

VALORISATION OF STEEL SLAG THROUGH PELLETISATION AND CO₂ SEQUESTRATION

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Introduction

Steel slag is an alkaline residue from steel-making industry. It accounts for about 25% of the total residue production in China's iron and steel-making area, with an accumulation of 101 million tons per year.¹ Steel slag has been applied as aggregate or cement replacement in concrete.^{2,3} However, drawbacks such as the presence of free CaO (f-CaO) and the low hydraulic activity due to the thermal history significantly hinder the development of the steel slag market.⁴ On the other hand, steel slag shows high reactivity to carbonation on basis of the high CaO content. It is reported that pressed carbonated steel slag possesses significantly higher compressive strength than the non-carbonated group.⁵ In addition, carbonation is also able to stabilise some hazard elements of the steel slag and turn CO₂ into calcium carbonates, which was believed to be a more stable method for CO₂ sequestration. Extensive studies of carbonation on steel slag have been carried out including carbonating ground steel slag powder in a rotating packed bed and realising a CO₂ capture capacity of 165 kg per day,⁶ etc.

Pelletisation is a well-known technique for the fabrication of artificial pellets, which was adopted in construction area as well in order to solve the shortage of natural aggregates. Therefore, this paper aims to develop a value-added steel slag product *via* granulating steel slag powder into pellets and solidifying by CO₂ curing in order to achieve both economic and environmental benefits.

Materials and methods

Basic oxygen furnace slag (BOFS) powder shown in Figure 1 a) was used in this study. It was cooled by water spraying method and then ground into powder. It is dark brown in colour with a mean particle size of 6 µm. Chemical and mineralogical compositions tested by X-ray fluorescent (XRF) and X-ray diffraction (XRD) indicated that the BOFS consisted of 42.1% CaO, 21.7% Fe₂O₃, 16.5% SiO₂, 6.7% MgO, 4.8% MnO and 3.5% Al₂O₃, etc. The predominant mineral phases were portlandite (Ca(OH)₂), gamma dicalcium silicate (γ-Ca₂SiO₄) and srebrodolskite (Ca₂Fe_{1.052}Al_{0.665}Mg_{0.133}Si_{0.133}O₅).

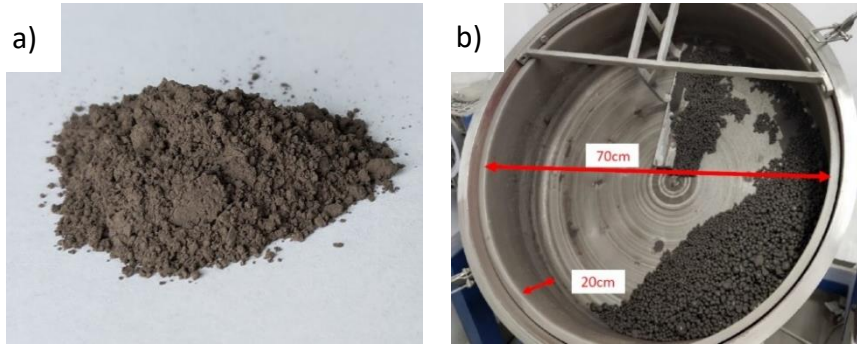


Figure 1: a) BOFS powder and b) pan pelletiser

Pelletisation was carried out in a customised pan pelletiser with 100% BOFS powder. The pelletiser shown in Figure 1 b) is 70 cm in diameter and 20 cm in collar height with a scraper stuck to the bottom surface. 4 kg BOFS was fed into the pelletiser at one time. During practical operations, the tilting angle and revolution speed were fixed at 45° and 15 rpm respectively. Spraying water was supplied continuously during the pelletisation process and the final liquid to solid ratio was 0.16. Immediately after the pelletisation process which lasted for 20 minutes, the fresh pellets became hard enough for handling and they were transferred to CO₂ chamber or lab shelves for different curing approaches. Temperature, humidity and CO₂ concentration in CO₂ chamber were controlled at 20°C, 65%, 20% respectively while the temperature and humidity in lab condition were about 15°C and 50%. For the pellets cured in lab condition, PA was designated as the notation, while for those cured in CO₂ chamber for the first 4 days and then in lab condition for the following days, PC was designated. After 7- or 14 days of curing, the final pellets with the diameters between 4.75 and 20 mm was sieved and tested.

Dry loose bulk density and 24-hour water absorption were assessed as per ASTM C29 and C127 respectively. Crushing strength and CO₂ uptake were determined by California bearing ratio tester and thermogravimetric analysis (TGA) respectively according to Equation (1) and (2):

$$\sigma \approx 2.8P/\pi d^2 \quad (1)$$

$$\text{CO}_2(\text{wt}\%) = \Delta m_{\text{CO}_2} / m_{105^\circ\text{C}} \quad (2)$$

where σ is the crushing strength, P is the load at failure, d is the mean diameter of the pellets, $\text{CO}_2(\text{wt}\%)$ is the CO₂ uptake, Δm_{CO_2} is the weight loss due to the CaCO₃ decomposition and $m_{105^\circ\text{C}}$ is the weight of the sample at 105°C.

The f-CaO contents in the pellets were also determined using the combination of the ethylene glycol method (GB176-2008) and TGA.

Results and discussion

Physical properties

The final aggregates after curing were shown in Figure 2 a). They are brownish grey with no visible pores or cracks on the surface. The loose bulk density of both types of pellets was about 1200 kg/m³ as shown in Figure 2 b), which is negligibly higher than the threshold set for lightweight aggregate in EN 13055-1 but quite significantly higher than 880 kg/m³ specified in ASTM C330. Besides, the different curing approaches did not lead to a significant difference in density of PA and PC pellets.

