APPLICATION OF STOCKPILED BASIC OXYGEN FURNACE SLAG IN RAILWAY BALLAST MATERIAL

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Declaration

I hereby, declare that this manuscript, application of stockpiled BOF slag in railway ballast material, is the result of my own work except for quotations and citations which have been duly acknowledged. I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or international institution.

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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 using 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 in Kazakhstan is verified.

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Chapter 1 - Introduction

1.1 Preamble

One of the most crucial development paths of the world industries is related to sustainable development. Primarily, this trend should influence the steel production industry as it produces waste that has no settled application in the market. The most common waste type from the steelmaking process that is being stockpiled in quantities of billion tons annually is BOF slag. Considering its very low utilization rate, the further increase in volume represents alarming outcomes, such as scarcity of land resources because of the open disposal of BOF slag.

Nowadays, an enormous amount of research is being conducted to increase the scope of BOF slag utilization. One of the successful approaches is related to the railway industry, especially the application of slag for railway ballast material (RBM). Countries such as Brazil and USA are successfully testing the slag as RBM in real scenarios. One of the primary purposes of this research is to localize the findings to the local market. Consequently, the results are used to check the potentiality of utilizing aggregates in railway ballast by complying with the specified requirements (GOST).

1.2 Thesis Problem Statement

The continual production of steel, which generates a lot of waste material, is at the forefront of human advancement. One of these wastes is BOF slag. BOF slag has limited reusability, and the increasing production rate makes it a severe environmental issue. Therefore, there is a need to improve the reusability of BOF slag. One of the attempts made by Kazakhstani researchers for such improvement is the use of BOF slag as a secondary material in civil engineering. The utilization of BOF slag as RBM presents a promising solution to the challenge of reducing the amount of BOF slag in circulation in Kazakhstan. This approach would support the most cost-effective means of long-distance travel via railway transportation while simultaneously curbing the negative impact of the current practice of acquiring crushed stones for railway ballast.

1.3 Aims and Objectives

This thesis aimed to conduct a feasibility study on stockpiled BOF slag from a steel plant in the Karaganda region, Kazakhstan, as an alternative material for railway ballast. Such evaluation was done by analyzing the material by performing several tests that help to determine the physical, mechanical, chemical, and environmental properties of BOF slag as RBM. Consequently, the results were used to check the potentiality of utilizing aggregates in railway ballast by complying with the specified requirements (GOST). Therefore, the main objectives of this thesis are summarized below:

- Laboratory investigation of stockpiled BOF slag to evaluate their conformity as RBM in Kazakhstan.
- Conversion of BOF slag into valuable material.
- Preparing the appropriate physical, mechanical, environmental, and chemical test methods to assess the BOF slag for railway ballast in Kazakhstan.

1.4 Research Hypothesis

Several recent research represented the undesirability of using fresh BOF slag in the construction and transportation industries due to its expansion characteristics. This issue can be solved by artificial aging of the material. However, this research hypothesizes that the stockpiled BOF slag already satisfies the railway ballast requirements according to GOST standards. Therefore, it is enough to have natural weathering conditions.

1.5 Thesis Structure

This thesis is divided into five chapters. Chapter one will introduce the thesis with a quick background, a problem statement, and the overall aim and objectives of the research. Chapter two will focus on the literature review, from the origin of BOF slag to its characterization, the current usage of BOF slag, the problems of BOF slag as a secondary raw material, railroad ballast, and finally, the requirements of materials to satisfy as RBM. Chapter three will describe the stockpiled BOF slag, the experimental procedure, and the overall methodology of the research. The experimental part will start by testing the description according to the GOST, ASTM, and BS EN manuals. Chapter four will present the experimental results and discussion. The main findings of the experimental results will be presented to ascertain their conformity with the appropriate standards. Conclusions regarding the findings will be discussed in Chapter 5, followed by a list of references.

Chapter 2 - Literature Review

2.1 Steelmaking

Steelmaking involves two distinct processes, Basic Oxygen Steelmaking, and Electric Arc Steelmaking, which differ in the raw materials used and the methods employed to transform them into molten steel. Iron ore is mixed with limestone and coal and placed in a blast furnace for the Basic Oxygen Steelmaking process. The resulting molten iron contains impurities like carbon, phosphorus, and silicon [1], which are reduced to a desirable level by burning with oxygen in a converter [2]. On the other hand, Electric Arc Steelmaking recycles steel scraps by melting them in an electric arc furnace, resulting in slag and molten metal [3]. The end products of these processes are slag and molten metal that is eventually transformed into steel [4, 5].

2.2 BOF slag: the general characteristics

BOF slag is a waste product of the steelmaking process obtained during the conversion of iron into crude steel under controllable heat in the furnace. The impurities of molten ore are burned out by the injection of oxygen, which produces waste with different oxide compounds [2]. Overall, the composition of BOF slag varies from production to production due to the variation in molten ore composition. However, it generally consists of silicates, manganese, iron, calcium, and oxides [6]. According to the approximate calculation, 1 ton of waste will be produced during each metric ton of steel making [7]. Reporting the total production rate, [8] suggested that steel industries produce about 200 Mt of BOF slag annually. The further destiny of these slags is being stockpiled in landfills. It could pose of decrease in land resources as there is a geometrical increase in waste production and scarcity of its application, especially in Kazakhstan [5].

2.3 BOF slag: Usage

The BOF slag is already being utilized in several developed countries. However, it is only in its experimental phase for different purposes. For example, the countries like Japan and Australia use BOF slag as a fill layer in transportation or highway engineering; China utilizes it in the concrete production industry; Norway uses it as soil fertilizer in agriculture [9, 10]. To date, the use of BOF slag as RBM has been suggested. [11] revealed that BOF slag improves the railway's lateral resistance performance. Hence, the application of BOF slag in the railway industry as ballast material demonstrated good potential for the future of BOF slag.

Another example was the justification of the application of BOF slag as RBM by [12]. As a result, multiple case studies using them in the railway industry are being examined. The notable ones are Rio Railways, the Toronto-Montreal railway route, and the California-Nevada border [13].

2.4 Railway Ballast

The layout of a railway track is divided into two main parts: the substructure and the superstructure. The substructure comprises ballast, sub-ballast, and subgrade, while the superstructure comprises steel rails, sleepers, and fastening systems [14]. Railway ballast, a coarse granular material between the sub-ballast and the rails [15], is vital for distributing train loads along the rails and sleepers to the roadbed [12]. Therefore, it should possess specific characteristics, including the ability to withstand sudden impact, resist abrasion, be thick enough to resist lateral stresses and prevent sleeper movement. The ballast must also be resistant to weathering and chemicals and impervious to moisture to avoid freezing during winter [16]. It is essential to carefully consider the standards and selection criteria for RBM because they gradually lose their functionality over time due to deformation, degradation, and breaking [17].

