Recycling of Basic Oxygen Furnace Slag as a Raw Material for Autoclaved Aerated Concrete Production

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Abstract: The purpose of this study was to recycle basic oxygen furnace (BOF) slag in the production of autoclaved aerated concrete (AAC), and to examine the influence on the properties of AAC products. The magnetic substances in the BOF slag accounted for about 15 wt.% and the magnetic proportion increased as the particle size decreased. The nonmagnetic portion of the BOF slag was acquired by a magnetic separation process and its major constituents were Ca (~42 wt.% as CaO) and Si (~35 wt.% as SiO2), which are the essential elements of AAC. When using the BOF slag for AAC production, the bulk density and compressive strength of the specimens decreased as the amount of slag increased. The results of the performance analysis revealed that at appropriate water–solids ratios, using 15 wt.% or less of the BOF slag was beneficial to the properties of the AAC products. In general, it should be feasible to recycle the BOF slag in the production of AAC. However, the foreign elements introduced by the BOF slag can alter the formation and structure of hydrates, including tobermorite, and thus affect the properties of the AAC product, a potential issue that needs to be addressed.

Keywords: steel slag; reuse and recycling; autoclaved aerated concrete; lightweight materials; tobermorite

1. Introduction

Steel slags, including basic oxygen furnace (BOF) slag, electric arc furnace (EAF) slag, and secondary refining slag, are byproducts of the steel-making industry, and the typical weight ratio of steel slag to crude steel output is 0.1–0.15 [1]. In 2018, the world crude steel production was about 1808 million tons [2]; accordingly, the annual output of steel slags was estimated to be 181–271 million tons. BOF slag accounts for approximately half of the total steel slag output, and is usually recycled for cement production, road construction, hydraulic engineering works, engineering construction fills, fertilizers, and other applications [3,4]. In Taiwan, about 1.5 million tons of BOF slag are generated annually, and most of this is reused as asphalt aggregates and backfilling materials. However, in recent years, the restrictions on the use of slag have become increasingly strict because of rising concern about the environment, and thus slag recycling routes are gradually closing. Consequently, the BOF slag is piling up due to the imbalance between generation and consumption, and this is a threat to the steel-making industry.

Since most of the current ways of reusing BOF slag are high-cost and low-benefit, the trade market for BOF slag is stagnant, and some surplus slag is now treated and dumped as industrial waste. Therefore, developing a practical and economic recycling method for BOF slag and enhancing the value of slag-derived products are important research topics. Many studies have reported that the major constituents of BOF slag normally include calcium, silicon, and iron compounds, and some heavy metals, such as chromium, manganese, barium, zinc, and vanadium, are present in trace amounts [1,5]. Although BOF slag has high potential to be reused as a construction material based on...
its main components, and some studies have proven that the heavy metals contained in such slag are immobile [6,7], the volume expansion caused by free CaO and MgO is the main concern with regard to the resulting properties of any materials produced this way [8–10]. Wang et al. [10] indicated that the absolute volume of the solid phase increases by about 98% when CaO reacts with H₂O to form Ca(OH)₂, which results in volumetric instability and thus restricts the use of BOF slag.

While CaO is harmful to the properties of BOF slag, it is an essential ingredient of autoclaved aerated concrete (AAC). AAC is an inorganic, lightweight material and has several useful properties, such as thermal insulation, fire resistance, and soundproofing, which make it a high-value building material. AAC is traditionally made from lime (CaO), silica sand (SiO₂), cement, and water, and is aerated by chemical reactions or mechanical methods [11–13]. Furthermore, an autoclave curing process is employed to drastically increase the mechanical strength of the aerated mortars. Under high-pressure steam conditions, CaO can react with SiO₂ and water to produce crystalline hydrates (e.g., tobermorite) and this reaction contributes to the greater mechanical strength of AAC [14,15]. As such, using BOF slag as a raw material for the production of AAC seems feasible, because BOF slag is mainly composed of calcium and silicon compounds, and the free CaO should be consumed in the autoclave curing process, thus overcoming the problem of volumetric instability.

