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A study on the mechanical and electricity properties of cement mortar added with GGBFS and piezoelectric powder

Wen-Ten Kuo, Shyh-Haur Chen, Her-Yung Wang *, Jhan-Cyue Lin

Department of Civil Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung 807, Taiwan, ROC

HIGHLIGHTS

- We provide the feasibility of mixing GGBFS with PZT.
- The compressive strengths with the replacement of GGBFS of the control group is slightly higher than the strength of PZT.
- The electricity generated by the transmission process decreases under higher voltage.
- The electricity increases with compressive strength in a SSD state.
- The electricity decreases as the compressive strength increases in an OD state.

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ABSTRACT

Environmental concerns regarding energy savings and carbon reduction have been promoted worldwide to mitigate the greenhouse effect. Taiwan, which is located in the plate junction, experiences frequent earthquakes, abundant rainfall during the typhoon season, and frequent natural disasters. Improvements in the intelligent disaster prevention functions of buildings are imperative. This study employs the volumetric method. In the control group, cement was replaced by ground granulated blast furnace slag (GGBFS); in the PZT group, 5% of the fine aggregate was replaced with piezoelectric powder to create cement mortar. The mechanical and electricity properties were tested to assess the correlations among flow, compressive strength, water absorption, and electricity at 50 V and 100 V. At the curing age of 28 days, the compressive strength of the control group was in the range of 29.1–1.7 MPa, whereas the compressive strength of PZT was in the range of 26.8–30.0 MPa. The control group exhibited higher results (1786–2075 Ω) in the electricity property test under 50 V, whereas PZT exhibited lower results (1368–1562 Ω). The compressive strength and results of the electricity property tests demonstrated that the compressive strength and electrical resistance decreased as the replacement of GGBFS increased. The strength of the control group was higher than the strength of PZT because 5% of the fine aggregate was replaced by the piezoelectric material and the piezoelectric material was water-resistant. Thus, the piezoelectric material could not be effectively combined with fine aggregate and cement.

1. Introduction

Taiwan, which is located in the plate junction, experiences frequent earthquakes, copious rainfall during the typhoon season, and frequent natural disasters. As a result, improvements in the disaster prevention functions of buildings are imperative. Due to continuous change and improvements in science and technology, piezoelectric composite material has become the focus of development; this trend has diverted attention from the fields (mechanical, electrical and electronic engineering) to the field of civil engineering. In addition to mitigating the functional deficiencies in the original substrate, piezoelectric material is capable of affecting the design of the controller or sensor, which greatly increases the functionality of civil engineering materials. Consequently, concrete, which has been the predominant material in most civil engineering applications, is no longer simply characterized by superior compression resistance. Piezoelectric material surpasses concrete with regard to many intelligent functions, such as self-monitoring, self-healing and mechanical sensing. If used properly, the damage caused by catastrophic events may be reduced, and more business opportunities can be created [1–7]. The production of artificial aggregate is a promising alternative to the recycling of some industrial byproducts. The utilization of industrial waste materials, such as FA (fly ash) and GGBFS (ground granulated blast furnace slag), in the production of articulate aggregate has been practiced by some researchers [8].

* Corresponding author. Tel.: +886 7 3814526x5202; fax: +886 7 3961321.
E-mail address: wangho@kuas.edu.tw (H.-Y. Wang).

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GGBFS is fabricated by rapidly cooling blast furnace cinders with water to produce high contents of glassiness and high activity and cementing properties. GGBFS can be ground and mixed with cement to generate a pozzolanic reaction and to form hydrate C–S–H gel, which is similar to clinker. The properties of the hydrate C–S–H gel, which informed with cement as its principal component, are such that it can be substituted for cement in proper quantities. The addition of a mineral admixture to concrete improves its workability and enhances its durability and ultimate strength. The admixture can replace partial cement or fine aggregate, which improves the material quality, expands the range of application of the material, and positively contributes to material cost savings and the recycling of waste resources [9].

According to the manufacturing process, GGBFS is a significantly variable material due to the variability of its chemical composition. Due to the latent hydraulic properties when mixed with clinker cement, the hydration of slag is directly related to its hydraulic properties: the dissolution of slag glass fractions is ensured by hydroxyl ions (OH^-) generated from the hydrolysis of Portland $Ca(OH)_2$, which are produced by the hydration of clinker [10,11]. Traditional piezoelectric materials can be divided into three types: piezoelectric ceramic, piezoelectric polymer and piezoelectric composite material [12,13]. Common piezoelectric materials include lead zirconatetitanate (PZT), quartz, $BaTiO_3$, PLZT and PVF_2. PZT is piezoelectric ceramic with superior piezoelectric effects, and has been employed in various civil engineering applications. Traditional piezoelectric intelligent materials have progressed considerably in mechanical and medical domains. Piezoelectric intelligent materials have been employed in civil engineering and building construction. The reaction behaviors of the mechanics, deflection or thermal expansion of traditional piezoelectric materials in machines or alloys are not identical to the behaviors of reactions inside concrete. Although bridges, side slopes and RC buildings employ traditional piezoelectric materials (e.g., piezoelectric ceramic or piezoelectric polymer) as inductors, the deformation compatibility of these traditional piezoelectric sensors and cement-based structures is worse than the deformation compatibility of cement-based piezoelectric composite materials. Therefore, the piezoelectric sensor applied to machines (metals) may be inapplicable to civil engineering and building construction. The development of cement-based piezoelectric composite materials is promoted to enable a more effective use of piezoelectric materials [14–17].

