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Characterization of stockpiled Basic Oxygen Furnace (BOF) slag for railway ballast material application

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ABSTRACT: Railway ballast usually uses natural crushed stone to transfer the load from the rails to the ground. However, the material has a detrimental impact on the environment as the extraction of it is a destructive process, and it is also prone to degradation and fouling in rail tracks. Therefore, this research evaluates the Basic Oxygen Furnace (BOF) slag as an alternative to traditional ballast material in the Kazakhstani railway industry. The tested BOF slags were grouped into top and bottom stockpiled with a mean age of 3–4 years and 10 years, respectively. GOST standards were mainly utilized to analyze the feasibility of the use of BOF slag in Kazakhstan. As a result, both types of BOF slag represented complete satisfaction with the proposed standards. Therefore, the potentiality of the application of stockpiled BOF slag for railway ballast material is verified.

1 INTRODUCTION

Continuous steelmaking, which generates massive waste, is a critical factor in human development; one of these wastes is BOF slag. However, BOF slag poses a severe environmental threat due to its limited potential for reuse and increasing production volume (Naidu et al., 2020). BOF slag has been used for different purposes in the developed countries such as USA, German, and France (Yi et al., 2012). For instance, it is utilized as a part of cement production process in China, as highway pavement in Japan and Australia. BOF slag is also currently used in some parts of Europe to improve agricultural soil condition (e.g., Gencel et al., 2021, Proctor et al., 2000). Another initiative that is being made worldwide to further reduce the amount of BOF slag in circulation is the use of BOF slag as a railway. BOF slag has been utilized as a railway ballast in Brazil, USA, Canada, and Iran (Hussain and Hussaini, 2022). Previous research on BOF slag concluded that BOF slag has higher resistance against lateral pressure and more resistance to breakage when compared with natural crushed stones that are currently utilized as railway ballast (Koh et al., 2018). Therefore, this study characterized the stockpiled BOF slags to apply them to railway ballast materials in Kazakhstan.

2 EXPERIMENTAL WORKS

2.1 *Sample preparation*

The BOF material used in this experimental work was collected from the steel plant located near Karaganda in Kazakhstan. A series of laboratory tests were conducted to investigate the chemical, physical, mechanical, and environmental properties of top and bottom stockpiled BOF slag. The top material has a mean age of 3-4 years, whereas the bottom material has been stored for 10 years in a stockpiled condition. Before starting the main experimental work, the material required preliminary treatment and sorting because the excessive water and

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dirt on the aggregates could directly affect further tests. Thus, the first step was oven drying the samples for 48hours at 95°*C* and sieving them according to the GOST standard (GOST 7392, 2014). The sieve sizes were chosen according to the standard for category B materials (square-sized sieves). The samples were sieved through different sieve sizes by shaking the machine for 10 minutes.

2.2 *Experimental methods*

Multiple tests were chosen to assess the slag in an application as ballast material. The most significant ones were selected from physical property requirements, strength, and resistance to environmental conditions. The physical property of BOF slags was evaluated by the Specific Gravity test conducted according to GOST 7392 - 2014. Mechanical properties of the BOF were investigated by Los Angeles (LA) abrasion method using ASTM C535 and aggregate crushing value (ACV) test according to BS 812-110. LA abrasion test was carried out to determine the abrasion resistance and toughness of the aggregates, while ACV test was performed to relatively measure the strength of aggregates needed to resist gradual compressive loads and to crush resistance. Environmental properties were determined through freeze and thaw and organic impurity tests. The freeze and thaw testing was conducted to assess the durability of BOF slag and its resistance to weathering and disintegration by repeated freezing and thawing processes. Meanwhile, an organic impurity test was performed to check the presence of injurious organic impurities. Both tests were carried out according to the GOST 7392 - 2014.

3 RESULTS AND DISCUSSION

3.1 *Chemical property tests*

X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM) were conducted to analyze the chemical property of the stockpiled BOF slags. According to the results presented in Figure 1, stockpiled BOF material has Portlandite ($Ca(OH)_2$), Silicon Oxide (SiO_2), Calcite ($CaCO_3$), Periclase (MgO), Lead Arsenate ($PbAs_2O_6$), Wurtzite (FeO) and others. Comparing both types of BOFS, it can be seen that the intensity of compounds like portlandite and lime is approximately the same, meanwhile, the intensity of SiO_2 (Silicon oxide) is larger in the bottom BOF rather than in the top BOF (Table 1) which indicates that the bottom BOF slag has weaker structure, therefore, is more likely to break. The results for top materials which have a mean age of 3 to 4 years are better than for bottom slag with a mean age of 10 years caused by differences in materials from batch to batch.

Table 1. RIR values of free-lime, portlandite and calcite in top and bottom BOF slag.

BOF type	f-CaO	Portlandite, $Ca(OH)_2$	Calcite, $CaCO_3$	SiO_2
Top	2.54	1.40	1.49	3.04
Bottom	2.54	1.40	2.00	3.31

Along with elemental composition, surface pictures displayed the information regarding the compound of BOFS. The hexagonal plate shape of stockpiled BOF is dictated by the aging of the material that is typical for $Ca(OH)_2$ which forms as long as the material ages and free lime reacts to form portlandite ($Ca(OH)_2$) and calcite ($CaCO_3$). Figure 2 shows the propagation of $Ca(OH)_2$ and $CaCO_3$ that explains the hexagonal shape formations on the surface of the BOF slag.