However, some studies have reported that using alternative materials and industrial byproducts for AAC production may affect the properties and microstructures of the resulting AAC products [11,16–19]. Cai et al. [11] used iron tailings as an AAC raw material and showed that an increase in the iron tailings content reduced the mechanical strength of AAC. This is because the amount of calcium silicate hydrates (C-S-H) and tobermorite decreased markedly when increasing the ratio of iron tailings. Huang et al. [16] reused the copper tailings and blast furnace slag for AAC production and found that the foreign Mg and Al atoms can substitute the Ca and Si atoms of tobermorite, respectively, and change the morphology and microstructures of the AAC products. Karakurt et al. [18] replaced the silica sand in AAC with natural zeolite and noted that the unit weight and water requirements changed as a result of this. The particle size of zeolite also affected the mechanical properties of the AAC. Although BOF slag seems to have the potential for AAC production, little is known about its influence on the process parameters and properties of the resulting AAC. Accordingly, the purpose of this study was to use BOF slag to partially replace lime and silica sand in AAC production, and to examine the effects on the properties of the AAC products.

2. Materials and Methods

2.1. Materials

The BOF slag used in this work was generated from a steel mill in Kaohsiung, Taiwan. In the slag treatment plant, the BOF slag was crushed and sieved into four particle sizes, namely, AC-F (<3.5 mm), AC-II (3.5–7 mm), AC-III (7–15 mm), and AC-VI (15–25 mm), whose average weight percentages were 51.3 wt.%, 6.4 wt.%, 24.3 wt.%, and 18.0 wt.%, respectively. Because the AC-F had the smallest particle size and normally accounted for over half of the BOF slag, it was selected as a raw material for AAC production here. The moisture and ash contents, loss on ignition (LOI), magnetic and nonmagnetic proportions, particle size distribution, and chemical composition of the BOF slag were analyzed in this study. After magnetic separation and grinding to below 75 µm, the slag was ready to be used for the preparation of AAC specimens.

2.2. Preparation of AAC Specimens

The preparation of AAC specimens included three basic steps: raw material mixing, foaming and precuring, and autoclave curing. At first, silica (SiO₂, Alfa Aesar, 99.5%), lime (CaO, Merck, >97%), cement (ordinary Portland cement equivalent to ASTM Type I), and the BOF slag were precisely weighed in accordance with the experimental design, which is given in Table 1. For the reference raw mix, the weight ratio of silica:lime:cement equal to 70:25:5 was obtained from our previous
study [20]. Since the BOF slag contained some CaO and SiO$_2$, the amounts of lime and silica added were adjusted based on the composition of the slag to keep the Ca/Si molar ratio of raw mixes constant. Aluminum powder (Alfa Aesar, 99.5%) was employed as a foaming agent, and 0.5 wt.% was added to the mixture. These raw materials were put into a steel bowl and then mixed with an electric blender until the mix had become homogeneous. Secondly, water was then added into the raw mix at a specific water–solids ratio (0.55–0.70 L/kg) and then blended to a mortar as soon as possible. The mortar was poured into cast-iron molds (50 mm cube) where it was allowed to expand. After standing for 30 min, the expansion of the mortar was nearly finished, and the parts bulging out of the molds were then scraped off. The specimens in the molds were immediately put in a moist closet where the relative humidity was about 95%, and the temperature was controlled at 23 ± 2 °C. After precuring in the moist closet for 24 h, the hardened specimens were removed from the molds. Finally, the hardened specimens were cured by using an autoclave with a proportional–integral–derivative controller in order to complete the hydration reactions, and thus AAC specimens were obtained. The autoclave curing temperature was controlled at 189 °C (the corresponding steam pressure was about 1216 kPa) and the curing time was 16 h.

| Table 1. Raw mix composition of AAC specimens. |
|-----------------------------------------------|
| Raw Mix | Silica | Lime | Cement | BOF Slag |
|--------|--------|------|--------|----------|
| Reference | 70.0 | 25.0 | 5.0 | 0.0 |
| S05 | 67.5 | 22.6 | 4.9 | 5.0 |
| S10 | 64.9 | 20.2 | 4.9 | 10.0 |
| S15 | 62.4 | 17.8 | 4.8 | 15.0 |
| S20 | 59.9 | 15.4 | 4.8 | 20.0 |
| S30 | 54.8 | 10.5 | 4.7 | 30.0 |
| S40 | 49.7 | 5.7 | 4.5 | 40.0 |