The crushing strength and water absorption of PA and PC pellets were tested at different ages. As mentioned above, CO₂ curing for PC group lasted only for 4 days since the formation of carbonate shell hindered the diffusion of CO₂ and the following curing in lab condition was designed for the further hydration of unhydrated phases. As depicted in Figure 2 c), PA and PC pellets gained 1.07 and 3.44 MPa respectively at 7 days and were still developing with time. The highest strength of 5.24 MPa was recorded for PC-14 d and the strength of PC pellet was about 3 times higher than the PA pellet. Precipitation of calcium carbonate during CO₂ penetration filled the pores inside the pellets and thus lead to the enhancement of crushing strength. However, PC group gained higher extra strength even when the CO₂ curing was over. This may be attributed to the fact that carbonation can greatly accelerate the hydration of dicalcium silicate. Similarly, water absorption was significantly reduced from 14% to 11% when CO₂ curing was applied, as shown in Figure 2 d). Even though this positive influence was mitigated at 14 days when the water absorption of PA pellets became comparable with PC, it was still much lower than artificial pellets made from other wastes^{8,9}.

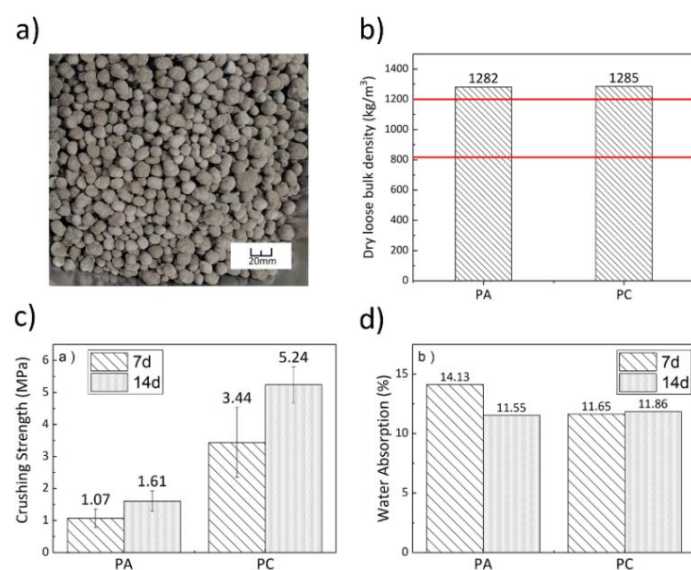


Figure 2: a) pellets, b) bulk density, c) crushing strength and d) water absorption

f-CaO content and CO₂ uptake

The BOFS used in the study possessed 42% calcium oxide, in which 1.4% of f-CaO was incorporated. After carbonation process, the f-CaO incorporated in the BOFS was reduced from 1.4% to 0.3%, which was believed not to cause any soundness problems. Besides, TGA result showed that the CO₂ uptake of PA and PC pellets was 2.48% and 9.64% respectively, which demonstrated that up to 96 kg CO₂ could be sequestrated when 1 ton of pellets were produced. This significantly reduced the carbon footprint of pellet production and thus can be a great environmental benefit.

Conclusions

BOFS powder was used in this study as the raw material for pelletisation and CO₂ sequestration. The final green pellets possessed the crushing strength of up to 5.24 MPa which was 3 times higher than the pellets without carbonation. The water absorption of the pellets was about 11%, significantly lower than pellets made from other waste materials reported in the literature. Carbonation can also stabilise the BOFS by reducing f-CaO content to an extremely low level and the CO₂ uptake was believed to be an added-value for the green pellets.

References

1. Y. Jiang, T. C. Ling, C. Shi, S.Y. Pan, "Characteristics of steel slags and their use in cement and concrete—A review", *Resour Conserv Recy*, **136** 187-197 (2018).
2. Q. Wang, P. Yan, J. Yang, B. Zhang, "Influence of steel slag on mechanical properties and durability of concrete", *Constr Build Mater*, **47** 1414-1420 (2013).
3. N. Palankar, A. R. Shankar, B. M. Mithun, "Durability studies on eco-friendly concrete mixes incorporating steel slag as coarse aggregates", *J Clean Prod*, **129** 437-448 (2016).
4. C. Shi, S. Hu, "Cementitious properties of ladle slag fines under autoclave curing conditions", *Cement Concrete Res*, **33** (11) 1851-1856 (2003).
5. Z. Ghoulah, R. I. Guthrie, Y. Shao, "Production of carbonate aggregates using steel slag and carbon dioxide for carbon-negative concrete", *Journal of CO₂ Utilization*, **18** 125-138 (2017).
6. S. Y. Pan, Y. H. Chen, C. D. Chen, A. L. Shen, M. Lin, P. Chiang, "High-gravity carbonation process for enhancing CO₂ fixation and utilization exemplified by the steelmaking industry", *Environ Sci Technol*, **49** (20) 12380-12387 (2015).
7. P. Tang, H. J. H. Brouwers, "Integral recycling of municipal solid waste incineration (MSWI) bottom ash fines (0-2 mm) and industrial powder wastes by cold-bonding pelletization", *Waste Manage*, **62** 125-138 (2017).
8. P. Gunning, C. D. Hills, P. J. Carey, "Production of lightweight aggregate from industrial waste and carbon dioxide", *Waste Manage*, **29** (10) 2722-2728 (2009).