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Utilization of ferronicle slag for the manufacture of rotary kiln lining refractories

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ABSTRACT

Ferronickel slag waste from the nickel ore processing industry can be used as a refractory raw material for the inner wall lining of rotary kilns. However, the use of this waste still needs to be studied for its properties to meet the standards for its use in the industry. The purpose of this study was to find the optimal composition of a refractory mixture consisting of ferronickel slag, magnesium oxide (MgO), and aluminum oxide (Al_2O_3). The percentage composition of ferronickel slag and MgO was changed, while Al_2O_3 remained constant. The characterization of the refractories that had been made was carried out through a series of tests consisting of chemical composition testing using X-ray Fluorescence (XRF), porosity testing, bulk density, permanent linear change (PLC), and cold crushing strength (CCS). The results of the analysis showed that the ferronickel slag used as the main material in this study contained silica (SiO_2), magnesium oxide (MgO), and iron oxide (Fe_2O_3) which supported the properties of the refractories that had been made. The optimal refractory composition is 90% slag and 10% MgO, resulting in a porosity of 25.56% and a bulk density of 1.74 g/cm³, indicating a balance between strength and thermal insulation. The PLC green value of -0.8667% and the PLC dried value of -.1177% indicate good dimensional stability. The CCS test for the best composition produces a cold compressive strength of 1.44 MPa. The study indicate that refractories have thermal and mechanical resistance that supports their use as rotary kiln lining materials.

Keywords: Ferronickel slag; refractories; rotary kiln; mechanical properties; thermal properties.

1. Introduction

Ferronickel slag waste is a by-product produced from the nickel ore smelting process in the nickel metallurgy industry. The nickel ore smelting process is generally carried out in a furnace that heats the nickel ore together with additional materials such as coal and coke to produce ferronickel, which is a mixture of nickel and iron. During the smelting process, a complex chemical reaction occurs between nickel ore, additional materials, and fuel that produces toxic gases such as sulfur dioxide (SO_2) and carbon monoxide (CO). In addition to toxic gases, the smelting process also produces solid waste in the form of slag, which consists of a mixture of various metal oxides such as nickel oxide (NiO), iron oxide (Fe_2O_3), and other oxides formed as a result of reduction and oxidation reactions in the smelting furnace. Ferronickel slag, which is generally amorphous and has low commercial value, is currently largely underutilized and poses potential environmental hazards. On the other hand, industries such as cement, chemical processing, and waste treatment heavily rely on rotary kilns, which require high-performance refractory linings capable of withstanding extreme temperatures, chemical corrosion, and abrasion. Utilizing ferronickel slag as a raw material for refractory production offers economic benefits by reducing the cost of new materials and logistics, while also providing environmental advantages by lowering the volume of industrial waste [1][2].

The rotary kiln is one of the important equipment in various industries because of its crucial role in the production process. One of its main uses is in the cement industry, where this tool functions to create the high temperatures needed to calcine raw materials into cement clinker. This process involves complex chemical changes and requires stable temperatures for hours. In addition to the cement industry, rotary kilns are also used in the chemical industry to calcine various materials such as lime and dolomite, producing products such as burnt lime and burnt dolomite. Not only that, rotary kilns also play a role in waste processing, for example, in the process of pyrolysis, combustion, or calcination of waste to reduce volume or make it safer. With their diverse capabilities, rotary kilns are one of the main pieces of equipment in various industrial sectors, playing an important role in complex and diverse production processes [3][4]. Rotary kiln refractory lining is an important component in various industries, such as cement production, chemical calcination, and waste treatment. Its main function is to maintain thermal stability and ensure that the kiln works optimally during the production process [5]. Refractories are installed in rotary kilns as linings to withstand the high temperatures required in the process of burning raw materials into clinker. The performance of this lining greatly affects the efficiency of maintenance costs, kiln operations and the quality of the final product. Therefore, the refractory material used must be resistant to high temperatures, chemical corrosion, and abrasion in order to maintain the integrity of the structure and overall performance of the kiln. The selection of the right refractory material and optimal lining design are crucial factors in kiln planning and operation [6][7]. In addition, innovations in refractory technology continue to be developed to extend the service life of the lining, reduce energy consumption, and increase production efficiency. By understanding the characteristics of refractory materials and lining design principles in depth, the industry can optimize kiln performance and improve the effectiveness of the production process [8][9].