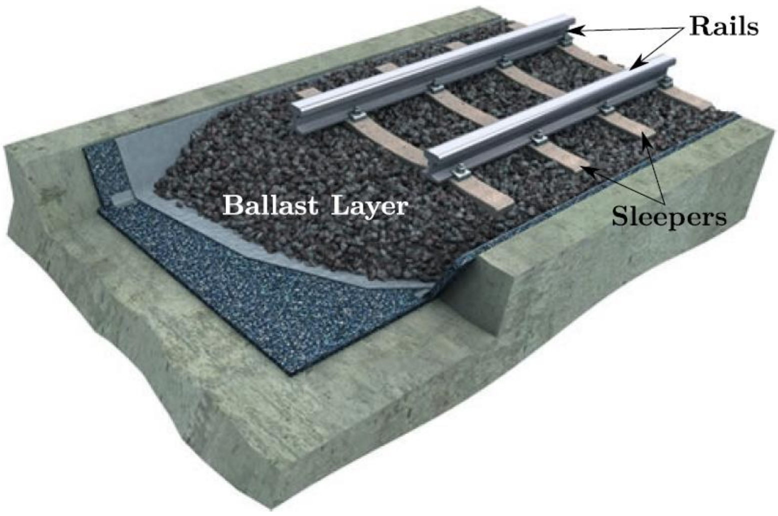

Figure 2.1: Illustration of the rails, sleepers, and ballast layer.
Source: [18]

2.5 The main challenges of BOF slag as RBM

One of the main challenges of using BOF slag as an RBM is related to its expansive characteristics. The fresh BOF has considerable free lime content (CaO and MgO). The further hydration reaction of free lime expands it into larger-sized compounds like calcium hydroxide. The expansion generates excessive internal stress that forms cracks [19]. However, there are also methods to neutralize undesirable expansions. According to [12], aging the material for half of the year could significantly decrease the expansion impact. The idea behind aging is related to the acceleration of material expansion to its maximum volume before utilization [20]. Overall, there are two methods to age material such as artificial and natural. One of the best methods for uniform maximum expansion quickly is accelerated artificial aging treatment using steam. The hydration reaction occurs considerably faster. However, it is an expansive method [21]. Fouling of the material is also an essential issue in railway ballast. The problem relates to accumulating weathered ballast material or other contaminants in the voids [15]. It poses a significant decrease in strength and tends to worsen drainage. Moreover, the water on the ballast surface could execute the expansion reaction of the BOF slag. It can be solved by adequately maintaining ballast [22].

2.6 Railway Ballast Material: Specification

The railway is one of the vital transportation networks in the world, especially since it has considerable importance to Kazakhstani economics. Usually, the ballasted track is utilized in the railway industry as it is cost-effective and can sustain the usual rail loads [14]. Natural crushed stone is usually used as RBM to transfer the load from the rail track to the soil while ensuring proper drainage [23]. There are primary requirements for it. Ballast materials are high-quality rocks mined and sorted to appropriate sizes and are typically characterized as uniformly graded, irregularly shaped, hard, and rough-surfaced. Standards, however, vary depending on criteria such as rock quality and the suitability of the rock [24]. According to [25], the general ballast material properties for RBM purposes are hardness, abrasion, grain size, shape, gradation, and mineral composition. This led to the implementation of various materials that meet specific requirements, such as limestone, slag, and crushed granite. Another common requirement is related to gradation characteristics. Recently, small-sized aggregates (< 20 mm in diameter) were commonly utilized for higher maintenance efficiency. However, the increase in load due to the increase in speed affected the size. Therefore, larger-sized aggregates with diameters up to 80 mm became popular to resist new loadings [26]. [26] also demonstrated good coherency between the gradation type and aggregate size. As a result, uniform gradation with large aggregate sizes could provide better drainage to the road (better stability) and minimize ballast degradation. Also, the average aggregate size used for RBM is approximately 20 to 50 mm, and their diameters vary from 6 to 64 mm [23]. The rest specifications for the ballast varies according to the location due to the different track loads, ballast type, weather conditions, and economic factor. As a result, the following Table 2.1 summarizes the main ballast requirements based on the different standards.

Table 2.1: Ballast specification for different standards

Specification	GOST	BS EN	ARTC	AREMA	AS	CN	IS
Nominal aggregate size (mm)	22.4-63	-	-	37.5-45	> 36	-	-
Flakiness index, %	< 15	< 15-25	≤ 30	≤ 5	< 30	-	-
Lightweight particles, %	-	-		< 3.5	-	-	-
Los Angeles Abrasion Test, %	< 12	< 12-24	< 25%	< 30	< 30	< 30	< 30
Micro Deval Abrasion, %	-	< 15	-	-		< 9	-
Aggregate Crushing Value, %	-	< 22	< 25	-	< 25	-	< 25
Aggregate Impact Value, %	< 4	< 14-22	-	-	-	-	< 20
Specific Gravity	> 2.4	-	-	-	> 2.5	> 2.6	-
Absorption capacity, %	< 2	-	-	≤ 2	-	-	-
Freeze and Thaw, %	< 5	-	-	<10	-	-	-
Soundness by sodium sulfate, %	< 5	-	-	< 5	-	< 5	-

Chapter 3 - Material Description and Test Procedure

3.1 Materials

The stockpiled BOF slags used for this thesis were obtained from a steel plant in the Karaganda region, Kazakhstan. Since the thesis aims to localize the research findings to Kazakhstan, conducting the tests using local BOF slag materials is essential. Overall, the stockpiled BOF slag is divided into two parts: Top Stockpiled and Bottom stockpiled. The two BOF slag under investigation differ according to their mean age: the Top BOF slag is a BOF slag that has been stockpiled for 3-4 years, while the Bottom BOF slag has been stockpiled for at least ten years.

3.1.1 Chemical Composition

The X-ray fluorescence analysis was used to determine the chemical composition of the stockpiled BOF slags. As presented in Table 3.1, the slags contain high-weight percentages of CaO and Fe_2O_3. The CaO content is higher in the bottom BOF slag than the top BOF slag, while both have similar Fe_2O_3 percentages. Manganese oxide (MnO) and silicon oxide are also present in both samples but in minimal amounts. Trace amounts of sulfur trioxide (SO_3) and Cr_2O_3 are found in both BOF slag, with a slightly higher concentration in the top BOF slag. Overall, Table 3.1 demonstrates that there are differences between the two types of BOF slag.

Table 3.1: Chemical composition of Stockpiled BOF slag

Composition	CaO	Al_2O_3	SiO_2	SO_3	MgO	Fe_2O_3	MnO	Cr_2O_3	Others
Top, %	29.18	1.09	8.69	0.23	6.24	20.24	1.73	0.73	31.87
Bottom, %	33.94	0.79	6.74	0.21	6.31	21.21	2.04	0.45	28.31

3.1.2 Particle size distribution

To compute the particle size distribution of the stockpiled BOF slag and classify them into usable sizes. They were sieved in accordance with GOST 7392-2014 specifications. The sample was oven dried to achieve a uniform mass, and it was then sieved through sieve openings ranging in size from 50 to 0.03 mm, stacking each sieve on top of the next. A mechanical shaking sieve machine was used to sieve the sample for 10 minutes (Figure 3.1). The total amount of sample that had been retained on each sieve was added up and used to estimate the particle size distribution of the BOF slag (Figure 3.2).

