

Research Article

Dodola Iron Ore as Sustainable Iron Source for Clinker Production: Quantitative Analysis of Quality, Reactivity, and Environmental Benefits in Ethiopia

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Abstract

The rapid industrialization of Ethiopia, catalyzed by major infrastructure projects like the Great Ethiopian Renaissance Dam (GERD), Koysha Hydroelectric Dam, Road and Railway Expansion, and Industrial Parks has necessitated a strategic shift toward domestic raw material sourcing for cement production. This study evaluates the technical and mineralogical viability of Dodola iron ore, hosted within the Precambrian meta-gabbro suites of the Bale Administrative Region, as a sustainable iron corrective for Portland cement clinker. Quantitative geochemical analysis reveals a distinctive composition characterized by an average total iron (Fe_2O_3) content of 45.6% and a significant titanium dioxide (TiO_2) concentration of 11.12%. While standard industrial thresholds typically limit TiO_2 to less than 1.0%, this research demonstrates that at controlled concentrations, the titanium acts as a potent mineralizer that reduces the clinker melt viscosity and lowers the liquid phase formation temperature by 50°C to 100°C. This "soft burning" effect optimizes kiln efficiency, facilitates a potential 6.44% increase in alite content, and reduces the carbon footprint associated with high-heat calcination and long-range logistics. The integration of Dodola iron ore into a recalibrated raw mix offers a dual benefit of improving clinker reactivity while aligning the Ethiopian cement sector with national "Green Growth" and circular economy objectives.

Keywords

Dodola Iron Ore, Clinkerization Kinetics, Titanium Dioxide Mineralizer, Raw Mix Optimization, Ethiopian Cement Industry

1. Introduction

The rapid industrialization of Ethiopia, fueled by transformative infrastructure projects like the Great Ethiopian Renaissance Dam (GERD), has created an urgent demand for a robust domestic supply of hydraulic binders. Given that the construction of the GERD alone required over 10 million tonnes of cement, the strategic exploration of iron ore is essential for national industrial self-sufficiency. This analysis evaluates the

technical viability of Dodola iron ore as a raw material for Portland cement clinker production, focusing on its chemical composition and mineralogical reactivity. By optimizing the raw mix with local iron sources, the Ethiopian Cement production sector can improve clinker quality while simultaneously reducing its carbon footprint through more efficient kiln operations and localized sourcing. [1].

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1.1. Geological and Tectonic Framework of the Bale Administrative Region

The geological evolution of the Dodola area, situated within the Bale Administrative Region, is foundational to the formation and mineralogical quality of its iron occurrences. This region is primarily underlain by the crystalline basement of southern Ethiopia, consisting of Precambrian metamorphic rocks that have endured a history of poly-metamorphism and complex structural deformations. These lithologies are characterized by high-grade metamorphic assemblages that were subsequently modified by later retrogressive events, creating the distinct geochemical environments necessary for iron enrichment. Understanding these Proterozoic basement complexes is vital, as they represent the northern extension of the East African Orogen, where tectonic sutures and shear zones often control the localization of high-grade ore deposits. [2].

1.2. Lithological Units and Stratigraphic Sequence

The geological framework of the Dodola sheet is defined by a complex stratigraphic succession primarily composed of gneissic units and mafic to ultramafic complexes. Within the metamorphic basement, the Augen Biotite Gneiss (Abgn) and Biotite-Quartz-Plagioclase Gneiss represent high-strain environments characterized by significant tectonic deformation and migmatization. These units are mineralogically dominated by oligoclase, quartz, and biotite, with the presence of myrmekite and undulose extinction serving as indicators of intense structural stress [3]. Additionally, the occurrence of Garnetiferous Biotite Gneiss northeast of Melka Arba highlights a history of high-pressure metamorphism, subsequently followed by retrograde stages evidenced by the development of chlorite and epidote [4].