The use of ferronickel slag waste as a primary material in the production of fire-resistant coatings has great potential, both economically and environmentally. From an economic standpoint, repurposing this waste can significantly reduce production costs. By utilizing it as an alternative raw material, companies can cut expenses on new material purchases while also improving waste management efficiency. Moreover, since ferronickel slag is generally available near nickel production sites, transportation costs associated with sourcing raw materials from other locations can be minimized. This efficiency provides companies with a competitive advantage in an increasingly intense industrial market [10]. From an environmental standpoint, reusing ferronickel slag waste also has a positive impact. Waste that was once considered unusable and required extra management costs can now be repurposed, significantly reducing its environmental impact. This strategy helps lower the volume of waste sent to landfills while also mitigating the risks of soil, water, and air pollution. This initiative also aligns with sustainable business practices, enhancing the company's standing as an environmentally responsible organization. In general, utilizing ferronickel slag waste in fire-resistant coating production provides a cost-efficient solution while offering substantial environmental benefits. By adopting this method, companies can balance economic efficiency with environmental responsibility, supporting the long-term sustainability of their operations [11].

Over the past decade, several studies have explored the potential of ferronickel slag as a raw material for refractories. Utilized ferronickel slag waste as raw material for refractory production by adding MgO followed by compaction and a roasting process at 1200°C for 30 minutes with a heating rate of 5°C/min. The results showed that the forsterite (Mg_2SiO_4) and spinel phases increased with higher MgO addition, and the maximum compressive strength was achieved with the addition of 30 wt% MgO [12]. Developed a novel strategy to produce refractory materials from hazardous ferronickel slag through microwave sintering with the addition of 25 wt% sintered magnesia. As a result, a high-quality refractory material was obtained at 1350°C for 20 minutes, with properties including a refractoriness of 1730°C, bulk density of 2.80 g/cm^3, apparent porosity of 1.6%, and compressive strength of 206.62 MPa [11]. Verified the feasibility of utilizing ferronickel slag as a raw material for refractory production with the addition of magnesia, based on thermodynamic analysis and testing at various sintering temperatures. Thermodynamic calculations showed that MgO reacted with SiO_2 to form forsterite and enstatite, while reactions with Fe_2O_3/Al_2O_3 produced magnesia spinels. The resulting refractory material had a refractoriness of 1580°C, a bulk density of 2.88 g/cm^3, a compressive strength of 106.9 MPa, and an apparent porosity of 5.8% [10]. Investigates the use of ferronickel slag, an industrial by-product, as a supplementary cementitious material (SCM) to reduce the cement industry's carbon footprint. Compared to standard curing, the compressive strength of ferronickel slag (FNS) cement paste increased by 8.2% and 33.8%, respectively, while connected porosity decreased by 18.9% and 17.3% [13]. Investigated the use of two types of industrial byproducts—FeNi slag and Electric Arc Furnace (EAF) slag combined with natural sand as concrete aggregates, and compared them with concrete made using natural limestone aggregates. The results showed that concretes with higher EAF slag content exhibited superior mechanical strength at both 7 and 28 days compared to other mixtures and limestone-based concretes [14].

Although previous studies have demonstrated promising potential, their focus has remained limited to the utilization of ferronickel slag as a raw material for refractories and cement in general, rather than its application as a refractory lining material for rotary kilns. In fact, the use of ferronickel slag waste as a refractory lining in rotary kilns presents an intriguing potential that warrants further investigation. Currently, the industry generally relies on refractory materials from primary raw materials, such as synthetic refractory materials or certain minerals. With growing awareness of the need for sustainability and industrial waste reduction, ferronickel slag waste is being recognized as a possible alternative raw resource. To maximize its potential, a examination of the relevant material properties was carried out required, including chemical composition, bulk density, porosity, permanent linear change (PLC), and cold crushing strength (CCS). With this comprehensive insight, ferronickel slag waste can be better utilized to produce refractory linings that are both efficient and effective. Therefore, further research comprehensive and well directed is urgently needed to explore the full capabilities of ferronickel slag waste in this context.