Figure 3.1: Mechanical sieve shaker

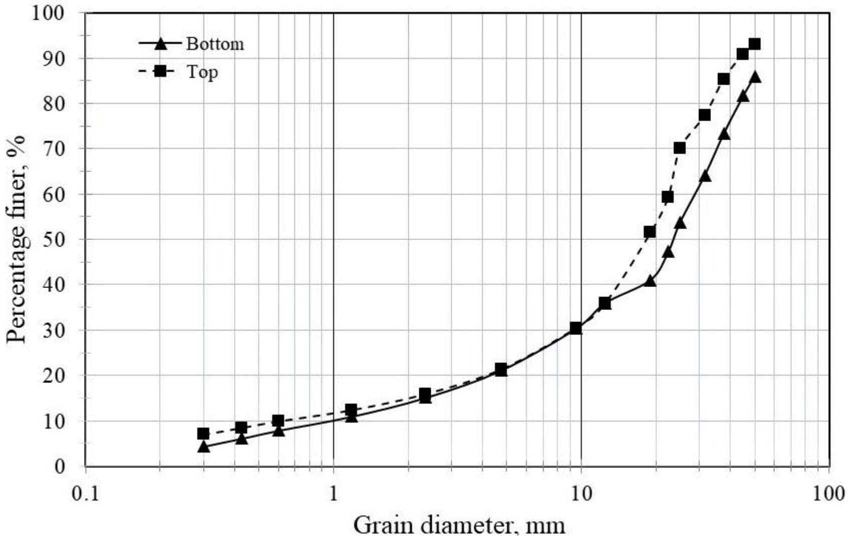

Figure 3.2: Particle size distribution curve of Stockpiled BOF slag

3.2 Experimental Procedures

The study evaluates the feasibility of using BOF slag as an alternative to traditional RBM. Thus, this thesis mainly consists of an experimental approach to assessing the BOF slag. After comparing ballast requirements from different standards summarized in Table 2.1, the list of essential tests was prepared and grouped. Consequently, to obtain the parameters from Table 3.2, the material was tested and assessed generally according to GOST 7392 standard for railway ballast because the potentiality of the use of the material is evaluated for the local Kazakhstani railway market. However, it was required to consider other specifications, such as

ASTM C123 and AS 1141, because the limitation of lightweight particles and aggregate crushing value was considered an essential requirement missing in GOST.

The research procedure is summarized in Figure 3.3 and divided into four stages: literature review, sample collection, testing, and discussion of results. Upon review of previous research on BOF slag, samples were collected from the steel yard in the Karaganda region, Kazakhstan. The sample was analyzed for physical, mechanical, environmental, and chemical properties. The outcome of these tests was compared with the GOST standards for the properties of RBM. However, there are cases where other close standards with similar testing procedures were considered for requirement because they were missing in the GOST standard.

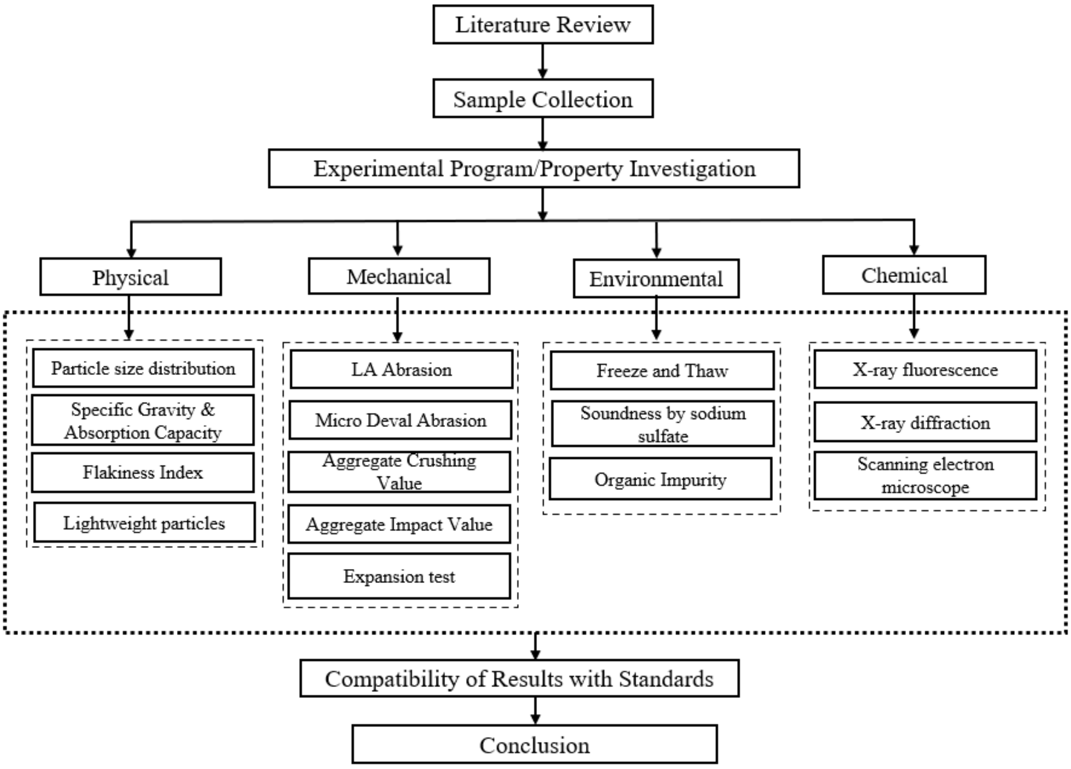

Figure 3.3: Experimental program flow chart

Table 3.2: Testing Details of Stockpiled BOF slag evaluation

Ballast Properties	Test Methods	Test Standard
Physical	Specific Gravity & Absorption Capacity	GOST 7392-2014
	Flakiness Index	GOST 7392-2014
	Lightweight particles in aggregate	ASTM C123/C123M-11
Mechanical	Los Angeles Abrasion	GOST 7392-2014
	Micro Deval Abrasion	Canadian Standard LS-618
	Aggregate Crushing Value	BS 812-110: 1990
	Aggregate Impact Value	BS 812-112:1990
	Potential Expansion by Hydration reaction	ASTM D4792M-13
Environmental	Freeze and Thaw	GOST 7392-2014
	Soundness test by Sulfate Attack	ASTM C88M-18
	Organic Impurity	GOST 7392-2014
Chemical	X-ray fluorescence	Axios Max PANalytical
	X-ray diffraction analysis	SmartLab (Rigaku) X-ray diffractometer
	Scanning Electron Microscope	Zeiss Crossbeam 540

3.3 Physical Properties

The physical properties of RBM are essential criteria for its selection. They establish the materials' gradation, fragmentation, and drainage ability. The physical behavior of the stockpiled BOF slag was assessed by their particle distribution, as shown in Figure 3.2, the number of flaky materials, and lightweight particles present in it.

3.3.1 Specific Gravity (SG) and Absorption Capacity (AC)

Specific gravity and absorption capacity are also important factors when selecting ballast. Specific gravity quantifies the density of ballast and is a crucial factor in determining its strength. Absorption capacity is the quantity of water ballast can absorb before it becomes saturated. According to GOST 7392-2014, two test samples of aggregate retained on a 22.4 mm square sieve were prepared and tested. The sample's specific gravity was determined by weighing it in saturated-surface dry (SSD), submerged, and oven-dry states. First, samples were washed and dried in an oven to remove dust and dirt. The samples were then immersed in room-temperature water for 24 hours to obtain a saturated state, with the water level never falling below 20 mm above the sample. After removing the sample from the water, the aggregate was dried with a damp towel and weighed. The samples were then weighed by completely submerging them in a water vessel. Finally, samples were dried in an oven at 95°C and weighed again.

The specific gravity and the absorption capacity of stockpiled BOF slag were calculated using the following equations.

$$SG = \frac{W_{OD}}{W_{SSD} - W_{sub}} * \rho_w \tag{3.1}$$

The samples' absorption capacity and moisture content are calculated using Eqs 3.1 and 3.2, respectively.

$$AC = \frac{W_{SSD} - W_{OD}}{W_{SSD}} * 100\% \tag{3.2}$$

ρ_w - Density of water

W_{SSD}- sample weight at saturated-surface dry condition.

W_{OD}- sample weight at oven-dry condition.

W_{sub}- sample weight submerged in water.