2.3. Material Testing and Analysis Methods

The LOI of the original BOF slag was determined by burning the samples at 950 °C for 3 h. A dry drum magnetic separator (Outokumpu, Model MOS (10) 111−15) was used to separate the magnetic and nonmagnetic portions of the BOF slag. The chemical composition analysis of the BOF slags (original, magnetic, and nonmagnetic) was conducted with an inductively coupled plasma-optical emission spectrometer (ICP-OES, PerkinElmer, Optima 2000 DV) following a microwave-assisted acid digestion procedure. The samples were digested with nitric, hydrochloric, and hydrofluoric acids at ~175 °C for 24 min in a high-performance microwave digestion unit (Milestone, START D). X-ray diffraction (XRD) was applied to characterize the mineralogical compositions of the magnetic and nonmagnetic BOF slags, using an X-ray diffractometer (Bruker, D8 Advance) with Cu-Kα radiation.

The bulk density and compressive strength of the AAC specimens were determined according to ASTM C1693 [21]. Thermal analysis was conducted to study the compounds in the AAC specimens, and a simultaneous differential scanning calorimetry and thermogravimetric analyzer (DSC-TGA, TA Instrument, SDT 2960) was employed for this. Approximately 20–50 mg of AAC powder was loaded into an alumina crucible for analysis, and the furnace temperature was programmed to rise from the ambient temperature to 1000 °C at a heating rate of 10 °C/min. This thermal analysis was performed under a dynamic nitrogen atmosphere (100 mL/min). The microstructure of the AAC samples was observed using a scanning electron microscope (SEM, Hitachi S-3000N).

3. Results

3.1. Characteristics of BOF Slag

After sampling and delivery to the laboratory, the characteristics of the original BOF slag were analyzed immediately, and the results are given in Table 2. The moisture content of the original BOF
slag was only 5.57 wt.%, which should be attributed to the residual water during slag cooling. The ash content and LOI were 92.66 wt.% and 1.77 wt.% respectively, and thus there were almost no organic or combustible materials in the slag. The ash content on a dry basis was up to 98.12 wt.%, a characteristic which shows that the BOF slag should be suitable for the production of inorganic building materials. The original BOF slag still contained 15.29 wt.% of magnetic substances, although it had once been treated with a magnetic separation process in the slag treatment plant.

Table 2. Physical and chemical characteristics of original, magnetic, and nonmagnetic BOF slags.

| Item                        | BOF Slag          |
|-----------------------------|-------------------|
|                             | Original | Magnetic | Nonmagnetic |
| Moisture Content (wt.%)     | 5.57     | NA       | NA          |
| Ash content (wt.%)          | 92.66 (98.12) 1  | NA       | NA          |
| LOI (wt.%)                  | 1.77 (1.88) 1    | NA       | NA          |
| Magnetic proportion 1 (wt.%)| 15.29    | NA       | NA          |
| Nonmagnetic proportion 1 (wt.%) | 84.71  | NA       | NA          |
| Na                          | 4.63     | 4.77     | 4.60        |
| Mg                          | 6.60     | 6.10     | 6.69        |
| Al                          | 3.58     | 3.38     | 3.62        |
| Si                          | 16.43    | 17.91    | 16.16       |
| K                           | 1.52     | 1.68     | 1.49        |
| Ca                          | 29.60    | 25.50    | 30.34       |
| Fe                          | 16.09    | 20.96    | 15.21       |
| Cr                          | 860      | 1096     | 818         |
| Ni                          | ND 2     | ND 2     | ND 2        |
| Cu                          | ND 2     | ND 2     | ND 2        |
| Zn                          | ND 2     | ND 2     | ND 2        |
| Cd                          | ND 2     | ND 2     | ND 2        |
| Pb                          | ND 2     | ND 2     | ND 2        |

1 Dry basis. 2 ND: not detected (<2 mg/kg). 3 NA: not available.

Figure 1 shows the particle size distribution of the original BOF slag and its magnetic and nonmagnetic proportions in various particle size ranges. The 0.85–2.00 mm and 2.00–4.00 mm particles accounted for 46.70 wt.% of the BOF slag (22.62 wt.% and 24.08 wt.%, respectively), and the other particle size ranges accounted for 4.99–10.54 wt.% individually. It was observed that the particles that were <0.075 mm contained about 47 wt.% of magnetic substances, and the magnetic proportion of the BOF slag decreased with the increase in particle size. In this study, the magnetic substances in all particle sizes of BOF slag were separated out and the nonmagnetic portion was ground into powder < 0.15 mm to be used as an AAC raw material.