Associated with these gneissic rocks are patchy outcrops of amphibolite and substantial Meta-Gabbro (Mg) suites. The meta-gabbro, particularly on the Calido ridge, serves as the critical host for regional iron mineralization. This lithology is petrographically heterogeneous, containing a primary assemblage of labradorite, diopside, and olivine, with secondary alterations such as uraltized pyroxene and kelyphitic rims [5]. These mineralogical transitions suggest a sophisticated interplay between original magmatic crystallization and later metamorphic overprinting, which shaped the current geochemical landscape of the Dodola region.

The iron ore deposits within this succession are specifically confined to the meta-gabbro, meta-diorite, and meta-anorthosite suites. These ore bodies manifest as magnetite lenses, appearing in both massive and disseminated forms [6]. Dimensionally, these lenses are significant, typically ranging from five to twenty meters in width and extending between eighty and three hundred meters in length [7]. This

spatial distribution underscores the genetic link between the mafic-ultramafic intrusive complexes and the concentration of metallic oxides in the Ethiopian basement [3, 7].

2. Structural Evolution and Mineralization Controls

The distribution and orientation of the iron ore bodies are strictly controlled by three primary deformational events (D_1 , D_2 , D_3):

- 1) D_1 Deformation: Produced intrafolial, isoclinal recumbent folds (F_1). The axial traces of these folds trend nearly East-West. The dominant mineral fabric (S_1) is essentially parallel to the lithological layering.
- 2) D_2 Deformation: This is the most prominent structural event in the area, producing N-S trending F_2 folds. The F_2 structures include both synforms and antiforms, with the axial planes dipping moderately to steeply. Significant migmatization and pegmatite injection occurred synchronously with D_2 , particularly along the hinge zones.
- 3) D_3 Deformation: Characterized by high-strain shear zones, such as the Didimo and Gobeles shear zones, which trend NNW-SSE. These zones exhibit a dextral sense of shear and have mylonitized the surrounding country rocks. The D_3 event likely facilitated the final localization and shearing of the magnetite lenses.

The iron mineralization is described as late magmatic syngenetic in origin, with the ore bodies maintaining a trend and dip parallel to the host meta gabbroic rocks. This suggests that the iron was concentrated during the differentiation of the parent gabbroic magma before being tectonically re-oriented during the subsequent metamorphic cycles [6, 8].

2.1. Quantitative Analysis of Dodola Iron Ore Quality

The suitability of iron ore for cement clinker production is dictated by its total iron contents (Fe_2O_3) and the concentration of minor oxides such as TiO_3 and P_2O_5 . High-quality cement production requires a consistent chemical composition in the kiln feed to ensure stable kiln operation and predictable clinker mineralogy [9].

2.2. Chemical Composition and Comparison with Regional Deposits

Analytical data from the Melka Arba occurrences reveal a distinctive chemical signature. The total iron content averages 45.6%, which, while low for traditional steelmaking (typically >58%), is well-suited for cement manufacture as an iron corrective [10].

Table 1. Comparative geochemical analysis of Melka Arba and Bikilal (Western Wollega) iron ore deposits.

Chemical Parameter	Dodola (Melka Arba)	Bikilal (Western Wollega)	Industrial Threshold (Cement)
Total Iron (Fe _T)	45.6%	41.0%	>40.0%
Magnetic Iron (Fe _M)	24.1%	23.3%	N/A
Titanium Dioxide (TiO ₂)	11.12%	0.85% - 0.91%	<1.0% (standard)
Phosphorus Pentoxide (P ₂ O ₅)	0.15%	0.312%	<0.5%
Sulfur (S)	0.05%	Not Specified	<0.1%

The comparison between Dodola and Bikilal ores highlights critical differences in impurity profiles. The Bikilal ore is characterized by high gangue content, particularly silica (SiO₂ 36.2%-48.55%) and alumina (Al₂O₃ 6.4%-17.52%), which necessitates extensive beneficiation if used for steel. The Dodola ore, conversely, presents a significantly higher titanium concentration, reaching 11.12% (TiO₂). This high titanium content is a defining feature of the Dodola deposit and dictates the quantitative limits of its use in clinker production [11].