3.3.2 Flakiness Index test

The flakiness index test was conducted on Stockpiled BOF slag according to the GOST 7392-2014 method of examining a given aggregate's flakiness percentage. The aggregate passing sieve opening 63 mm and retained on 22.4mm were selected for the analysis. The samples were prepared by thoroughly washing and oven drying to remove the dust particles on their surfaces. The selected aggregates were then classified according to the opening in the BS thickness gauge (Figure 3.4a). The aggregates that pass through the opening slot of the gauge are considered flaky or needle-shaped. The percentage flakiness was computed as the ratio of the arithmetic sum of individual flakiness to the total mass of the tested sample (Equation 3.3).

$$Flakiness\ index\ (\%_f\ ) = \frac{\Sigma m_f}{\Sigma m_s} \cdot 100 \tag{3.3}$$

Where:

Σm_f = Total mass of flaky aggregates in aggregate selected for testing,

Σm_s- Total mass of sample selected for testing.

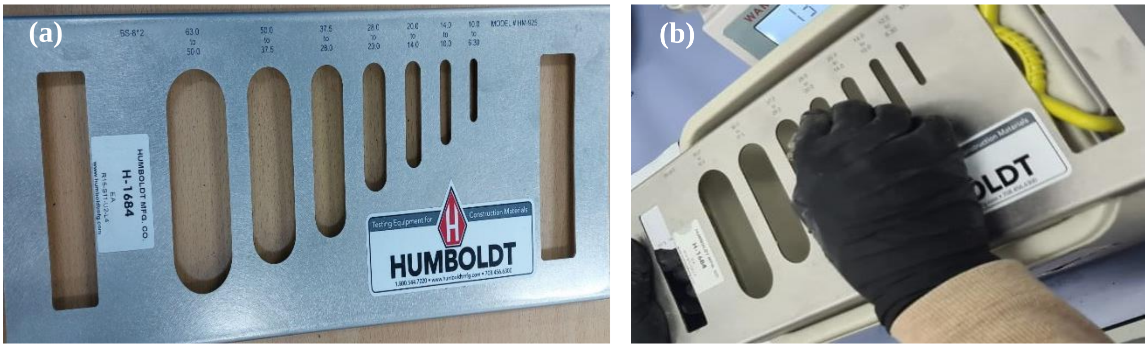

Figure 3.4: (a) BS thickness gauge (b) Flakiness index test

3.3.3 Lightweight Particle

To determine the percentage of lightweight aggregates in the stockpiled sample, this test was carried out per ASTM C123/C123M-11 standard. Zinc chloride was selected as the heavy of choice. The solution was prepared as specified in the standard with a specific gravity of 2.0. To make a zinc chloride solution with a specific gravity of 2.0, 1.6 kg of zinc chloride powder was mixed with 0.6 liters of distillate water. The stockpiled sample weighed 3 kg with aggregate sizes of 4.75, 9.5, and 12.5 mm and was washed, dried, and allowed to cool down to room temperature. The samples were then immersed in a heavy liquid three times the size of the sample tested. The liquid was continuously stirred while the decanted aggregate was continuously removed until no more particles rose to the surface of the liquid. Decanted particles were washed and dried, and the ratio of the decanted particles to the initial mass of the aggregate expressed in percentage is the number of lightweight particles in the aggregate.

3.4 Mechanical Properties

The most important indicator of RBM performance is its strength, and various mechanical tests measure the strength of RBM. To measure the mechanical properties of the stockpiled BOF slag, tests such as Los Angeles Abrasion, Micro Deval Abrasion, Aggregate Crushing values, Aggregate Impact Values, and the potential expansion rate of the aggregates were conducted.

3.4.1 Los Angeles Abrasion

The LA Abrasion test determines the hardness and durability of aggregates by measuring their resistance to degradation in an abrasion machine loaded with 12 steel balls and set to rotate at 30-33 revolutions per minute. This test was conducted according to the GOST 7392-2014 standard of measuring abrasion. The stockpiled sample retained on a sieve of 22.4 mm was selected for testing. Approximately 10 kg of sampling was used for testing. 5kg of aggregates retained on sieve 22.4mm and 25mm combined. Another 5kg on the sieve is 31.5 mm and 37.5mm. Two tests portion was prepared, and they were tested separately. First, 10kg of stockpiled BOF aggregates was loaded into an abrasion shelf drum, and the drum was tightly covered to prevent the escape of materials during the drum rotation. The drum was set for 1000 revolutions. At the end of the revolution, the aggregate was carefully unloaded and sieved through a 0.4mm sieve. The ratio between the mass of the BOF sample passing the 0.4mm sieve size to the total mass of the prepared sample gives the percentage abrasion loss of the sample. The test was repeated twice, and the arithmetic mean of the two tests represents the percentage abrasion of the stockpiled BOF slag

Table 3.3 Gradation of Stockpiled samples used in Los Angeles Abrasion Tests

Passing sieve, mm	**Retained sieve, mm**	**Sample mass, g**
45	37.5	2500
37.5	31.5	2500
31.5	25	2500
25	22.4	2500

Figure 3.5:Los Angeles abrasion test on stockpiled BOF slag.

3.4.2 Micro Deval Abrasion

The Micro-Deval abrasion test combines abrasion and grinding with steel balls in the water to determine aggregates' abrasion resistance and durability. The experiment was carried out according to the Canadian standard LS-618. The aggregates for the test were prepared with stockpiled BOF slag passing through a 19.0-mm sieve and retained on a 9.5-mm sieve. According to the standard, the total mass of the test sample was approximately 1500 g. First, the aggregates were washed and dried at 110 ° C in an oven. Next, 5000g of steel balls, each about 9.5mm in diameter, and two liters of water were added to the MD drum and prepared aggregates. The MD drum was then rotated at 100 revolutions per minute for two hours. Following the experiment, the mass loss was expressed as the ratio of the amount of material that passed through the 1.18mm sieve to the total mass of the sample. After the test was completed, the mass loss was calculated as a percentage of the material that passed through the 1.18mm sieve to the total mass of the test sample.

Table 3.4: Gradation of Stockpiled samples used in Micro Deval Abrasion Tests

Passing sieve, mm	**Retained sieve, mm**	**Sample mass, g**
19	16	375
16	12.5	375
12.5	9.5	750

Figure 3.6: Micro Deval Abrasion equipment

3.4.3 Aggregate Crushing Value

The aggregate crushing value (ACV) test measures the ability of a particular aggregate to withstand crushing when subjected to a load that increases gradually over time. The ACV test on stockpiled BOF slag was carried out according to the British Standard (BS 812-110: 1990). Aggregates passing through a sieve 14 mm and retained on a 10 mm sieve were prepared by washing and drying at 105 degrees Celsius for 4 hours. The test specimen was placed into an open-ended steel cylinder of a nominal 150 mm internal diameter in three layers; each layer was subjected to 25 strokes of a tamping rod dropped from approximately 50mm from the sample's surface Figure 3.7a. The prepared test specimen was placed in a compression testing machine and subjected to a uniform loading expected to reach 400KN after 10 minutes Figure

3.7b. The crushed sample was sieved on the 2.36 mm and consequently weighed. The aggregate crushing value is the ratio between the mass of the stockpiled BOF sample passing the sieve 2.36 mm and the test specimen's mass expressed in percentage. The test was repeated twice to improve the accuracy of the result, and the mean value of both tests is the ACV of the stockpiled BOF sample.

