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Study on the engineering properties and prediction models of an alkali-activated mortar material containing recycled waste glass

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HIGHLIGHTS

- The engineering properties and prediction models of an alkali-activated mortar material containing waste glass are performed.
- The prediction models of compressive strength, UPV and thermal conductivity are proposed.
- The compressive strength increases as the glass sand replacement initially increases and approached to maximum value when the replacement is 20%.
- The thermal conductivity decreases as the L/S initially increases and reached to its minimum when L/S = 0.55.

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ABSTRACT

In recent years, the global temperature has risen as greenhouse gases increase. With Taiwan's limited natural resources and the rise of environmental considerations, energy saving, carbon reduction and waste recycling are universal subjects at the present time. This study combined waste LCD (liquid crystal display) glass with alkali-activated slag mortar as a thermal insulating material and evaluated its engineering properties. Different liquid-solid ratios (L/S = 0.45, 0.50, 0.55 and 0.60) were used. The alkali equivalent was fixed at 1%, and the slag was replaced by glass sand (0%, 20% and 40%). Various engineering properties were tested at the ages of 3, 7 and 28 days. The results show that with more glass sand replacement and higher liquid-solid ratio values, the workability is better, and the slump and slump flow are higher. The compressive strength decreases as the liquid-solid ratio increases, and the compressive strength increases when the glass sand replacement is 0–20%. However, in contrast, when the replacement is 20–40%, the compressive strength decreases. The ultrasonic pulse velocity decreases as the glass sand replacement increases. The thermal conductivity increases with age, but the thermal conductivity decreases as the liquid-solid ratio initially increases, and the thermal conductivity is at its minimum when L/S = 0.55. When the L/S increases continuously, the thermal conductivity increases accordingly. The resistance to sulfate attack increases with the replacement and the liquid-solid ratio. The effect is the best when L/S = 0.60 and the glass sand replacement is 20%, meaning that a certain amount of waste LCD glass in the alkali-activated slag mortar can enhance the engineering properties. In addition, the prediction models for the compressive strength, ultrasonic pulse velocity and thermal conductivity of alkali-activated slag mortar material with waste LCD glass were deduced in this study. According to the comparison between the prediction analysis values and the test results, the compressive strength mean absolute percent error (MAPE) values are 4.37–5.52%, the ultrasonic pulse velocity (UPV) MAPE values are 0.01–1.53%, and the thermal conductivity (k_t) MAPE values are 0.82–2.68%. All the MAPE values are smaller than 10%, so the analytical models built have good forecasting accuracy.

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1. Introduction

With rapid industrial development in the 21st century, overexploitation causes severe environmental damage and aggravates the greenhouse effect. To attain the goals of environmental protection and sustainable development, energy saving and carbon reduction have been universally regarded subjects in recent years. Civil engineering and building construction are closely related to human life, and cement is one of the most frequently used materials for civil engineering and building construction. Cement production results in a great deal of CO_2. The total CO_2 emissions from the global

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cement manufacturing industry account for 5–7% of global total greenhouse gas emissions [1,2]. To reduce the environmental impact, cement consumption must be reduced. In an environment with limited resources, waste recycling is a new major topic. In recent years, alkali-activated inorganic polymer materials have been a new developing trend. Alkali cementation uses an alkaline agent and industrial by-products, such as slag and fly ash, for activation, such that good economic benefits and engineering properties are obtained, and it can be used as a green energy material to replace cement [3,4]. The alkali-activated inorganic polymer not only has high strength and workability but also has excellent fire resistance, thermal insulation and corrosion resistance. Alkali cementitious materials are a new type of environmentally friendly and economical material that is produced from industrial waste (e.g., fly ash and slag). This material possesses many excellent engineering properties, including a high compressive strength, light weight and low thermal conductivity [5,6].

With the development of the high-tech industry, LCD glass industry has grown greatly in recent years and is a rising major industry in Taiwan. With the rapid development and replacement of 3C products, a large amount of waste is produced, such as the defectives and alburnums derived from the process. In the last 10 years, waste glass has received attention again due to the high cost of disposal and environmental protection [7,8]. Waste LCD glass contains much silicon and calcium. Its properties are similar to those of natural sand. In addition to good grain shape, high hardness, good water permeability and durability, it has excellent fire resistance, thermal insulation and sound insulation properties [9,10]. Studies have shown that adding an appropriate amount of recycled material might improve the durability of lightweight aggregate concrete [11]. Waste glass for alkali-activated material engineering may supplement the impact properties of the material [12–15].