2. Method

This study will start from the analysis stage of the physical properties of the ferronickel slag waste. Standard laboratory analysis techniques will be used to test the chemical composition, physical properties, and thermal properties of ferronickel slag waste at this stage. Such analysis will allow us to appraise the potential of ferronickel slag waste as a raw material for rotary kiln lining refractories. Furthermore, the research will involve the development stage of the lining refractory manufacturing method. Based on the results of the analysis of the characteristics of the ferronickel slag waste material, various mixture formulas will be designed with the necessary additional materials to achieve the desired properties in the lining refractory. Mixing, compaction, and formation of the lining refractory will be performed following approved procedures. The second stage is to test the properties of the rotary kiln lining refractory after the lining refractory production is completed. Assessing the feasibility of ferronickel slag waste in the production of rotary kiln lining refractories will be based on the results of this test.

Refractory making

Ferronickel slag is dried then crushed and ground to a size of 200 mesh. After the size is uniform, several grams of sample are characterized using XRF (X-ray fluorescence). The prepared ferronickel slag sample is divided and additional materials are added, namely magnesia (MgO), aluminum oxide (Al_2O_3) and water. The addition of MgO is varied from 0-60% with an interval of 10%. The mass of slag is adjusted to the mass of MgO so that the total mass of slag and MgO is 100%. For the addition of Al_2O3 and water, it is made constant where Al_2O_3 is 10% and water is 10-20% of the total mass of slag with MgO (Table *1*). The molding process is carried out by mixing all the ingredients according to their respective compositions until evenly distributed and then inserting them into the mold (Figure *1*). The quality of the mixture is checked using the ball in-hand test technique (Figure *1*). Refractory molds consist of 2 sizes that are adjusted to the type of testing to be carried out. The mold size is 5x5x5 cm for porosity, bulk density and cold crushing strength tests, while the mold size is 5x5x15 cm for permanent linear change tests. The molded mixture is then dried at room temperature until it solidifies and hardens, then ovened at 150°C for ±12 hours for the drying process.

Figure 1. Mold and ball in-hand test technique

Table 1. Refractory material mixture composition (%)

Slag	MgO	Al_2O_3	Water
100	0	10	10
90	10	10	10
80	20	10	10
70	30	10	10
60	40	10	10
50	50	10	10
40	60	10	10

Refractory test

a. Porosity and bulk density test

The method used in porosity and bulk density testing uses the ASTM C 20–00 standard with the following testing procedures (Figure *2*):

The test material is castable refractory that has been cast in a cube shape with dimensions of 5x5x5 cm. The test material is dried in an oven at a temperature of 105-110^{o}C for ±2 hours. After cooling, the test material is weighed until its weight remains constant. The weight obtained is the dry weight (D), with an accuracy of 0.1 grams. The test material is then soaked in water and heated for 2 hours until boiling, but there is no contact with the bottom of the heater. After boiling, the test object is cooled to room temperature but still in water for at least 12 hours. The test material is then weighed in a submerged state with a weighing balance. The weight obtained is the weight in water (S) with an accuracy of 0.1 grams. The test object is then removed from the water and washed with a cloth to remove water on the surface of the test object. The test material is then weighed to obtain the dry surface weight (W) with an accuracy of 0.1 grams. The calculation of the exterior volume, porosity and bulk density of the test material follows the equation below.

$$\text{Exterior Volume, } V_E = W - S \quad (1)$$

$$\text{Apparent Porosity, } P\ (\%) = \left(\frac{W-D}{V_E}\right) x\ 100 \quad (2)$$

$$\text{Bulk Density, } B\ \left(\frac{g}{cm^3}\right) = \frac{D}{V_E} \quad (3)$$

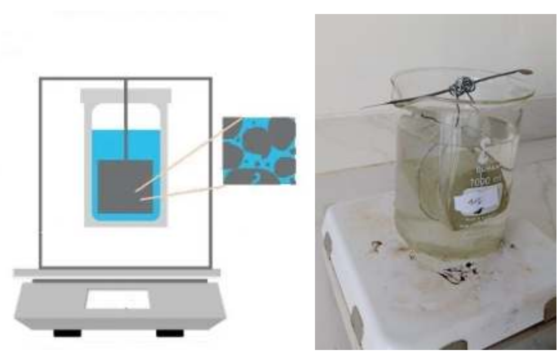

Figure 2. Porosity and bulk density test

b. Permanent linear change (PLC) test

PLC testing uses the ASTM C 134 test method which has been adjusted to the following procedure:

At room temperature, measure the initial length of the test material (a) green refractory with an accuracy of 0.025 mm on 4 sides of the test object. The test object is then dried in an oven for 12 hours at a temperature of 104–110°C. After being removed and cooled, the test object is measured again (b). The test object is then heated in a furnace at a temperature of 1200°C, left for 5 hours, removed, cooled to room temperature, and then measured again (c). The green-to-dried PLC and dried-to-fired PLC values are determined by the equation using the equation below.

