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Bloating mechanism of the mixture of thin-film transistor liquid-crystal display waste glass and basic oxygen furnace slag

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HIGHLIGHTS

- The bloating mechanism of the mixtures of waste glasses and slag were investigated.
- Producing synthetic lightweight aggregate from the mixtures was achieved.
- The release of CO_2 and a suitable viscosity to entrap released CO_2 resulted bloating.
- The effluent CO_2 exceeding 1000 °C was resulted from the reduction of Fe_2O_3.
- The variations in water adsorption can be roughly divided into three stages.

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ABSTRACT

This study produced a synthetic lightweight aggregate (LWA) of waste glass from thin-film transistor liquid crystal displays (TFT-LCD) combined with slag from blast oxygen furnaces (BOF). We investigated the bloating mechanism of the mixtures as well as the influence of the heat-treatment conditions (temperature and duration) on the properties of the LWA (bulk density, water absorption and compressive strength).

Our results indicate that the proposed mixtures bloat when the content of BOF slag is in the range of 20–40 wt%, resulting from the release of CO_2 through a reduction ($2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$) of the Fe_2O_3 contained within the BOF slag. The bulk density and compressive strength of the resulting LWA decreased with an increase in heat-treatment temperature and duration within the bloating temperature range. The water absorption of the resulting LWA was affected by the pore type (open or isolated), which depended on the viscosity at the surface of the material. Variations in water absorption characteristics can be divided into three distinct stages progressing with an increase in temperature: (1) water absorption increased from the onset of bloating and the specimens formed a number of open pores on the surface of the LWA due to the release of CO_2; (2) following the formation of the glazing phase, bloating proceeded and water absorption decreased due to the sealing of open pores, transforming them into isolated pores; (3) water absorption again increased through the continuous release of CO_2 from isolated pores, resulting in significant increasing of pore size which resulted the connecting of isolated internal pores.

1. Introduction

Lightweight aggregates (LWAs) accounts for a significant portion of the materials used in construction. The raw materials used in the production of natural LWA include clay, shale, and slate. Various forms of waste can also be used as raw materials for the production of synthetic LWA. Waste of this sort, such as reservoir sediment [1,2], sewage sludge [3,4], fly ash [5,6] and waste glass [7], must have at least one of the following characteristics: (1) have gas released under specific heat-treatment conditions; (2) conducive to the formation of a glaze layer on the surface of aggregate and provide sufficient viscous glassy phase to entrap released gas. The expansion characteristics of a mixture depend on the release of gas and the existence of a viscous glassy phase to entrap the gas. Thus, this study sought to identify the range of temperatures conducive to the release of gas and modify the chemical composition of the mixture for a proper viscosity within that temperature range.

This study mixed waste glass from thin-film transistor liquid-crystal displays (TFT-LCD) with slag from blast oxygen furnaces (BOF) to produce LWA. The criteria was established according to

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the gas production characteristics of BOF slag and the ability of TFT-LCD waste glass to provide a glassy phase for the entrapment of released gas and to form an impermeable surface. An impermeable surface would also result in an aggregate with higher compressive strength.

Previous studies have demonstrated the feasibility of using waste materials to produce LWA, when the chemical composition of the waste falls within the "expandable region" on Riley's ternary diagram [1,3,8]. Nonetheless, few researchers have sought to identify the specific gases that are released or the reactions involved in the bloating process [9]. In addition, heat-treatment processes to promote bloating have generally been developed through trial and error. This study adopted a more systematic approach to investigate the bloating mechanism associated with the addition of waste materials in the production of LWA.

Most of the waste materials used in the production of LWA contain a large amount of organic matter. In contrast, this study used TFT-LCD waste glass and the BOF slag, both of which contain little organic materials due to they were produced through a high temperature melting process. As a result, we were able to simply disregard the pyrolysis and volatilization of organic matter, making a two-stage heating process unnecessary.

This study investigated the production of synthetic LWA by mixing TFT-LCD waste glass and BOF slag in a single-stage heating process. Our main focus was on the bloating mechanism and the effects of heat-treatment temperature and duration on the properties of LWA (bulk density, water absorption and compressive strength).

2. Material and methods

2.1. TFT-LCD waste glass

The chemical composition of waste glass from TFT-LCDs produced in Taiwan is generally more consistent than traditional waste glass recycled from other sources, which helps to ensure the reproducibility of the resulting LWA. The results of analysis of chemical composition (Table 1) indicate that TFT-LCD waste glass contains mainly SiO_2 (66.13 wt%) and Al_2O_3 (17.36 wt%). The SiO_2 content enables the formation of a glassy phase.

2.2. BOF slag

The by-product of the steel-making industry composed mainly of blast furnace slag, BOF slag, and fly ash. The annual production of BOF slag in Taiwan is approximately 1.3 million tons. The addition of calcium carbonate to oxygen furnaces results in the presence of free lime (free CaO) within the BOF slag. Free CaO has demonstrated an undesirable tendency to promote expansion of the aggregate through hydration [10,11]. BOF slag can be reutilized without the problem of expansion as long as it undergoes carbonation or hydration to transform the free CaO into calcium carbonate ($CaCO_3$) or calcium hydroxide ($Ca(OH)_2$). Nonetheless, the need to deal with the resulting products of the carbonation process has necessitated the development of an alternative reutilization route for the disposal of BOF slag.