3.2 *Physical property tests*

According to the GOST specification, the specific gravity of the BOF should be more than 2.40. The top and bottom stockpiled BOF slags' specific gravities constitute 3.29 and 3.25,

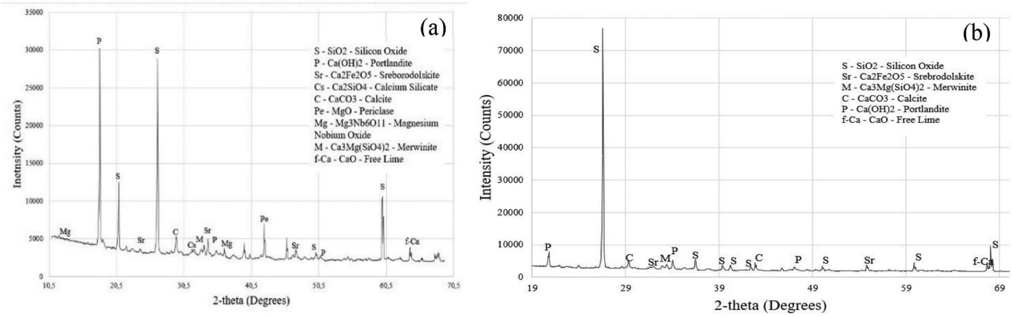

Figure 1. XRD for (a) Top and (b) Bottom BOF slags.

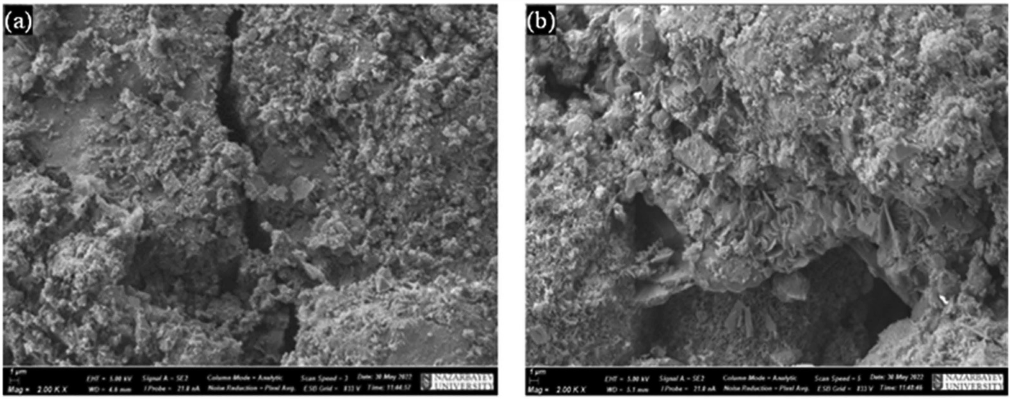

Figure 2. SEM images of (a) Top and (b) Bottom BOF slags.

respectively; satisfying the specification. As the aggregate's strength can be assessed by its specific gravity, the specific gravity that is more than the minimum required value signifies a strong aggregate, as in the case of the stockpiled BOF slag. As regards the absorption capacity, it is less than 2% required by British standards (BS EN 1097-6, 2022). The relatively low values for both stockpiled top (1.18%) and bottom BOF (1.15%) show low permeability of the BOF aggregates.

3.3 *Mechanical property tests*

Los Angeles abrasion and aggregate crushing value tests were performed to determine the strength properties of BOF slag. Both top and bottom stockpiled BOF slags satisfy the ASTM standard of railway ballast since their mass loss values of 22.8% and 23.9% respectively are less than 30% maximum mass loss standard set by AREMA. Therefore, BOF slag is strong enough to resist abrasion and wear and tear during usage. In terms of the aggregate crushing value test, the results have shown that aggregate crushing values for top and bottom stockpiled BOF slags are 19.3% and 20.5% respectively. According to the British Standard, the allowable value of the aggregate crushing value for railway ballast material should be less than 22% (BS EN 13450, 2020). The resulting values put the stockpiled BOF slags within the allowable limit as per the British Standard. Top stockpiled BOF slag provides a higher strength value in comparison to the bottom BOF slag, which makes top BOF slag more resistant to abrasion and crushing under the application of gradual compressive load.

3.3 *Environmental property tests (Freeze and Thaw test & Organic impurity test)*

Both stockpiled BOF slag satisfied the GOST requirement as their mass losses are 3.9% and 4.3% for top and bottom respectively and less than 5%. Therefore, the stockpiled BOF slag will provide great resistance to freeze and thaw in cold climate regions, where the freezing-thawing cycles occur constantly. As for the organic impurity test, it was observed that the sodium hydroxide solution that contains the samples was not colored, but there is a slight change in the turbidity of the solution. The solution colors do not match the reference colors of the ASTM color standard organic plate (ASTM C40M, 2020); this implies that there are no organic impurities present. It would be recommended to conduct preliminary treatment of aggregate by oven drying to burn out the undesirable organic impurity content.

4 CONCLUSIONS

The fast development of the railway industry in Kazakhstan leads to an increase in the extraction level of natural crushed stone for ballast application. The industry requires a sustainable solution that will be both economically and environmentally beneficial. Thus, the BOF slag stockpiled in the steelmaking industries could become a potential alternative to the traditional ballast material in Kazakhstan. Consequently, the sample BOF material was assessed by checking the compliance of its properties with the ballast requirements specified mainly in the GOST standard. As a result, the stockpiled BOF slag demonstrated complete compliance with the ballast material requirements of the obtained experimental program or testing standard. However, the superiority of top material over bottom could be noticed. According to the chemical analysis, the higher amount of SiO2 in the bottom BOF slag could lead to a comparable decrease in strength property. Nevertheless, the further assessment of BOF slag requires the practical investigation of performance in real-life scenarios.

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