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$$\text{PLC green to dried} = \frac{a-b}{a} \quad (4)$$

$$\text{PLC green to fired} = \frac{b-c}{b} \quad (5)$$

c. Cold crushing strength (CCS) test

Cold crushing strength tests of the refractory material according to the ASTM C133 standard are conducted to determine the room-temperature compressive strength of the material. The product being tested is the test product that gave the highest result from the previous porosity, bulk density and permanent linear change tests. In order to be able to carry out the test, the test material must be in the form of a 5×5×5 cm cube with parallel and flat top and bottom surfaces. The sample is placed between two parallel steel plates in a compression testing machine, and then loaded equally at some rate of loading until failure. Maximum force at the time of rupture is used to find the CCS value in MPa or kg/cm².

3. Results and Discussion

The sample preparation process is a very important initial stage in ensuring the accuracy and representativeness of the initial material characterization data. In this study, ferronickel slag was first dried to remove free water content that could affect the results of chemical analysis, especially for initial testing using the XRF (X-ray fluorescence) method, which is sensitive to humidity. The dried sample as shown in Figure *5* was then reduced in size through a crushing and grinding process to a size of 200 mesh (around 75 micrometers). A fine and uniform particle size is very important to obtain homogeneous and representative chemical analysis results. The 200 mesh size was chosen because this size is small enough to ensure an even distribution of elements in the sample. After particle size homogenization, a small amount of sample was taken to be analyzed using X-ray fluorescence (XRF). XRF is used because it has fast and accurate elemental analysis capabilities, especially in the determination of the major contents such as SiO_2, MgO, Al_2O_3, FeO/Fe_2O_3, and CaO in ferronickel slag. The results of this characterization will be the basis for determining the suitability of slag as a refractory raw material, as well as a reference for the formulation of mixtures and the addition of additional materials in the refractory manufacturing process.

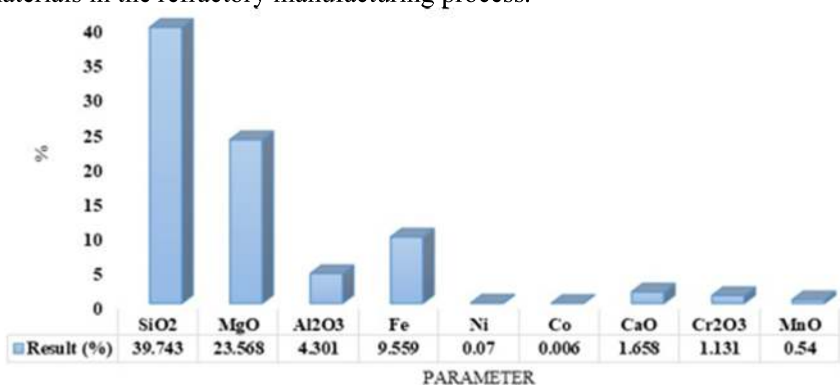

Figure 3. XRF test results of ferronickel slag samples

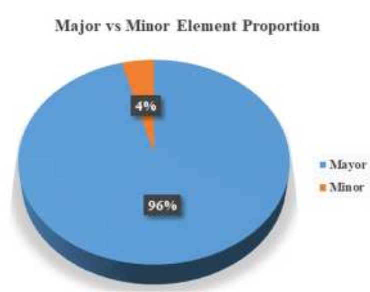

Figure 4. Major dan minor element chemical composition dan proportion

The results of the X-ray fluorescence (XRF) test on the ferronickel slag sample are shown in Figure *3* and Figure *4* above. The results show the main chemical composition of the analyzed ferronickel slag. The results of the XRF analysis of ferronickel slag show that this sample is dominated by metal oxides such as SiO_2, Al_2O_3, MgO, and FeO, with minor contents of NiO, Cr_2O_3, and CaO. SiO_2 and MgO found in significant amounts can contribute as refractory matrix-forming materials, providing thermal stability and resistance to high-temperature working environments. The MgO content is very important because it plays a role in increasing the refractory properties and resistance to thermal spalling. The presence of FeO can provide additional mechanical strength but can form a source of oxidation problems at high temperatures if the percentage is too high. The presence of Cr_2O_3 as an impurity can possibly provide chemical resistance to aggressive environments, i.e., the presence of alkaline slag in rotary kilns. CaO content is also significant to look at, as it can be used to add bonding properties when sintered, although a very high concentration will result in breakdown of structure. Based on the result of this chemical composition test, it indicates that ferronickel slag is extremely promising as a refractory base material because the majority of its components are thermally stable at high temperatures and possess good mechanical properties. But the presence of impurities as it could short the wanted refractory characteristics.