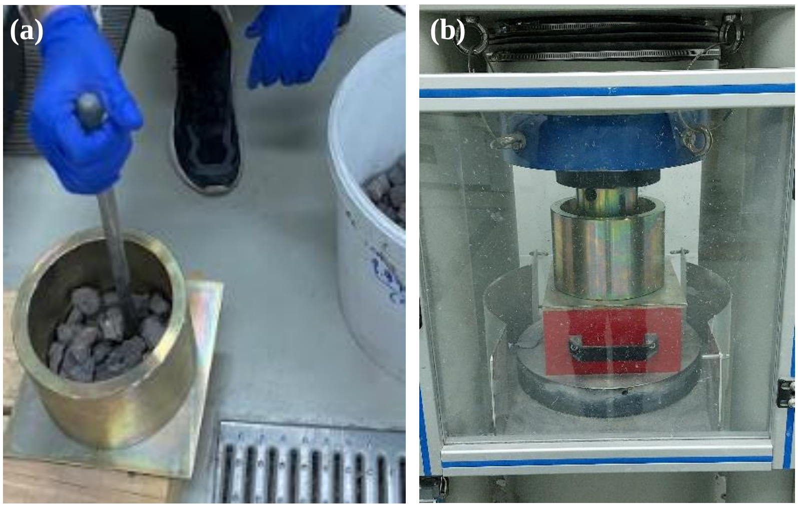

Figure 3.7: ACV (a) Tamping the sample (b) Sample under compression machine.

3.4.4 Aggregate Impact Value Test

As the name suggests, the Aggregate Impact Value test (AIV) measures the aggregate's resistance to the impact of sudden loading. AIV was carried out under BS 912-112:1990. The stockpiled BOF slag passing the 14mm sieve but retained at 10 mm was selected, and two test samples were prepared for an accurate result. First, the aggregate was washed and oven dried to a constant mass. Second, the sample was placed in a cylindrical measuring mold of 75mm internal diameter and 50mm depth in three equal layers. Each layer gently received 25 blows from a tamping rod. Third, the sample was weighed and transferred to another cylindrical mold attached to the bottom of the AIV equipment. The sample was then subjected to 15 quick blows from a hammer of about 14kg dropped from 380 mm height from the top of the sample. Finally, the sample was gently removed and sieved through a 2.36-mm sieve to determine mass loss.

Table 3.5: AIV observation table

Description	Sample 1, g	Sample 2, g	AIV, %
Total Mass of Stockpiled BOF slag W_1			
Mass of sample passing 2.36 mm sieve W_2			$(AIV_1 + AIV_2)/2$
AIV (%)	$W_2/W_1 * 100$	$W_2/W_1 * 100$	

Figure 3.8: AIV test setup

3.4.5 Potential Expansion of Aggregates from Hydration Reactions

One of the main drawbacks of using BOF slag in construction is its expansive nature in the presence of moisture. The expansion characteristics of the stockpiled BOF slag were checked according to the ASTM D4792M-13. It involves immersing a compacted sample of an aggregate in a water bath at a temperature of 70°C for 14 days. The optimum moisture content and dry unit weight of the aggregates was first established using a mold of 15.24 cm in diameter and 17.78 cm in height. Next, the sample was compacted in three layers by applying fifty-six blows from 30 cm above the top of the sample. The compacted sample was submerged in the water bath at 70°C. Water volume was such that there was free access to water to the top and bottom of the mold. The compaction mold was equipped with a dialed gauge, the reading of which was taken twice daily. The first reading on the dial gauge was recorded after 30 minutes, forming the base reading of the expansion test. The specimen was allowed to expand for 14 days, continuously recording the reading. The water bath was covered to prevent the evaporation of the water, and water was constantly added to keep the samples wholly immersed in water.

Figure 3.9: Expansion procedures for stockpiled BOF slag

3.5 Environmental Properties

The durability and weathering resistance of stockpiled BOF slag under harsh weather conditions, like in Kazakhstan, is an essential criterion for selecting ballast.

3.5.1 Freeze and Thaw

A freeze and thaw test was required to simulate the conditions that the ballast will endure in cold climates, where water can freeze and expand, causing damage to the ballast. It entails immersing stockpiled BOF slag in sodium chloride solution for several hours, draining the solution, and drying the aggregate in an oven. The GOST 7392-2014 test method prepared a sodium sulfate solution. First, 250 g of anhydrous sodium sulfate (Na_2SO_4) was dissolved in 1 liter of distilled water heated to 40 ° C by gradually adding sodium sulfate with thorough stirring until the solution was saturated. Then, the solution was allowed to cool to room temperature and left for at least 48 hours before the test. A total of 5 kg of stockpiled aggregate in sizes 37.5, 31.5, 25, and 22.4 millimeters were chosen. The first stage involves immersing the samples in Na_2SO_4 solution for 20 hours, then drying in an oven for 4 hours and cooling them for 2 hours. The subsequent cycles begin with 4 hours of immersion in solution, followed by 4 hours of drying and 2 hours of cooling. The samples were sieved after 3, 5, and 10 cycles through a 22.4 mm control sieve to determine the mass loss after each cycle. The final mass loss was calculated after 15 cycles by subtracting the sample mass retained on the 22.4 mm sieve from the initial mass of the test sample.

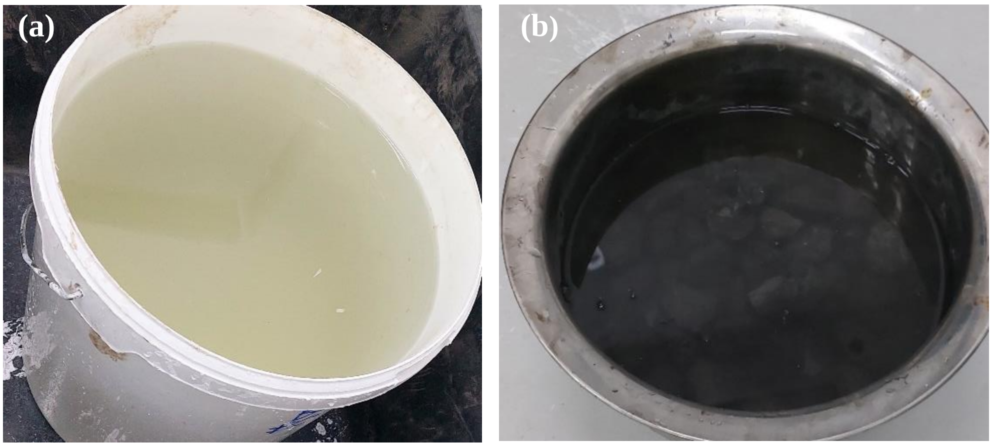

Figure 3.10: Freeze & Thaw process (a) Sodium Sulfate solution, (b) BOF sample in solution

3.5.2 Soundness test by Sodium Sulfate

A soundness test was required to determine the resistance of stockpiled BOF slag to weathering action, especially when exposed to wetting and drying cycles. ASTM C88M-18 was followed by dissolving 250g of anhydrous sodium sulfate solution in 1 liter of distilled water. The stockpiled BOF slag was prepared and classified per the manual by choosing samples ranging from 63 to 37.5 mm and 37.5mm to 19mm. The BOF slag was washed and oven dried for 24 hours to a constant mass. The sample was then immersed in a sodium sulfate solution for 17 hours before being drained, dried in an oven at 105 degrees Celsius for 6 hours, allowed to cool for 30 minutes, and then immersed in the solution for 17 hrs. again. The experimental procedure was repeated until the fifth cycle, at which point the sample was sieved according to the specifications in Table 3.6 to estimate the soundness loss.

