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A study of engineering and electricity properties of cement mortar added with recycled materials and piezoelectric powders

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HIGHLIGHTS

- This study uses recycled materials and PZT to enhance intelligent functions of original substrates.
- The addition of GGBFS and waste LCD glass powder reduces water absorption and internal porosity.
- In a high voltage environment, the resistivity generated during the delivery process is reduced.
- The resistivity increases in correlation with compressive strength in the SSD state of fly ash and GGBFS.
- The resistivity increases when the waste LCD glass powder is replaced in SSD and OD states.

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ABSTRACT

Due to increasing global energy saving, carbon reduction, environmental considerations, and the environmental change resulting from the greenhouse effect, and because Taiwan is located on the plate junction, where earthquakes frequently occur, and because there is an abundance of rainfall during typhoon season, which often cause natural disasters, it is necessary to enhance the disaster prevention of buildings. This study uses recycled materials (fly ash, ground granulated blast furnace slag (GGBFS), and waste Liquid Crystal Display (LCD) glass powder) and Pd-Zr-Ti piezoelectric (PZT) to enhance intelligent functions of original substrates. The volumetric method is used for the design. The control group uses recycled materials to replace cement [0%, 10%, 20%, and 30%]. The PZT group uses a PZT powder to replace 5% of fine aggregates to make cement mortar to test the correlation between engineering and electricity properties of flow, compressive strength, water absorption, ultrasonic pulse velocity (UPV) and resistivity (electricity at 50 V and 100 V). The mechanical and electrical effects of cement mortar of various groups are discussed to determine the correlation between impedance characteristics and mechanical behavior of cement mortar in different electrical field environments and aqueous states, to build an engineering-electricity relation database for recycled materials and PZT, and to determine the relationships between various variables. A pozzolanic reaction occurs in GGBFS after 7 days. A 30% GGBFS replacement (32.9 MPa) has the maximum compressive strength. A 20% waste LCD glass powder replacement (31.8 MPa) can fill up finer pores and accelerate hydration. The addition of GGBFS and waste LCD glass powder reduces water absorption and internal porosity. Water absorption increases when fly ash is replaced. The resistivity at 50 V is higher than resistivity at 100 V in an electrical field environment. Specifically, in a high voltage environment, the resistivity generated during the delivery process is reduced. Because the voltage increase improves conductivity inside the specimen, the resistivity is reduced. The resistivity increases in correlation with compressive strength in the SSD state of fly ash and GGBFS. The resistivity decreases when the compressive strength increases in the OD state. The resistivity increases when the waste LCD glass powder is replaced in SSD and OD states.

1. Introduction

In recent years, cement materials have been the most frequently used building materials in civil engineering of residential spaces or civilian construction [1]. After a long-term service of concrete structures, and due to the weather or living environment

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effects, the building exteriors become damaged, and the interiors are likely to be damaged as well. In addition, sometimes it is difficult to immediately detect a damaged interior, which highlights the importance of real-time structure monitoring system and safety inspections.

Taiwan is located on plate junction with frequent earthquakes and copious rain during the typhoon season. Additionally, many natural disasters frequently occur. Therefore, currently, the enhancement of disaster prevention of buildings has been an urgent issue. Because time progresses, buildings are developed into intelligent structures with self-inspection of buildings and active vibrational control of structures [2,3]. In addition to safety, energy conservation and carbon reduction of buildings are considered. In addition to the advancement of inhabited environments, the advancement of building materials is also significant. Because science and technology continuously change and improve, piezoelectric composite materials have gradually become in demand. Piezoelectric composite materials gradually transitioned from being used in mechanical, electrical and electronic engineering to civil engineering. These materials remedy functional deficiencies in original substrates and can be made into controllers or sensors due to their piezoelectric properties. The cement-based piezoelectric composite is developed to fabricate smart sensors in real-time structural health monitoring [4,5]. This significantly increases the functionality of civil engineering materials. Thus, the concrete materials, which are primarily used in civil engineering, are not only compression resistant. Furthermore, PZT adds many intelligent functions to concrete, such as self-monitoring, self-healing and mechanical sensing. If used properly, the damage caused by catastrophic events can be reduced, and numerous business opportunities can be created [6,7].