The refractory manufacturing process in this study adopted a composition variation approach, especially in the magnesia (MgO) content, to determine its effect on the physical and mechanical properties of ferronickel slag-based refractory materials. The addition of MgO was varied between 0% and 60% with an interval of 10%. This strategy aims to evaluate the extent to which increasing the magnesia content can improve the fire resistance, high-temperature resistance, and mechanical strength of refractory bricks. MgO is known as a refractory material that is very resistant to alkaline environments and extreme temperatures, so it is expected to improve the performance of ferronickel slag, which has a relatively high silica content (acidic). While maintaining the total mass between slag and MgO at 100%, composition balancing was carried out so that the comparison could be directly compared to the properties of the resulting material. The constant addition of 10% alumina (Al_2O_3) is designed to contribute to the formation of a stable high-temperature spinel phase ($MgAl_2O_4$) that may be utilized for increasing the strength of the microstructure of the refractory. Spinel exhibits excellent thermomechanical characteristics, and the incorporation of this will be expected to increase strength as well as resistance to thermal shock. Water is added in the ratio of 10–20% of the weight of slag and MgO to facilitate easier mixing and molding. The water content must be adequately controlled so that the mixture is plastic enough to mold but not liquid enough to cause particle segregation and high porosity.

All the ingredients are mixed until homogeneous with hand or mechanical mixing techniques, and the quality of the mixture is ensured with a ball-in-hand test, an easy technique to determine if the mixture contains sufficient moisture and consistency to shape. The method is widely used in the refractory industry to determine the cohesiveness of the mix without the use of special laboratory measuring equipment. Molding is carried out in two sizes: a) 5x5x5 cm: for testing porosity, bulk density, and cold crushing strength. b) 5x5x15 cm: for testing permanent linear change.

The dimensions for the molds for testing porosity, bulk density, and cold crushing strength have followed the general standards for refractory material testing (ASTM C134 and C20), while the molds for testing permanent linear change are adjusted but do not reduce the accurate representation of product performance in actual applications for rotary kiln linings. After molding, the samples are first dried at ambient temperature until they naturally harden. This is done to prevent cracking or deformation when heated. The sample is then oven-dried at 150°C for ±12 hours to enable the free water present to evaporate slowly without destroying the microstructure due to sudden release of water. This gradual dehydration also creates a precursor phase before sintering, which is usually carried out at high temperatures for the determination of the thermomechanical properties of the material.

Figure 5. Ferronickel slag and refractory samples

Porosity is one of the most important physical parameters in assessing the quality of refractory materials, especially for applications as linings in rotary kilns operating at high temperatures, extreme pressures, and aggressive chemical environments. This study conducted tests on the porosity of refractory materials, which resulted from mixing ferronickel slag and magnesium oxide (MgO) with various composition variations. The purpose of this test was to determine the effect of the slag and MgO ratio on the resulting porosity value and to assess its suitability based on the ideal standard for refractory material porosity, which is in the range of 15–25% [15] [16] [17]. Over-porosity will result in structural defects in the refractory since cavities in the material may become an entry site for hot gas, slag melt, or penetrating chemicals that can enhance material deterioration. At the same time, too high a porosity is also not favorable since it causes the material to become overly brittle and subject to cracking due to an uneven thermal expansion, especially when exposed to rapid extreme temperatures (thermal shock). Therefore, the ideal value of the porosity must be such that it exists in some specific range to achieve equilibrium between thermal resistance, mechanical strength, and chemical attack resistance.