Table 3.6: Sample selection for soundness test

Sieve size	Consisting of:	Mass, g	Sieve to determine mass loss
19.0 mm to 9.5 mm	12.5-mm to 9.5-mm 19.0-mm to 12.5-mm	330 ± 5 670 ± 10	8.0-mm
37.5 mm to 19.0 mm	25.0-mm to 19.0-mm 37.5-mm to 25.0-mm	500 ± 30 1000 ± 50	16.0-mm
63 mm to 37.5 mm	50-mm to 37.5-mm 63-mm to 50-mm	2000 ± 200 3000	31.5-mm

3.5.3 Organic Impurity

An organic impurity test was carried out according to GOST 7392-2014 to detect the presence of harmful materials in the stockpiled BOF slag. For testing, the stockpile samples that passed a 20-mm sieve were utilized. The sample of 130 cm^3 volume was poured into a measuring cylinder, then filled to a level of 200 cm^3 with 3% sodium hydroxide. The test samples were left in the solution for 24 hours and repeatedly stirred every 4 hours. After twenty-four hours, the color of the solution was compared to the color of the ASTM D 1544 standard organic plate. If the color of the sample solution is brighter than the reference colors, then no organic impurities are present. However, if the sample solution matches the standard color, the specified amount of organic impurities are present.

3.6 Chemical Analysis

The chemical composition of stockpiled BOF slag was analyzed by X-ray fluorescence (XRF) method, the crystalline phases of the elements were measured by X-ray diffraction (XRD), and Scanning Electron Microscope (SEM) analyzed the surface and elemental composition.

3.6.1 X-ray Fluorescence (XRF)

The oxide composition of BOF slags was evaluated using an Axios max X-ray fluorescence spectrometer by PANalytical

Figure 3.11. The equipment is available at the core facility of Nazarbayev University. The BOF slag samples of less than 30 microns were prepared using the Proctor Compaction apparatus before the sample was placed into XRF equipment for scanning.

Figure 3.11: Axios Max PANalytical for XRF

3.6.2 X-ray Diffraction (XRD)

X-ray diffraction analysis was conducted through SmartLab (Rigaku) X-ray diffractometer in the Core Facilities of Nazarbayev University Figure 3.12. First, powdered samples were placed into a diffractometer and analyzed with the following parameters: scanning range of 5-70 degrees and interval of 0.03 degrees to the crystalline phases of the stockpiled BOF slag. Subsequent results were processed using MDI Jade 6 software to identify the primary compounds by 2-theta diffraction angle and intensity.

Figure 3.12: SmartLab X-ray diffractometer

3.6.3 Scanning Electron Microscope (SEM)

Scanning electron microscopy (SEM) analysis was performed to observe the surface texture of the stockpiled BOF slag. The BOF slag was first grounded to a powder form before the analysis was performed by Zeiss Crossbeam 540 Figure 3.13. In addition, the sample was coated with gold foil before the SEM picture was taken to improve the quality of the images.

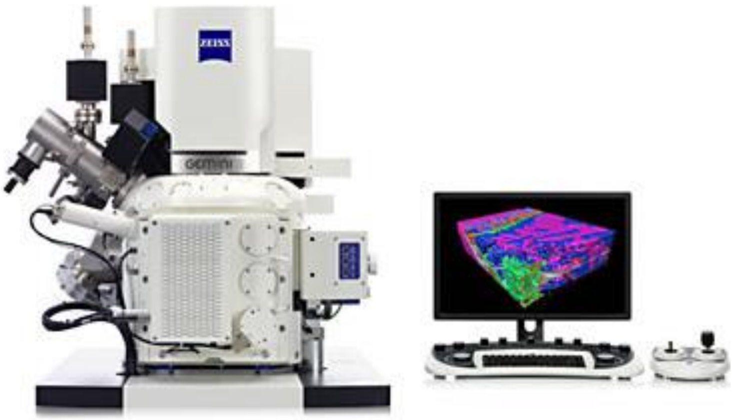

Figure 3.13: Zeiss Crossbeam 540

Chapter 4 - Results and Discussion

This chapter presents the findings of the experimental tests. The results are compiled in tables and compared with various standards according to the testing standard. This thesis aimed to localize the findings, but there are some situations where the Kazakhstan GOST standard lacks details on the requirements for selecting RBM based on a specific test. In this case, the tests were carried out in accordance with GOST standards, and the results were compared with a widely accepted standard. When the testing procedure or requirement is not specified in the GOST, an international standard(s) is used for the test and comparison.

4.1 Physical Properties

To fulfill the requirements of the GOST specification, the specific gravity of RBM must be greater than 2.4. According to the results in Table 4.1, the GOST specification is satisfied by the specific gravities of 3.29 and 3.25 for the top and bottom BOF slag, respectively. The stockpiled BOF slag has a low permeability, as measured by their absorption capacity, which is 1.18 and 1.15% for the Top and Bottom stockpiled BOF slag, respectively. The specific gravity of the stockpiled BOF slag is greater that the specific gravity of conventional aggregate used in ballast from [13, 27]. The stockpiled BOF slag also have a low absorption capacaity, much lower than the absorption capacity of 2% specified by GOST. The combination of these properties benefit the ballast because the material can offer lateral track support without becoming saturated.

Table 4.1 presents the flakiness index test results on stockpiled BOF slag samples. The flakiness index is a metric that characterizes the shape of the stockpiled BOF. Specifically, it quantifies the degree of elongation exhibited by an individual particle of the aggregate. A material exhibiting a high flakiness index is indicative of the existence of flat or elongated aggregates within it. Elongated aggregates in ballast are deemed unfavourable due to their proneness to breakage and inadequate interlocking properties between the constituent materials.

The flakiness index must be at most 15% to comply with GOST standards. The flakiness index ratio of the stockpiled BOF slag is significantly lower than the requirement; the top BOF slag demonstrates 9.67% flakiness, and the bottom BOF slag results in 10.12% flakiness. According to the GOST, both BOF slags meet the minimum requirement. This result is particularly better than the result of [7] who obtained the value of 22.4% for natural aggregates of Indian ballast. Moreover, the fact that the stockpiled BOF slag has a low flakiness index indicates that it contains a more significant proportion of cubic or rounded particles. These particles aid the drainage ability of ballast, can interlock with one another easily and will provide stable support for the track.

Lightweight aggregates are characterized by their porous nature, low density, and typically exhibit poor strength properties. These are undesirable properties in railway ballast. No significant lightweight particles were detected in the stockpiled BOF slag, as summarized in Table 4.1; there are less than 1% lightweight particles in the stockpiled BOF slag sample. This value is significantly lower than the 3.5% limit set by AREMA. Therefore, the stockpiled BOF slag is sufficiently dense enough not to float in a zinc chloride solution with a specific gravity of 2.0.

Table 4.1: Physical Properties of Stockpiled BOF slag results

Test	Top,	Bottom,	Requirement,	Method	Standard
Specific Gravity	3.29	3.25	> 2.4	GOST 7392-2014	KZ (GOST)
Absorption Capacity, %	1.18	1.15	< 2	GOST 7392-2014	KZ (GOST)
Flakiness Index, %	9.67	10.12	< 15	GOST 7392-2014	KZ (GOST)
Lightweight Particles, %	0.5	0.5	< 3.5	ASTM C123M-11	USA (AREMA)

4.2 Mechanical Properties

Table 4.2 displays the experimental test results for the mechanical properties of stockpiled BOF slag. The Los Angeles Abrasion test was conducted according to GOST and ASTM standards. The testing procedures for both methods are identical, but GOST is more conservative regarding the LA Abrasion requirement for RBM. ASTM uses a control sieve of 1.7 mm for the mass loss after testing, while GOST uses 0.4 mm. The LA Abrasion value is a crucial indicator of the quality of railway ballast. If the ballast has a low LA Abrasion value, it can withstand significant wear and tear without getting damaged. Ballast with a high LA Abrasion value is more likely to wear out quickly and needs to be replaced more often because it has a lower resistance to abrasion and impact. Standards and regulations for LA Abrasion vary from country to country; for instance, in the United States, the American Railway Engineering and Maintenance-of-Way Association (AREMA) requires that railway ballast not exceed a LA Abrasion value of 30%. The minimum acceptable mass loss for RBM for GOST, on the other hand, is 12%.

