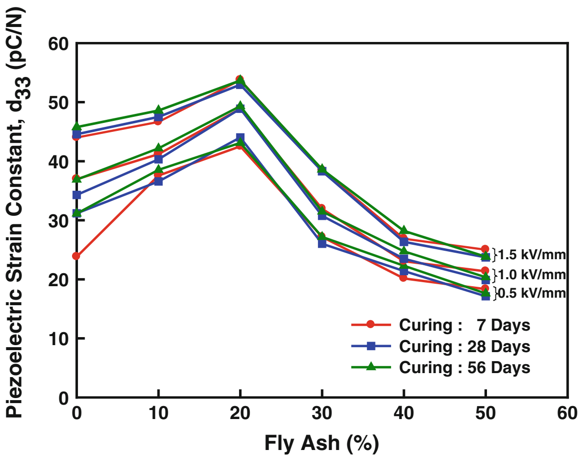
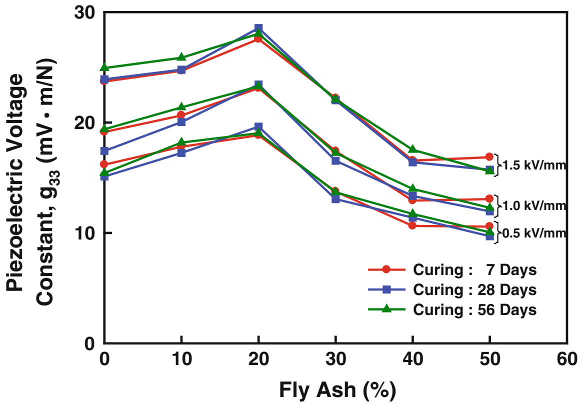


Fig. 77.9 Volume fraction of fly ash and g_{33}



77.4 Conclusions

Cement-based piezoelectric composites without adding water were pressed by a 80 MPa compression and cured for 7, 28 and 56 days respectively, after that, specimen were polarized by three poling voltages. Experimental data were measured daily till 60 days after the polarization. Experimental results are concludes as follows.

(1) Prior to polarization, capacitance, dielectric loss, and relative dielectric factor of FA-group materials increase as increasing fly ash, but decrease with curing time. However, adding fly ash to PP material will diminish ε_r after the polarization.
(2) All FA-group materials containing fly ash up to 50 vol.% replacement can be successfully polarized.

(3) Relative dielectric factor, d_{33} and g_{33} of PP and FA-group materials gradually increase with aging time, but have less effective to the effect of curing time. Meanwhile, increasing poling voltage will reduce ε_r, but increase d_{33} and g_{33}.
(4) To promote d_{33}, the content of fly ash had better not exceed 20 vol.% replacement of cement.
(5) Some g_{33} values of FA/cement composites, for example FA10 and FA20, are even greater than that of PZT ceramic.
(6) A 20 vol.% replacement of cement by fly ash is the best choice to improve the dielectric constant, piezoelectric strain factor and piezoelectric voltage factor of PZT/cement composites.
(7) Due to rapid increase of piezoelectric properties (ε_r, d_{33} and g_{33}) at early aging time, a suitable timing to represent piezoelectric properties of PZT/cement is to choose a relatively stable value after 50 days of the polarization.

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