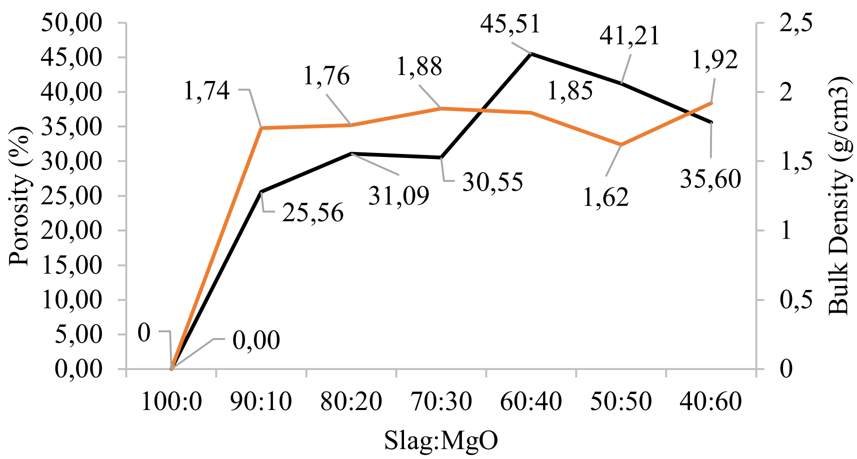

Figure 6. Porosity and bulk density test results

Porosity test data obtained from various compositions showed quite significant variations (Figure *6*). The composition of slag:MgO 100:0 showed a porosity value of 0%, this was because the sample was immediately destroyed when immersed in water. Meanwhile, the composition of slag:MgO 90:10 showed a porosity value of 25.56%, which was right at the upper limit of the ideal porosity range for rotary kiln applications, making this composition the best candidate of all the samples tested. This indicates that the addition of 10% MgO to the ferronickel slag matrix produces a fairly dense microstructure, with a fairly good particle distribution and interaction between phases so that open cavities in the material are still within the tolerance limit [19]. However, when the MgO content was increased to 20% (slag:MgO 80:20), there was a spike in porosity to 31.09%, indicating the formation of a more open and loose structure due to reduced cohesion between particles [20]. The porosity value continues to show a high tendency in the following compositions: 30.55% (slag:MgO 70:30), then jumps drastically to 45.51% (slag:MgO 60:40). This increase in porosity value can be explained by several main aspects. First, the increase in porosity in compositions with high MgO content is caused by the physical properties of MgO particles, which are hard, stiff, and non-plastic. In molding without pressure, MgO particles have difficulty arranging themselves tightly, so many cavities are formed. In contrast to ferronickel slag, which is finer and easily fills gaps, MgO causes the mixture to be less cohesive and have poor flow. As a result, the structure formed has many open pores after drying. Without external pressure, the dominant particle character greatly affects the density, so that increasing MgO tends to increase the porosity of refractory materials [13]. Second, in preparing the refractory mixture, ferronickel slag plays a role too as a filler because it has a finer particle size than magnesium oxide (MgO). Its fine particles can occupy interstices among larger particle grains, specifically of MgO, thus creating a denser structure and reducing the voids or pores in the mixture.

When the slag content is reduced and replaced with coarser MgO, the level of finer particles in the mix is considerably reduced. As a result, the intergranular voids are poorly filled, causing open porosity to rise extensively. This lack of balance between fine and coarse particles also reduces the mechanical interlocking property of the material upon molding, wherein the structure is loose and susceptible to void formation during drying [18].

Based on the results of the porosity test, the composition of 90% slag and 10% MgO showed the best composition because it had the lowest porosity. Lower porosity and lower pore size are generally better and preferred because lower porosity is able to hold the liquid phase and gas from infiltrating the refractory [21]. While refractories that have large porosity will generally result in damage to the refractory, such as corrosion [22]. Chemically, the relationship between ferronickel slag composition and porosity properties can be further linked to XRF results. Ferronickel slag is generally rich in SiO_2, Al_2O_3, MgO, and FeO. SiO_2 and Al_2O_3 tend to form glass phases that increase density, while MgO plays a role in stabilizing high-temperature phases such as periclase (MgO) or magnesia spinel. The addition of appropriate and excessive MgO will only increase open porosity. Therefore, the selection of the optimal slag and MgO ratio is very important to ensure good performance of the refractory in applications such as rotary kiln lining.