Stockpiled BOF slags fulfilled both GOST and ASTM requirements. Bottom BOF slag, with 11.4% and 17.9% mass loss according to GOST and ASTM, respectively, exhibited greater resistance to abrasion and breakage than Top BOF slag (11.7% and 18.9%). In terms of ASTM, the stockpiled BOF slag perform better than three out of five local ballast that was tested by [22], the result is also better than the abrasion value of dolomite according to [28]. The stockpiled BOF slag also have less mass loss than the natural aggregate of China as per [29]. Both Top and Bottom BOF slag is suitable for use as RBM regarding LAA Abrasion.

The Micro-Deval test assesses the degradation of aggregates under wet conditions, by subjecting them to the action of steel balls and water in a rotating steel drum. It takes into account degradation from both mechanical abrasion and weathering to simulate how an aggregate performs in the field when subjected to the traffic load in wet conditions. There is a small difference between the Micro-Deval abrasion values of the Top and Bottom BOF slag; nonetheless, both BOF met the minimum requirement of 9% of the Canadian standard. Like the abrasion resistance in a dry state, Bottom BOF slag, with a mass loss of 7.4%, performed better than Top BOF slag (8.4%) when it came to abrasion with steel balls in the presence of water.

Typically, a low ACV value is desirable for railway ballast to ensure desirable quality and durability over time. A lower ACV value indicates a ballast material that is strong and durable, whereas a higher value suggests a weak and unsuitable material for RBM. The ACV for the Top and Bottom stockpiled BOF slags is 19.3% and 20.5%, respectively, as shown in Table 4.2. The British Standard specifies that the allowable value of the ACV for RBM should be less than 22%, while the Australian Standard specifies that it should be less than 25%. Both standards employ a similar testing method, but the British standard takes a more conservative approach to mass loss. The stockpiled BOF slag satisfied British and Australian aggregate crushing requirements despite this and suitable for use as RBM.

The strength of a material increases as the value of AIV decreases. According to the data presented in Table 4.2, it can be observed that the Top and Bottom stockpiled BOF slag exhibits a mass loss of 15.5% and 16.1%, respectively; this ranks the stockpiled BOF slag as an exceptionally strong aggregate according to Indian Standards. The findings suggest that the impact of sudden loading has caused minimal destruction of the BOF slag. AIV test results followed a similar pattern to those of LA Abrasion and Micro Deval. Although the Bottom stockpiled BOF slag performed better than the Top stockpiled BOF slag, the maximum allowable mass loss for BOF slag is met by the British standard of 22% and the Indian standard of 20%.

Table 4.2: Mechanical Properties of Stockpiled BOF slag results

Test	Top, %	Bottom, %	Requirement, %	Method	Standard
LAA Abrasion	11.7	11.4	< 12	GOST 7392-2014	KZ (GOST)
	18.7	17.9	< 30	ASTM C535-16	USA (AREMA
Micro Deval	8.4	7.4	< 9	CS LS-618	Canada (CN)
Aggregate Crushing Value (ACV)	19.3	20.5	< 22	BS 812-110: 1990	UK (BS EN)
			< 25	T-205	Australia (AS)
Aggregate Impact Value (AIV)	16.1	15.5	< 22	BS 812-112:1990	UK (BS EN)
			< 20	IS.-2386	Indian (IS)

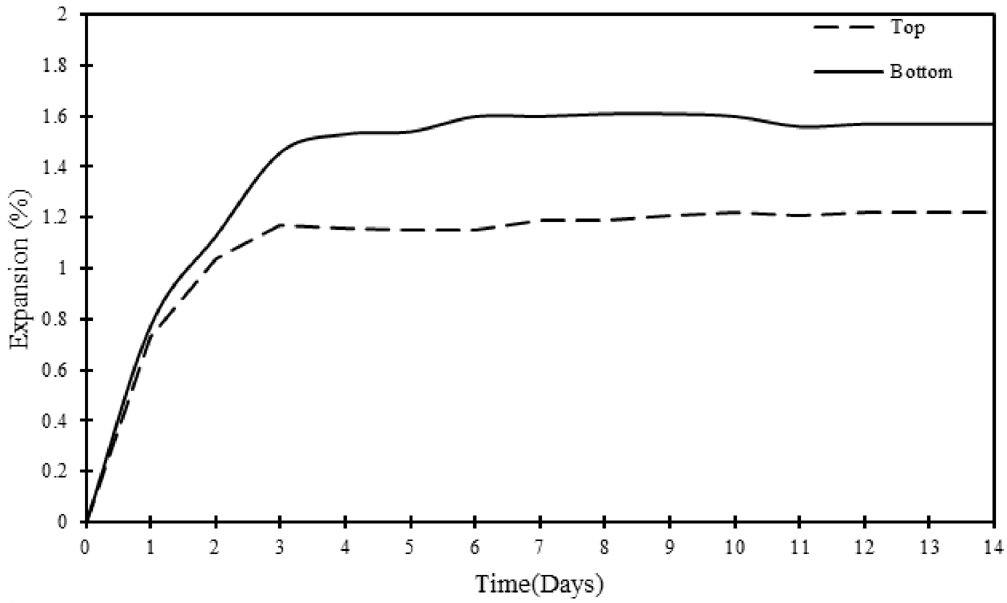

Figure 4.1: Expansion rate of Stockpiled BOF slag

Figure 4.1 shows the expansion rate of the stockpiled BOF slag for 14 days. There is an apparent identical trend in the expansion rate. Both BOF slags expanded until day four and remained relatively stable until day fourteen. The expansion rates of the Bottom BOF slag and the Top BOF slag after 14 days were 1.62 and 1.22 %, respectively. The expansion result is within the acceptable limit as per JIS A 5015 [30], which verifies the stockpiled BOF slag's natural weathering tendency. However, because the Top BOF slag is more exposed to air and moisture, it has aged more than the Bottom behavior slag; this explains why the Top BOF slag has a lower expansion rate than the Bottom BOF slag.

4.3 Environmental Properties

An efficient ballast material should retain its structural integrity and exhibit minimal or no deterioration following exposure to various freezing and thawing cycles. Table 4.3 displays the mass losses of BOF slag that have undergone 15 freeze and thaw cycles. The results indicate that the Top and Bottom stockpiled BOF slag experienced mass losses of 3.9% and 4.3%, respectively. The values fall below the minimum requirement of GOST, which requires that the ballast material exhibit a mass loss of no more than 5% after undergoing 15 cycles of freezing and thawing. Therefore, the Top and Bottom stockpiled BOF slag conforms to the standards set by GOST, exhibits remarkable durability against the detrimental effects of freeze-thaw cycles, and can endure the severe climatic conditions prevalent in Kazakhstan. To assess stockpiled BOF slag's stability, durability, and weathering resistance over time under varying climatic conditions. The soundness of the stockpiled BOF slag was evaluated using a sodium sulfate test, which involved exposing the material to wetting and drying cycles in a sodium sulfate solution. A low soundness loss indicates that the ballast material is more resistant to sulphate attack and, consequently, more resilient. Table 4.3 displays the results of the sodium sulphate-based soundness test for RBM. The relative values for the Top and Bottom BOF slags indicate a mass loss of 3.8% and 3.6%, respectively; the stockpiled BOF slag satisfied the AREMA minimum acceptable soundness loss of 5%. Therefore, the stockpiled BOF slag is resilient enough to provide long-term ballast performance in sulphate-containing environments.