According to previous studies, alkali cementitious material has quite a few advantages, and it is an engineering material with great potential for development. However, related engineering material characteristics lack systematic integrated and evaluation models. This report discusses the engineering properties of an alkali-activated slag mortar material with waste LCD glass and uses a hyperbolic function and a linear function to build prediction models for the engineering properties of the material, including compressive strength, ultrasonic pulse velocity (UPV) and thermal conductivity (k_t), as an evaluation reference for future studies.

2. Test program

2.1. Test materials

The physicochemical properties of the test materials used in this study are shown in Table 1 and are described below:

Table 1
Chemical and physical properties of materials.

Materials	Slag	LCD glass	Water glass
Physical properties Specific gravity	2.89	2.42	41.89
Chemical content (%)			
SiO_2	33.57	64.28	29.43
Al_2O_3	14.71	16.67	–
Fe_2O_3	0.36	9.41	0.01
CaO	41.18	2.70	–
MgO	6.42	0.20	–
SO_3	0.57	–	–
K_2O	0.29	1.37	–
Na_2O	0.19	0.64	9.51
TiO_2	0.52	0.01	–
P_2O_5	0.01	0.01	–
L.O.I.	0.58	–	–

1. Ground and granulated blast-furnace slag (GGBFS): ground granulated blast furnace slag is from the CHC Resources Corporation, and its properties conform to CNS12549. The main chemical constituents include CaO (41.18%), SiO_2 (33.57%) and Al_2O_3 (14.71%), the composition is similar to normal Portland cement, and the fineness is 4000 cm^2/g.
2. Sodium hydroxide solution: 98% pure NaOH solid alkali is mixed with distilled water to prepare a 5 M NaOH solution, which is kept still for 24 h and then stored in a clean acid- and alkali-resistant barrel.
3. Sodium silicate solution: it is so-called "water glass." The main constituents are 29.43% SiO_2 and 9.51% Na_2O, and its specific gravity is 41.89.
4. Waste LCD glass sand: waste LCD glass, recovered from the Chi Mei Optoelectronics Corporation, is dry ground by a crusher and a ball mill. This material consists of homogeneous fine particles passed through a No. 30 sieve. The main chemical constituents include SiO_2 (64.28%), Al_2O_3 (16.67%) and Fe_2O_3 (9.41%). Its properties are similar to those of natural sand, its specific gravity is 2.42, its density is 2500 kg/m^3, and its fineness is 3850 cm^2/g.

2.2. Test variables and production

In this study, the mix proportions were proposed by referring previous study [12]. The specimens were cast with variable liquid-solid ratios (L/S = 0.45, 0.5, 0.55 and 0.60) and replacements (0%, 20% and 40%) of sand by waste LCD glass sand when the alkali equivalent (N) equals to 1%, respectively. The alkali equivalent is the ratio of equivalent of sodium oxide (Na_2O) to the weight of GGBFS in sodium hydroxide (NaOH) solution. The L/S is ratio of liquid (alkaline solution) to solid (GGBFS and glass) by weight. The mix proportions are shown in Table 2. In terms of the specimen manufacturing process, the NaOH is mixed thoroughly with the sodium silicate solution and kept still. The GGBFS and glass sand are poured into the mixing pan for a period of dry mixing, mixed with the alkaline solution for approximately 40 s, and then poured into a 50 * 50 * 50 mm specimen mold. The mold is removed after one day. The specimen is cured at room temperature, and the engineering properties are tested at the ages of 3, 7 and 28 days.

2.3. Test items and specifications

The slump test follows ASTM C109. The slump flow test follows CNS 14842. The setting time test follows ASTM C403. The compressive strength test follows ASTM C39. The ultrasonic test follows ASTM C597. The thermal conductivity test follows ASTM E1225-13. A portable thermal conductivity-measuring instrument is used. The sulfate resistance test follows ASTM C1012, (24 h in a drying oven followed by 24 h of immersion in sulfate at the age of 28 days constitutes one cycle, and there are five cycles). Loss of weight and changes in appearance are observed.

3. Experimental results and analysis

3.1. Workability

Fig. 1 shows the relation between slump and slump flow after the addition of LCD glass sand. For example, when L/S = 0.50, the slump of the 40% replaced is higher than the control group (replacement 0%) by 34.4%, and the slump flow is increased by 103.3%, meaning that the slump and slump flow increased with the glass sand replacement. The glass sand has a preferable workability due to its no absorbency, and the slump and slump flow increase with increasing liquid-solid ratios. The specimens with

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