The chemical compositions of the original, magnetic, and nonmagnetic BOF slags are shown in Table 2. Comparing the original to magnetic BOF slags, the Ca content decreased from 29.60 wt.% to 25.5 wt.%, while the Fe content increased from 16.09 wt.% to 20.96 wt.% after the magnetic separation process. The nonmagnetic BOF slag contained 30.34 wt.% of Ca (42.48 wt.% as CaO) and 16.16 wt.% of Si (34.63 wt.% as SiO₂), and thus should be capable of partially replacing lime and silica sand in AAC production. In terms of heavy metals, Ni, Cu, Zn, Cd, and Pb were absent, and only trace amounts of Cr were found in the BOF slag. The concentrations of Cr in the original, magnetic, and nonmagnetic BOF slags were 860, 1096, and 816 mg/kg, respectively, which are compatible with the results of a previous study (Cr: 440–2000 mg/kg) [1]. Chaurand et al. [22] used X-ray absorption near-edge structure (XANES) spectroscopy to examine the Cr species in BOF slag and found that it is present in the trivalent form (a less-mobile and low-toxic form), and that speciation does not change during the natural aging and leaching processes. Accordingly, the Cr existing in the BOF slag should not raise environmental issues during reuse or recycling.
Figure 1. Particle size distribution of the original BOF slag and its magnetic and nonmagnetic proportions in various particle size ranges.

Figure 2 shows the XRD patterns of the magnetic and nonmagnetic BOF slags. Quartz (SiO2), portlandite (Ca(OH)2), calcite (CaCO3), calcium silicate (Ca2SiO4), wustite (FeO), and srebrodolskite ((CaO)2·Fe2O3) were clearly present in both the magnetic and nonmagnetic BOF slags, and Brand and Roesler [23] reported a similar mineralogical composition of BOF slag. The significant differences between the magnetic and nonmagnetic BOF slags were the presence of magnesia (MgO) in the nonmagnetic BOF slag and the higher diffraction intensity of magnetite (Fe3O4) in the magnetic BOF slag. These findings suggest that a magnetic separation process can further remove the iron-rich particles of the BOF slag, and this should be conducive to it being used as a raw material for AAC.

Figure 2. XRD patterns of magnetic and nonmagnetic parts of BOF slags.
3.2. Properties of AAC Specimens Produced with BOF Slag

The bulk density and compressive strength of the AAC specimens produced with 0–40 wt.% BOF slag at a water–solids ratio of 0.70 L/kg are shown in Figure 3. In the reference specimen, which was produced without the BOF slag, the bulk density was 780 kg/m³ and the compressive strength was 13.32 MPa. When using the BOF slag as a raw material for AAC production, the bulk density of the AAC specimens gradually decreased from 780 kg/m³ to 670 kg/m³ in the range of 0–30 wt.% of BOF slag, and then dropped to 554 kg/m³ with 40 wt.% of BOF slag added. On the other hand, the compressive strength of the AAC specimens produced with 5 wt.% and 10 wt.% of the BOF slag was higher than that of the reference specimen (15.81 MPa and 14.70 MPa, respectively), and further increasing the amount of BOF slag added made the compressive strength fall drastically to 1.49 MPa. These results may be attributed to the fact that small amounts of impurities from slag promote the nucleation of hydration phases while excessive impurities interfere with the hydration reactions. In sum, under the same water–solids ratio, the BOF slag can enhance the compressive strength of AAC products when low amounts are added, but then reduces this when greater amounts are used; moreover, the BOF slag can significantly reduce the bulk density of AAC products. These results imply that the AAC specimens produced with the BOF slag require less water than the reference specimen at a comparable bulk density.

![Bulk density and compressive strength of the AAC specimens produced with BOF slag.](image)

Figure 3. Bulk density and compressive strength of the AAC specimens produced with BOF slag.