2.3. Mineralogical Phases in the Ore

The primary ore mineral is magnetite (Fe₃O₄), accompanied by substantial amounts of ilmenite (FeTiO₄), which accounts for the high titanium levels. The presence of ilmenite as a solid solution or discrete phase within the magnetite is characteristic of magmatic (Fe-Ti type) iron deposits of Precambrian age found in the Melka Arba and Bikilal areas. These deposits typically originate from mafic-ultramafic intrusions where vanadium is hosted within the (titano) magnetite and ilmenite lattice [11]. Secondary minerals often include hematite and trace sulfides, while the gangue minerals are primarily silicates derived from host meta-gabbros, such as plagioclase, pyroxene, and hornblende.

In this system, titanium acts as a substitute for iron. Specifically, Ti⁴⁺ ions preferentially substitute for Fe³⁺ in the ferrite phase (C₄AF), which has a maximum solubility for titanium of approximately 18%. This substitution weakens the crystallinity of the ferrite and frees up additional iron oxide to react with CaO and Al₂O₃, effectively increasing the total volume of the interstitial phases [8].

2.6. Effects on Clinker Mineralogy and Microstructure

The incorporation of titanium from the Dodola ore affects the balance between the major clinker phases: Alite

2.4. Chemical Reactivity and Clinkerization Kinetics

In the cement kiln, iron oxide acts as a fluxing agent, lowering the temperature at which the liquid phase forms and facilitating the diffusion of calcium ions to react with silica. The clinkerization process involves four primary stages: evaporation of moisture (<100°C), dehydration (100-430°C), calcination of limestone (900-982°C), and final reaction in the burning zone (~1450-1510°C) [4, 12].

2.5. Influence of Titanium Dioxide on the Liquid Phase

The 11.12% TiO₂ in the Dodola ore significantly alters the thermodynamic properties of the clinker melt. Titanium dioxide is a potent mineralizer; at a concentration of approximately 1% in the clinker, it can lower the temperature of the first liquid phase appearance by 50°C to 100°C [13]. This enables what is known as "soft burning," where reactions proceed at lower thermal inputs, thereby reducing fuel consumption and refractory wear [14].

The quantity of the liquid phase at 1450°C can be calculated by incorporating the TiO₂ contribution into the standard Lea and Parker formula:

$$\%Liquid\ phase(1450^{\circ}C = 3.0.Al_2O_3 + 2.25.(Fe_2O_3 + TiO_2) + MgO$$

(C₃S), Belite (C₂S), Aluminate (C₃A), and Ferrite (C₄AF). Experimental data suggests the impacts of titanium incorporation into clinker on cement quality [14, 15]. The addition of moderate amounts of titanium dioxide (TiO₂), up to approximately 1.3%, functions as an effective mineralizer in cement clinker production by reducing the melt's viscosity and surface tension. This rheological shift accelerates the dissolution of lime and its subsequent reaction with belite, ultimately increasing the alite content by roughly 6.44% [16]. Furthermore, titanium influences the phase balance by favoring the formation of tricalcium aluminate (C₃A) over tetracalcium aluminoferrite (C₄AF), though concentrations exceeding 1.5% can trigger a polymorphic transformation in

C₃A from a cubic to an orthorhombic crystal structure [17]. Beyond phase chemistry, these minor elements significantly alter crystal morphology, often resulting in reduced grain sizes for both alite and belite; however, they can also lead to "cannibalized" alite clusters and rounded belite crystals characterized by ragged, irregular edges [18].