The resistance of a specimen can be measured by the bipolar probe method. The electrical resistance of a specimen is obtained by measuring the voltage at one end and applying the direct current to the other end. The principle is described below. The bipolar probe measurement method uses two probes to measure the resistance of a specimen. The bipolar principle dictates that the current input and voltage output utilize the same electrode. According to electrode geometry, the current path can assume a straight line or an arc [18,19]. Using this method, it is difficult to measure the region size for obtaining the accurate resistance. If the parallel plates are used as measuring probes, the current path assumes split flow; therefore, the resistance of the specimen can be measured by placing parallel plates on both sides of the specimen [18,20].

2. Experimental programming

2.1. Experimental material

The cement used in this study was composed of Type I Portland cement produced by the Taiwan Cement Corporation. Its properties conformed to the specifications of CNS61 for Type I Portland cement. The mixing water conformed to the specifications of CNS1237 for concrete mixing water. The fine aggregate was collected from the Ligang District and conformed to CNS 1240 for fine aggregate. The furnace slag, which consisted of GGBFS produced by the CHC Resources Corporation, was ground to a fineness of 4500 cm^2/g. Its properties conformed to the specifications of CNS 12549 for furnace slag. The PZT piezoelectric material comprised S-44-type PZT piezoelectric powder purchased from Sunnytec Electronics. It contained a density of 7.7 cm^3/g. Table 1 lists the physical properties of the materials and Table 2 displays the chemical properties of the materials.

2.2. Experimental variables and methods

Table 3 shows that the standard mix design used in this study for cement mortar follows ASTM C109 specifications. The cement–water–sand ratio was fixed at 1:0.64:2.75. The volumetric method was employed. In the control group, cement (0%, 10%, 20%, 30%) was replaced by GGBFS. Five percent of the fine aggregate was replaced by PZT piezoelectric powder per ASTM C109 specifications. The flow of the fresh mixture was tested, and a 5 cm*5 cm*5 cm cement mortar specimen was fabricated and solidified. After 24 h, the form was removed and cured in saturated limewater. The compressive strength and water absorption were tested per ASTM C109 and ASTM C642-90, at the ages of 1, 7, 28 and 56 days. The electric property was tested in both SSD and OD states. The resistance was tested after voltages of 50 V and 100 V and a fixed current of 0.01 A was obtained at the ages of 1, 7 and 28 days.

SSD: Remove the specimen from the curing tank; wipe the surface of the water, so that it was within the saturated surface dry.

OD: specimen in the oven at 100 °C environment for 24 h, so that no internal moisture was dried state.

2.3. Treatment of specimen for electric property test

The cured square specimen was air dried outside and saturated inside. Impermeable sand paperwith three types of fineness were used to plane the specimen surface. Conductive silver paste was spread on two smooth sides of the specimen and allowed to dry. An appropriate length of conductive copper foil tape was cut

Table 1
The physical properties of material.

Items	Specific gravity	Water absorption (%)	F.M	Specific area (cm^2/g)
Fine aggregate	2.65	2.3	3.1	–
Cement	3.15	–	–	3500
GGBFS	2.8	–	–	4500
PZT	7.7	–	–	–

Table 2
The chemical properties of material. Unit: %.

Properties	Cement	GGBFS	PZT
SiO_2	20.22	33.79	–
Al_2O_3	4.96	13.59	–
Fe_2O_3	2.83	0.36	–
CaO	64.51	41.33	–
MgO	2.33	7.26	–
LOI	2.4	1.1	–
SO_3	2.46	0.1	–
Alkalis	0.48	–	–
$PbZrO_3$	–	–	55
$PbTiO_3$	–	–	45

Table 3
Unit weight of mix design. Unit: kg/m^3.

No.	Cement	GGBFS	PZT	Sand	Water
S0	543	–	–	1494	348
S10	462	48			
S20	408	97			
S30	353	145			
PZT-S0	543	–	217	1420	
PZT-S10	462	48			
PZT-S20	408	97			
PZT-S30	353	145			