Figure 4 presents the bulk density and compressive strength of the AAC specimens produced with the BOF slag at different water–solids ratios. Generally, reducing the water–solids ratio simultaneously increased the bulk density and compressive strength of the AAC specimens. At a water–solids ratio of 0.6 L/kg, the AAC specimen produced with 10 wt.% of the BOF slag had the highest bulk density (910 kg/m³) and compressive strength (22.42 MPa). However, an excessively low water–solids ratio greatly reduced the flowability of AAC mortars, thus causing the failure of molding operations (e.g., 0.60 L/kg for 5 wt.% of the BOF slag and 0.50 L/kg for 40 wt.% of the BOF slag). When the amount
of BOF slag added was raised to 40 wt.% (Figure 4f), the bulk density of the AAC specimens greatly increased with the decrease in the water–solids ratio, while the compressive strength only slightly increased. The AAC mortars prepared with the BOF slag required less water, probably because in addition to CaO, the slag contained calcium silicates, Ca(OH)$_2$, and CaCO$_3$, which do not consume water in the same way as the reaction between CaO and H$_2$O to form Ca(OH)$_2$. Another possible reason for this may be the larger particle size of the BOF slag.

**Figure 4.** Bulk density and compressive strength of the AAC specimens produced with (a) 5 wt.%, (b) 10 wt.%, (c) 15 wt.%, (d) 20 wt.%, (e) 30 wt.%, and (f) 40 wt.% of BOF slag at different water–solids ratios.
Because the compressive strength and bulk density of the AAC specimens varied simultaneously, it was difficult to directly uncover the influence of BOF slag on the properties of the AAC. In some previous studies [18,19,24], a performance factor (Pf) was used to examine the variation in the relation between compressive strength and unit weight. The Pf value is defined as the proportion of compressive strength to unit weight and can be regarded as the relative compressive strength provided by a lightweight material with a unit weight equal to one. Figure 5 shows the Pf values of the AAC specimens produced with the BOF slag at different water–solids ratios. It can be seen that the Pf values increased when low amounts of BOF slag were added, and then decreased drastically when higher amounts were used. Moreover, the AAC specimens prepared at lower water–solids ratios had higher Pf values. Despite the fact that the compressive strength decreased when the amount of BOF slag or water–solids ratio increased, the results of the performance analysis indicated that the AAC specimens produced with 5–15 wt.% of BOF slag at water–solids ratios of 0.60–0.70 L/kg had better performance than the reference specimen (0 wt.% of BOF slag). These findings show that using BOF slag as a raw material could be beneficial to the properties of AAC products when the amount of BOF slag added is not over 15 wt%.

The standard specification for AAC is described in ASTM C1693 [21], and the physical requirements of AAC are listed in Table 3. By comparison with the experimental results of this study (Table 4), it was found that none of the AAC products met the requirements for the Class AAC-2 because of the excessive bulk density. However, the AAC products prepared with 5–40 wt.% of the BOF slag at some specific water–solids ratios can meet the requirements for the Class AAC-4, and some of them can also achieve those for Class AAC-6. In the cases failing to meet the standard specifications, the AAC specimens had enough compressive strength but their bulk density was over the limits when the amount of the BOF slag was 30 wt.% or less. On the other hand, the AAC specimens produced with 30 wt.% and 40 wt.% of the BOF slag failed to meet the standards mostly due to insufficient compressive strength. Therefore, the amount of slag added should be carefully selected, as should the water–solids ratios when using BOF slag for AAC production.
### Table 3. Physical requirements for AAC (ASTM C1693).

| Strength Class | Compressive Strength (MPa) | Nominal Dry Bulk Density (kg/m³) | Density Limits (kg/m³) |
|---------------|---------------------------|---------------------------------|------------------------|
|               |                           |                                 |                        |
| AAC-2         | 2.0                       | 400                             | 350–450                |
|               |                           | 500                             | 450–550                |
|               |                           | 500                             | 450–550                |
|               |                           | 600                             | 550–650                |
|               |                           | 700                             | 650–750                |
|               |                           | 800                             | 750–850                |
| AAC-4         | 4.0                       |                                 |                        |
|               |                           | 500                             | 450–550                |
|               |                           | 600                             | 550–650                |
|               |                           | 700                             | 650–750                |
|               |                           | 800                             | 750–850                |
| AAC-6         | 6.0                       |                                 |                        |
|               |                           | 600                             | 550–650                |
|               |                           | 700                             | 650–750                |
|               |                           | 800                             | 750–850                |