One of the main parameters in evaluating the quality of refractory materials is bulk density. Bulk density is directly related to the mechanical resistance and the ability of the material to withstand extreme conditions such as high pressure and thermal shock. Based on test data (Figure *6*), the addition of MgO to ferronickel slag has a significant effect on the bulk density value of the material. At 100% slag composition without MgO, the bulk density data was recorded at 0 g/cm³, which was caused by the destruction of the sample when placed in water. When MgO was added as much as 10% (slag:MgO composition 90:10), the bulk density was recorded at 1.74 g/cm³. The addition of MgO, namely at the compositions of 80:20 and 70:30, resulted in an increase in bulk density to 1.76 g/cm³ and 1.88 g/cm³, respectively. This increase in bulk density value indicates that at this composition range, MgO helps strengthen the bonds between particles in the material structure, resulting in a denser material. At a composition of 60:40, however, the bulk density decreased slightly to 1.85 g/cm³, indicating a balance between the impact of MgO on the structure of the material and the development of density. The material is still dense enough for refractory applications in this condition. A more significant decrease in bulk density occurred at the composition of 50:50 with a value of 1.62 g/cm³, indicating that the addition of quite high MgO began to have a negative impact on the density of the material. This can reduce the mechanical strength and resistance of the material under severe operating conditions. Interestingly, at the composition of slag:MgO 40:60, the bulk density increased again to 1.92 g/cm³, which can be either due to a change in the structure of the material or the crystalline phase to achieve a higher density even though it contains a high level of MgO. indicating that the addition of comparatively high MgO began to show an adverse effect on the density of the material. This phenomenon can reduce the mechanical strength and resistance of the material under severe operating conditions. Surprisingly, at the composition of slag:MgO 40:60, the bulk density increased again to 1.92 g/cm³, possibly due to structural or crystalline phase changes in the material towards having a higher density despite the high proportion of MgO [11][12][23]. Results of Bulk Density test are also closely related to Porosity test results. Tends to be typically that the higher the bulk density, the lower the porosity, which indicates that the denser the structure of the material and there are fewer open pores. This is clearly seen in the composition of slag: MgO 70:30 and 40:60, where the highest bulk density is obtained in the composition of slag: MgO 40:60 of 1.92 g/cm³. Conversely, when porosity increases, the bulk density decreases as shown in the composition of slag: MgO 60:40 with a bulk density value of 1.85 g/cm³. Based on the standard bulk density value for rotary kiln refractories (bulk density> 2.0 g/cm³) [15], the results of this study indicate that the bulk density values obtained are all still below the standard.

Permanent Linear Change is an important parameter that reflects the dimensional stability of refractories after going through heating and cooling cycles. The PLC value, both in green (before high-temperature heating) and dried (after high-temperature heating) conditions, provides an indication of whether the material undergoes permanent expansion or shrinkage after heating.

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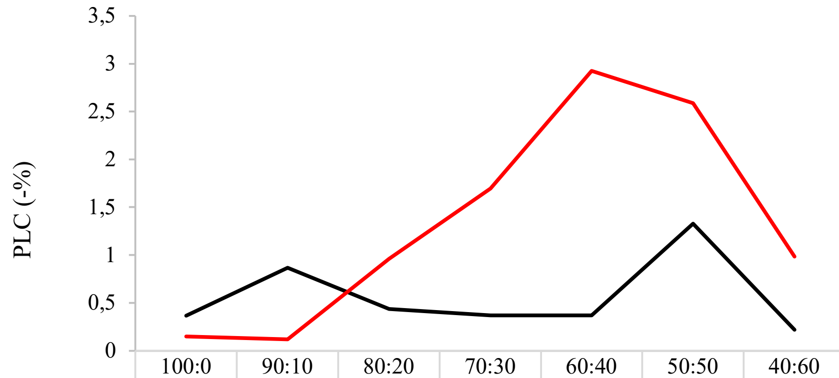

	100:0	90:10	80:20	70:30	60:40	50:50	40:60
PLC Green (-%)	0,3681	0,8667	0,4362	0,3716	0,3698	1,3283	0,2177
PLC Dried (-%)	0,1512	0,1177	0,9606	1,6955	2,9239	2,5860	0,9852

Slag:MgO

Figure 7. Permanent linear change test results

According to the data provided (Figure 7), the variation in ferronickel slag composition and MgO content has a significant effect on the PLC value. At 100% slag composition and 0% MgO, green PLC is -0.3681% and dried PLC is -0.1512%. This negative value indicates that the refractory material experiences a small permanent shrinkage when heated, indicating a chemical reaction and physical process that occur during heating. Based on XRF data, this chemical reaction can be caused by the presence of components that, when heated, produce new phases that have a lower melting point than other materials, causing melting and phase movement when the temperature increases. When these phases melt, local melting occurs on the surface or in the structure of the material. This melting triggers the development of cavities, pores, and volumetric deformation that cannot return to their original state when cooled, causing permanent dimensional changes [15].