The BOF slag mainly contains Fe_2O_3 (33.38 wt%) and CaO (41.37 wt%), both of which can act as fluxing agent to decrease the viscosity of the glass, thereby enhancing the viscous flow of the glassy phase at high temperatures, resulting in the entrapment of released gases [3]. Nonetheless, the content of fluxing agent must be carefully controlled to prevent the viscosity of the glassy phase from dropping too low, which would allow the gases to escape from the glazed surface.

Table 1
XRF results of TFT-LCD waste glass and BOF slag (wt%).

Waste materials	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Others
Glass	66.13	17.36	0.02	1.03	7.66	1.21
BOF slag	8.61	1.49	33.38	7.80	41.37	5.88

Others: NaO, TiO_2, P_2O_5, V_2O_5, Cr_2O_3, MnO_2, SrO and SnO_2.

3. Experimental methods

TFT-LCD waste glass and BOF slag proceeded ball milled to obtain a fine glass powder with a required particle size of <75 μm. The chemical composition of the powders was analyzed using wavelength-dispersive X-ray fluorescence analysis (WDXRF) (Advant'XP-397, Thermo ARL). And the residual carbon in BOF slag was analyzed using an elemental analyzer (Heraeus, CHNOS Rapid F002, Germany).

The most important factor influencing bloating is that both of the formation of a sufficiently viscous glassy phase and the release of gas within a temperature range. This study used a thermal analyzer/mass spectrometer (TA/MS, Linseis Pt-1600, Germany) to determine the temperature range conducive to the release of gas from the waste materials and to identify these effluent gases. The MS can classify various effluent gases according to their m/z (mass to charge ratio) and the amounts of specific gases can be quantified by different intensity of ion current produced in its detector. Therefore, the ion current indicates the quantities of effluent gases produced. TA/MS analysis was performed on powdered samples (<75 μm) at a heating rate of 10 °C/min in an alumina cell within an atmosphere of air or inert gas (N_2) using analytical grade Al_2O_3 powder as a reference. Weight loss and the identification of gaseous compounds through decomposition or gasification at high temperatures can be used as an indication of thermal instability in waste materials. Identifying the molecular weight of the released gaseous compounds can help to characterize the bloating mechanism and underlying chemical reactions.

Viscosity is another important factor associated with bloating. To overcome the difficulties involved in identifying viscosity conditions, this study conducted a preliminary bloating test in a tube high-temperature furnace equipped with an infrared camera and a cathode ray tube (CRT). The bloating of a sample within a given temperature range indicates that the sample has a glassy phase sufficient to provide the viscosity required to entrap released gases. Preliminary bloating tests were performed on disc specimens with a diameter of approximately 20 mm and a height of 5 mm. The samples were obtained by pressing the mixed powders into a cylindrical steel die at 35 MPa at room temperature using a uniaxial press (No. 3850, CARVERR). We prepared samples with various ratios of TFT-LCD waste-glass to BOF slag to identify the combinations capable of producing a suitably viscous glassy phase within a temperature range conducive to the release of gas for the manufacture of LWA. To ensure homogeneity in the mixed samples, a batch mixture of 100 g was mixed by ball milling (150 rpm for 60 min). In this manner, the expansion process of specimens could be observed and recorded to identify the temperature range in which bloating occurred. The samples that demonstrated bloating within the range at which gasses were released were selected for the following analysis of LWA properties.

The following experiments were undertaken to investigate the effects of heat-treatment temperature and duration on the properties (water absorption, bulk density and compressive strength) of bloated samples. Analyses were performed on disc specimens with a diameter of approximately 13 mm and a height of 10 mm. Heat-treatment was conducted using a high-temperature furnace. Porosity and bulk density were analyzed using Archimedes principle in accordance with ASTM A373 standards [12]. Compressive strength was determined in accordance with NIEA 207.22C standards (Taiwan) [13]. The formed granules were upper and lower horizontal polished. Granules with height to diameter ratio at least 1.0 were used as testing specimens and the results were calculated according to the following equation.

$$\sigma_c = \frac{P}{A}$$

where σ_c ($kgf \cdot cm^{-2}$) was the compressive strength; P (kgf) was the load applied when the specimen crashed and A (cm^{-2}) was the cross-sectional area of specimen. The surface and internal microstructure of the resulting LWA was characterized using scanning electron microscopy (SEM, FEI Quanta 200, Japan).

4. Results and discussion

4.1. Bloating mechanism

Fig. 1 illustrates the weight changed with increasing temperature. The rate of weight loss of TFT-LCD waste glass was approximately 0.25 wt% at 25–1100 °C, indicating good thermal stability. As shown in Fig. 1, the BOF slag (Air) underwent significant weight loss at 370–430 °C and 545–700 °C, and a slight weight loss above 1000 °C. These weight losses may be accompanied by the release of gas conducive to bloating, particularly at high temperatures above 1000 °C because a glassy phase sufficient to provide the viscosity required to entrap released gases. The results also show that the weight of the BOF slag increased within the temperature range of 700–1000 °C, which may be due to the oxidation of Fe-containing materials and resulting in the formation of Fe_3O_4 and Fe_2O_3. For verification, we conducted thermal-gravity analysis in the absence