### Table 4. Comparison between experimental results with the ASTM C1693 specifications.

| BOF Slag (wt.%): | Water–Solids Ratio (L/kg) | Bulk Density (kg/m³) | Compressive Strength (MPa) | ASTM Specifications |
|------------------|---------------------------|----------------------|----------------------------|---------------------|
|                  |                           |                      |                            | AAC-2 | AAC-4 | AAC-6 |
| 5                | 0.65                      | 846                  | 17.42                      | Fail 1 | Pass  | Pass  |
|                  | 0.70                      | 781                  | 15.81                      | Fail 1 | Pass  | Pass  |
| 10               | 0.60                      | 910                  | 22.42                      | Fail 1 | Fail 1| Fail 1|
|                  | 0.65                      | 820                  | 16.37                      | Fail 1 | Pass  | Pass  |
|                  | 0.70                      | 748                  | 14.7                       | Fail 1 | Pass  | Pass  |
| 15               | 0.60                      | 887                  | 19.29                      | Fail 1 | Fail 1| Fail 1|
|                  | 0.65                      | 802                  | 10.78                      | Fail 1 | Pass  | Pass  |
|                  | 0.70                      | 730                  | 8.44                       | Fail 1 | Pass  | Pass  |
| 20               | 0.60                      | 861                  | 12.68                      | Fail 1 | Fail 1| Fail 1|
|                  | 0.65                      | 782                  | 9.74                       | Fail 1 | Pass  | Pass  |
|                  | 0.70                      | 705                  | 7.33                       | Fail 1 | Pass  | Pass  |
| 30               | 0.65                      | 861                  | 11.87                      | Fail 1 | Fail 1| Fail 1|
|                  | 0.60                      | 819                  | 8.45                       | Fail 1 | Pass  | Fail 2|
|                  | 0.65                      | 693                  | 5.31                       | Fail 1 | Pass  | Fail 2|
|                  | 0.70                      | 669                  | 3.86                       | Fail 1 | Fail 2| Fail 2|
| 40               | 0.55                      | 841                  | 5.65                       | Fail 1 | Pass  | Fail 2|
|                  | 0.60                      | 725                  | 3.38                       | Fail 1 | Fail 2| Fail 2|
|                  | 0.65                      | 649                  | 2.57                       | Fail 1 | Fail 2| Fail 2|
|                  | 0.70                      | 554                  | 1.49                       | Fail 1 | Fail 2| Fail 2|

1 The bulk density is higher than the limits. 2 The compressive strength is lower than the limits.
3.3. Influence of BOF Slag on the Microstructures of the AAC Products

The results of thermal analysis for the AAC specimens produced with the BOF slag are shown in Figure 6. The TG and DSC curves show two endothermic peaks accompanied by losses of weight, and one exothermic peak without any such loss. It is known that the endothermic peak near 450 °C is related to the decomposition of calcium hydroxide ($\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$), and the other endothermic peak located around 700 °C is attributed to the decarbonation of calcium carbonate ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$). Both Ca(OH)$_2$ and CaCO$_3$ can be regarded as unreacted calcium compounds persisting in the AAC specimens. With regard to the exothermic peak, Yang et al. [25] studied the high-temperature phase transition of tobermorite and indicated that tobermorite can progressively convert to wollastonite ($\text{CaSiO}_3$) at elevated temperatures, and an exothermic peak without weight loss appears at about 861 °C in the DSC curves. In Figure 6, the results showed that Ca(OH)$_2$ and CaCO$_3$ were negligible in the reference specimen, while they were more significant in the AAC specimens produced with the BOF slag. The residual Ca(OH)$_2$ may be attributed to the hindrance to the formation of hydrates caused by impurities in the BOF slag, and the residual CaCO$_3$ could be directly introduced into the AAC specimens by the BOF slag. Furthermore, the exothermic peak related to tobermorite became less significant when increasing the amount of BOF slag that was added. Connan et al. [26] indicated that the integrated area and height of the exothermic peak were closely correlated with the level of compressive strength. These findings suggest that the formation of tobermorite in the AAC specimens was hindered by the addition of BOF slag, and this could be a partial explanation for the reduction in compressive strength noted above.