Based on PLC Green data, all samples after MgO addition showed a decrease in dimensional shrinkage of up to -0.2177%. These results indicate that reducing the slag composition and increasing the MgO composition make the resulting refractory structure tend to be stable in the early stages of its formation as a refractory brick. This is likely due to the initial reaction between MgO and the components in the slag that began to occur even though it had not gone through full heating. Producing good dimensional stability at the green body stage so that it does not pose a risk of deformation before the drying or firing process. When compared with the PLC Dried test results, based on the test data, it can be seen that the PLC Dried value tends to increase (more negative) along with the increasing MgO content in the mixture, which reflects the occurrence of greater permanent linear contraction after further heating or sintering. At a composition of 60% MgO, the PLC dried reached -2.9293%, the highest value of all samples. On the other hand, the PLC Green value actually shows a smaller trend with increasing MgO, which indicates that the material, when still in a wet or unsintered condition, has better dimensional stability. This relationship shows that although increasing MgO improves the initial stability during formation (green body), at high temperatures, MgO can trigger significant phase reactions and structural shrinkage, such as the formation of spinel ($MgAl_2O_4$) or forsterite (Mg_2SiO_4) phases that cause larger volume changes and permanent contraction [15]. The composition of 90% slag and 10% MgO showed the best performance compared to other composition variations. Under these conditions, the PLC green value was recorded at -0.8667%, and the PLC dried was -0.1177%, which is one of the smallest shrinkage values. This minimal shrinkage indicates that the refractory with this composition has good dimensional stability after heat treatment, which is very important for applications as rotary kiln linings. This result is supported by the chemical composition of ferronickel slag based on XRF analysis, where the content of the main oxides, such as FeO and SiO_2, still provides structural stability, while the addition of MgO forms a magnesia-spinel phase that contributes to thermal resistance without causing excessive shrinkage. With optimal dimensional stability, the composition of 90% slag and 10% MgO is the right choice to improve the reliability and longevity of refractories in high-temperature applications, such as rotary kilns.

Table 2. Cold crushing strength test results

Slag (%)	MgO (%)	Al_2O_3 (%)	Water (%)	CCS	
				KgF/Cm^2	MPa
90	10	10	10	14.68	1.44

Cold Crushing Strength is an important mechanical refractory parameter for evaluation because it is a measure of the mechanical strength of the material under ambient temperature conditions. CCS testing is conducted to determine that the refractory will be able to withstand working loads in severe environmental conditions without failure of the structure. In this study, CCS testing was only conducted on a composition of 90% slag and 10% MgO because this composition has shown the best results from previous porosity, bulk density, and permanent linear change tests. The test results in Table 2 showed a CCS value of 14.68 kgf/cm² or the equivalent of 1.44 MPa. The cold crushing strength value of this sample is within the range of values generally applied to refractories for lining kilns such as rotary kilns, although it is relatively lower than the general standard value, which is above 20 MPa [15]. These results indicate that although the composition of 90% slag and 10% MgO shows minimal shrinkage (good dimensional stability), this does not guarantee optimal mechanical performance. The low CCS value actually indicates that the microstructure is still loose and brittle, possibly because the sintering process has not been maximized and the dominance of slag does not support the formation of strong phases. This can be seen from the chemical composition of 90% slag, where ferronickel slag still contains many amorphous and brittle silicate phases, while the MgO content of only 10% is not enough to form strong phases such as forsterite (Mg_2SiO_4) dominantly.

4. Conclusion

Ferronickel slag has high potential as a refractory raw material for rotary kiln lining. The XRF test results show that this slag contains main compounds such as SiO_2, MgO, FeO, and Al_2O_3, which are important in the formation of refractory materials. The content of SiO_2 and FeO provides structural strength, while MgO contributes to increasing thermal stability and mechanical strength through the formation of the spinel phase. Refractories made with a composition of 90% slag and 10% MgO show the best physical and mechanical properties, with a porosity of 25.56% and a bulk density of 1.74 g/cm³. The low Permanent Linear Change value indicates the dimensional stability of the material after the heating process, although the Cold Crushing Strength value is still below standard.

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