Table 4.3: Environmental Properties of Stockpiled BOF slag results

Test	Top, %	Bottom, %	Requirement	Method	Standard
Freeze and Thaw	3.9	4.3	< 5%	GOST 7392-2014	KZ (GOST)
Soundness by sodium sulfate	3.8	3.6	< 5%	ASTM C88M-18	USA (AREMA)

Ballast material with organic impurities can cause serious issues, like clogged drains and overgrown vegetation. After 24 hours of immersion of stockpiled BOF slag in sodium hydroxide solution and comparisons to the ASTM color plate, it was observed that the soidium hydroxide solution did not change color, but the turbidity did. In addition, the solution colors do not match the reference colors of the color standard organic plate, indicating that the stockpiled BOF slag sample does not contain any organic impurities.

4.4 Chemical analysis

X-ray diffraction analysis was carried out using a SmartLab (Rigaku) X-ray diffractometer. Figure 4.2 shows the XRD patterns of the stockpiled BOF slag, which reveal a variety of crystalline phases. The most prevalent of these phases are Portlandite ($Ca(OH)_2$), Silicon Oxide (SiO_2), Calcite ($CaCO_3$), Periclase (MgO), and sreborodolskite ($Ca_2Fe_2O_5$). The presence of portlandite (Ca(OH)2), a product of the hydration process of free lime, indicates that a significant portion of the free lime present on the material has undergone hydration, due to the influence of water during the natural weathering process of the stockpiled BOF slag.

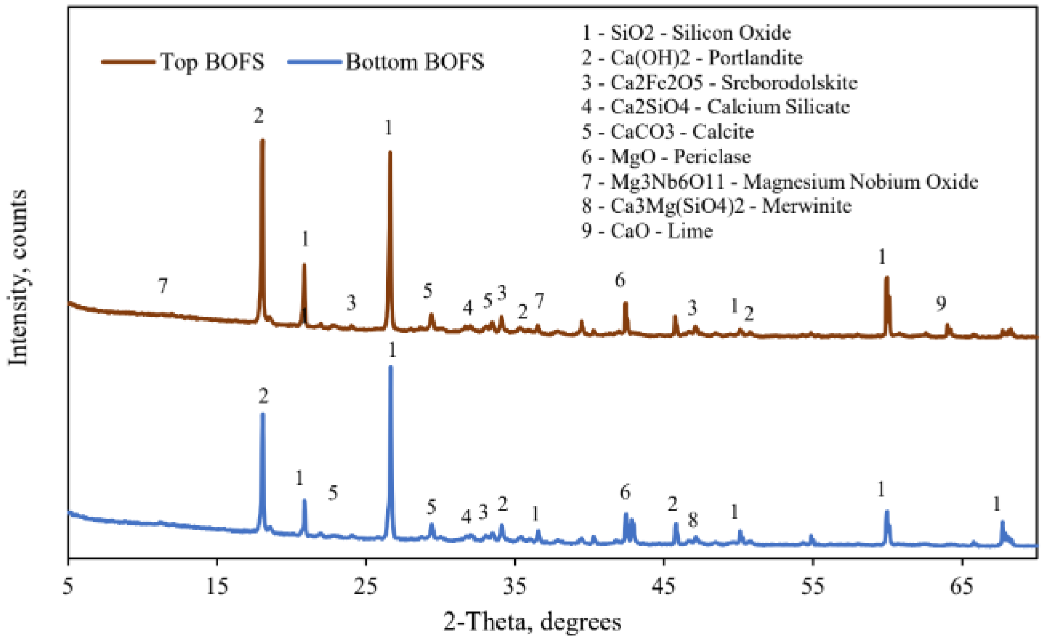

Figure 4.2: XRD patterns of Top & Bottom BOF slag

The surface images captured by a scanning electron microscope revealed information about the composition of stockpiled BOF slag. It was observed that stockpiled BOF slag has grains with a needle shape and surfaces with a plate shape. The plate shape is dictated by the aging of the material that is typical for portlandite ($Ca(OH)_2$), which forms as long as the material ages and free lime reacts to form portlandite ($Ca(OH)_2$) and calcite ($CaCO_3$). Plate shapes are more prominent in the Bottom BOF slag than in the Top BOF slag, which could be explained by their mean age differences of ten and three to four years, respectively.

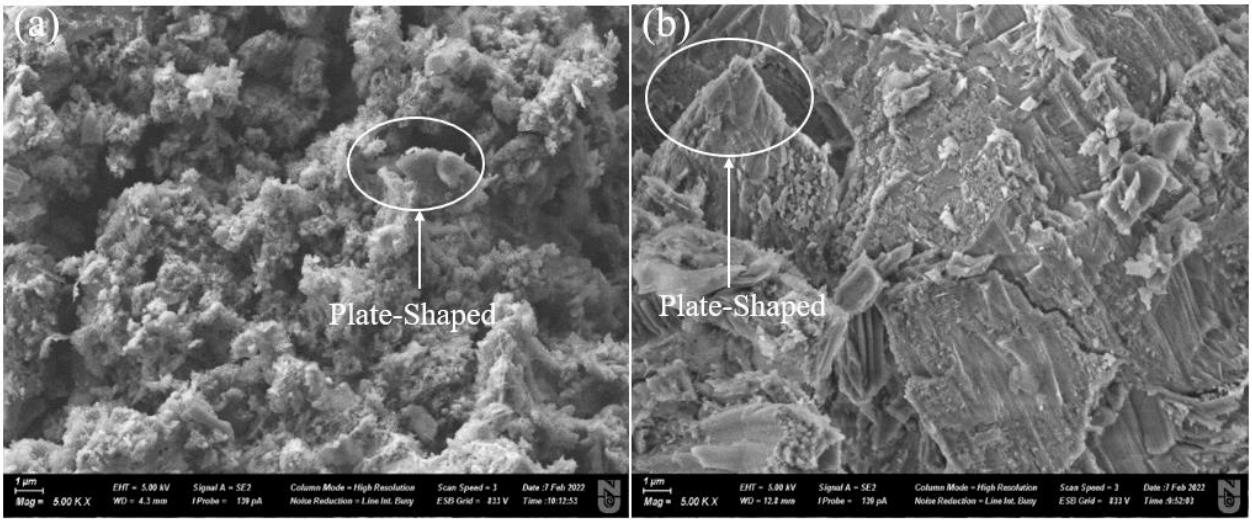

Figure 4.3: Stockpiled BOFS surface picture (a) Top, (b) Bottom

Chapter 5 - Conclusions

This study analyzed stockpiled BOF steel slag samples in terms of their physical, mechanical, environmental, and chemical properties. Several testing methods were developed. The stockpiled BOF slag from the Karaganda region of Kazakhstan was subjected to a series of laboratory tests to determine whether it complies with the GOST standards that govern the materials used in railway ballast in Kazakhstan. The following observations are made:

1. All the obtained results were found within limits as per the GOST requirement of railway ballast materials in Kazakhstan.
2. Stockpiled BOF slag samples contain less than minimal flaky materials. It indicates that it will provide for proper drainage, an important requirement to limit the fouling rate of railway ballast.
3. Stockpiled BOF slag aggregates were found to have good resistance against fragmentation, crushing, surface abrasion, and sudden loadingThey satisfy all the mechanical properties of aggregate used in Railway ballast.
4. The expansion results are much lower than the minimum requirement of the Japanese standard. However, it indicates that it is enough for stockpiled BOF slag to have natural aging processes.
5. Stockpiled BOF did not show vulnerability to the change in condition when subjected to freeze and thaw under sodium sulfate solution. Furthermore, it didn’t weather easily, indicating that it is ideal for railway ballast in the harsh Kazakhstan weather.

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