Figure 6. TG and DSC curves of AAC specimens produced with (a) 0 wt.%, (b) 15 wt.%, and (c) 30 wt.% of BOF slag.
Figure 7 presents the SEM images of the AAC specimens produced with 0 wt.%, 15 wt.%, and 30 wt.% of the BOF slag. In the reference specimen, produced without the BOF slag (Figure 7a), the tobermorite existed as platy- and lath-like structures. By comparison with the reference specimen, the structure of tobermorite changed to lamellar and leafy crystallites when using 15 wt.% of the BOF slag for the AAC production (Figure 7b). In the AAC specimen produced with 30 wt.% of the BOF slag (Figure 7c), grass-like structures were observed, which should be related to the C-S-H phases. Mostafa et al. [27] studied the characteristics of tobermorite and reported that the structure changed due to the substitution of aluminum and sulfate ions. Mostafa [17] examined the influence of air-cooled slag on the physicochemical properties of AAC and indicated that the tobermorite formation was retarded and a grass-like C-S-H structure was observed when the replacement of sand with slag was up to 50 wt.%. As with the air-cooled slag, some impurities such as aluminum and magnesium ions can be introduced into the AAC specimens by reusing the BOF slag as a raw material, and therefore this could affect the morphological features of tobermorite. Moreover, Różycka, and Pichór [28] suggested that an alteration in the structure of tobermorite might cause a reduction in the compressive strength of AAC when a greater amount of waste is used.

![Figure 7. SEM images of the AAC specimens produced with (a) 0 wt.%, (b) 15 wt.%, and (c) 30 wt.% of BOF slag.](image-url)

4. Conclusions

Some conclusions can be drawn from the results of this work, as follows. The finest fraction (<3.5 mm) sieved out by the slag treatment plant typically accounts for over half of the BOF slag, and it seems to have the potential for AAC production. Although a magnetic separation process was carried out in the slag treatment plant, there was still about 15 wt.% of magnetic substances present in the BOF slag, and the magnetic proportion increased as the particle size of the slag decreased. After further removing the magnetic substances in the laboratory, the nonmagnetic portion of the BOF slag was selected for AAC production. The major constituents of the BOF slag were Ca and S, and therefore it should be suitable to partially replace lime and silica sand with the BOF slag for the production of AAC. In terms of heavy metals, only Cr was detected in the BOF slag, and it should not cause any environmental concerns because many studies have proven the stability of Cr in such slag.
When using the BOF slag for AAC production, the bulk density and compressive strength of the specimens generally decreased along with the amount of slag added. In addition, the AAC specimens produced with the BOF slag required less water to achieve comparable levels of bulk density. The performance analysis showed that using the BOF slag as a raw material was beneficial to the properties of the resulting AAC products if the amount added was 15 wt.% or less. At appropriate water–solids ratios, the AAC products prepared with 5–40 wt.% of the BOF slag can meet the requirements for Class AAC-4, and some of them can also achieve those for Class AAC-6. In general, it should be feasible to recycle the BOF slag in the production of AAC. However, the foreign elements introduced by the BOF slag can influence the formation of tobermorite and alter the structure of the hydrates, thus further affecting the properties of the AAC product. This is a potential issue that needed to be considered when reusing BOF slag in the production of AAC. Moreover, the CaCO$_3$ in the BOF slag dose seem not to participate in the tobermorite formation reactions that occur during autoclave curing. The total Ca/Si molar ratio that is traditionally considered in the composition design may thus be insufficient. Perhaps future research could examine the reactivity of CaCO$_3$ under high-pressure steam conditions, and CaCO$_3$ might be excluded from the reactive calcium compounds in the composition design of AAC raw materials.

In the economic aspect, reusing BOF slag for the AAC production can not only save the waste treatment cost, but also create a high-value product. Moreover, the traditional backfill method for disposing of BOF slag could affect soil or groundwater due to the release of alkali components and trace heavy metals. Recycling BOF slag as a raw material of AAC will avoid this possible pollution and reduce the use amount of natural resources. Generally, this study indicates a potential recycling method for BOF slag having both economic and environmental benefits.

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