Fly ash, which is produced in Taiwan, is primarily a Class F (low Ca content) fly ash with CaO content lower than 10%. The ash is a combustion product of anthracite and soft coal, and it contains a high SiO_2 and Al_2O_3 content. When fly ash is used as a pozzolanic concrete admixture, the particle size distribution, morphology and surface characteristics of fly ash have a considerable effect on water mixing of fresh concrete, its workability and strength development rate [8–10]. The hydration of GGBFS is slower compared with cement because hydroxide ions, which are released during cement hydration, rupture and dissolve the vitreous texture of GGBFS and consume Ca $(OH)_2$. This forms a C-S-H gel hydration product that gradually enhances the compactness of concrete, and, thus, the hardened properties of concrete are strengthened [11–13]. Waste LCD glass is a general industrial waste, applicable to cement mortar. It contributes to the pozzolanic reaction in concrete, and when its content in the concrete mix is approximately 30%, there is a significant strength development [14–16]. The addition of waste glass to the medium and low strength concrete effectively fills up the pores in the concrete and provides better durability, surface resistivity, acid resistance, salinity tolerance, alkali resistance, chloride ion penetration and concrete ultrasonic pulse velocity [17,18].

In general, PZT is characterized by high output, slight displacement, quick response, high energy conversion rate and zero electromagnetic interference. When it is added to cement-based materials and is connected to a buzzer, it forms a simple early warning system or performs an intelligent self-healing function of damaged materials [19–21]. The compatibility of a traditional piezoelectric transducer and a cement-based structure is lower compared with the cement-based piezoelectric composites. The cement-based piezoelectric composites are developed to use the PZT more effectively [22–24]. The 0–3 cement-based piezoelectric composites combine PZT particles with the cement in a three-dimensional direction. Thus, any shape can be made. Because there are polarization condition limitations, the specimen element size is small. In terms of material compatibility, cement is a porous material, and PZT has a higher specific gravity than cement. The impedance, interfacial bond and material compatibility between the two materials warrant an addition study and discussion. When the PZT volume content of cement-based piezoelectric composites is higher than 70%, it is likely to be polarized. When PZT is sintered, it has sufficient compactness, low dielectric loss and high capacitance. Because piezoelectricity of 0–3 cement-based piezoelectric composites is not yet mastered, the practical application of civil construction needs to be developed. It can be used as an intelligent system of actuators and sensors for structures in the future and can be made into cement piezoelectric ground tiles, building switch sensors or other intelligent building elements with a piezoelectric effect [25,26]. The findings indicate that the 0–3 cement-based piezoelectric sensor meets all requirements of application in construction engineering, and is feasible to be utilized in concrete structures [27,28].

The resistivity of the specimen can be measured by the bipolar probe method, where the voltage is measured at one end, a direct current is applied to the other end, and the resistivity of the specimen is calculated. In a bipolar approach, the current input and voltage output use the same electrode, and the current path can be a straight line or an arc that matches the electrode geometry. However, using this method, it is difficult to obtain the measured region size to accurately calculate the resistivity. If parallel plates are used as a measuring probe, the current path has a parallel flow. Thus, the specimen resistivity can be measured by attaching parallel plates at both sides of the specimen [29–31].

In this study, the proportion of PZT to cement-based piezoelectric composites exceeds 50%. Thus, it should be polarized and electrified to generate a piezoelectric effect. PZT has a high price per unit and contains lead. Therefore, it cannot be used in large quantities to prevent harm to the human health. To sum up, this study discusses the mixing of cement mortar with recycled materials (fly ash, GGBFS, waste LCD glass powder), combined with the characteristics of PZT, to control the cost. In total, 5% of PZT is added without changing the process. The polarization treatment and electrification test, engineering, mechanical and electricity properties are analyzed to discuss the effect of recycled materials and PZT on durability and electricity properties of cement mortar without changing its basic engineering properties [32]. A reference database is compiled for engineers and academicians to use with a hope that the use of recycled materials and PZT results in an economic benefit, by monitoring building safety, and contributes to the development of nondestructive inspection techniques for monitoring the health of buildings.

2. Test program

2.1. Test materials

1. Cement: Type I Portland cement produced by Taiwan Cement Corporation was used; its properties conformed to the Type I Portland cement specified in ASTM C150 [33].
2. Mixing water: Conforms to ASTM C94 [34] concrete mixing water.
3. Fine aggregate: The aggregate originated from the Ligang District and conformed to ASTM C33 [35].
4. Fly ash: Class F fly ash from the Taiwan Taipower Xing-Da Thermal Power Plant and conformed to ASTM C618 [36].
5. GGBFS: GGBFS was produced by the CHC Resources Corporation and was ground into 4500 cm^2/g. Its properties conformed to ASTM C989 [37].
6. Glass powder: TFT-LCD waste LCD glass sand was ground into 6000 cm^2/g.