2.7. Phosphorus and Setting Time Constraints

The 0.15% P₂O₅ in the Dodola ore is relatively low and falls

well within the permissible limits for Portland cement. In clinker, phosphorus forms a solid solution with belite (C₂S), stabilizing the α' polymorph [19, 20]. While high levels of phosphorus (above 0.5-1.0%) can retard the setting time and reduce early strength by inhibiting the formation of alite, the low dosage provided by the Dodola ore is likely to act as a mild mineralizer without adverse effects. Studies show that clinkers containing up to 0.70% P₂O₅ exhibit mineralogy and properties similar to low-phosphorus controls. [18, 21].

Table 2. Other components of Iron Ore influencing in clinker property.

Component	Optimal Range in Clinker	Potential Effect of Excess
TiO ₂	0.5% - 1.0%	Retarded setting; reduced early strength
P ₂ O ₅	< 0.5%	Decomposition of alite into belite + free lime
Free Lime (<i>f</i> -CaO)	< 1.5%	Unsoundness; expansion in concrete

Industrial Feasibility and Integration into Ethiopian Plants

The Ethiopian cement market, valued at over 451 million dollars in 2025, is characterized by a surge in demand for high-strength Portland and blended cements to support urban and infrastructure projects. The utilization of Dodola iron ore as a substitute for imported iron correctives must be evaluated within the context of current manufacturing infrastructure [22, 23].

2.8. Raw Mix Design and Optimization

The integration of Dodola iron ore into Portland cement production necessitates a sophisticated recalibration of the raw mix traditionally composed of 80% limestone and 20% clay due to its unique mineralogical profile characterized by

high concentrations of both Fe₂O₃ and TiO₂. While standard mix designs utilize minor additions of iron ore (1-5%) and silica sand to stabilize the Lime Saturation Factor (LSF), Silica Ratio (SR), and Alumina Modulus (AM), the presence of titanium dioxide introduces a potent synergistic effect; because TiO₂ lowers the eutectic temperature and behaves as a secondary fluxing agent within the clinker melt, it enhances the effective liquid phase formation beyond the capacity of ferric oxide alone. Consequently, the reassignment of these chemical moduli must account for this increased fluxing efficiency to optimize burnability and prevent excessive coating in the kiln, ensuring that the final mineralogical phases specifically the ratio of alite to belite remain within structural specifications [24, 25].

Table 3. Raw mix ratio of Clinker production including iron ore.

Raw Material	Typical Dosage	Primary Function
Limestone	80% - 90%	Source of CaO
Clay/Laterite	5% - 15%	Source of SiO ₂ and Al ₂ O ₃
Iron Ore	1% - 3%	Source of Fe ₂ O ₃ ; fluxing agent
Silica Sand	0% - 5%	Correction of SR

2.9. Environmental and Sustainability Benefits

The strategic integration of indigenous Dodola iron ore into

Ethiopia’s industrial framework represents a pivotal alignment with the nation’s "Green Growth" trajectory and its ambitious Nationally Determined Contributions (NDCs) under the Paris Agreement. By transitioning toward local mineral

sourcing, Ethiopia addresses the significant carbon footprint of the cement sector an industry responsible for roughly 5% to 8% of global anthropogenic CO₂ emissions, largely driven by the high heat calcination of limestone and the intensive combustion of fossil fuels. Utilizing local iron ore as a fluxing agent not only optimizes the clinkering process by lowering kiln temperatures, thereby reducing thermal energy demand, but also curtails the indirect emissions associated with the long-range logistics of imported raw materials. This shift fosters a circular economy model that enhances national resource mineral security while directly mitigating the environmental impact of one of the world's most carbon-intensive manufacturing processes. [26, 27].

3. Conclusion

The Dodola iron ore deposit, specifically the magnetite-ilmenite occurrences in the Melka Arba area, offers a technically superior and sustainable solution for the Ethiopian cement industry. Its unique chemical profile, characterized by 45.6% total iron and 11.12% titanium dioxide, provides a dual benefit: it serves as an effective iron corrective while simultaneously acting as a powerful mineralizer to enhance kiln efficiency.

Quantitative analysis confirms that the titanium and phosphorus levels in the ore are manageable within standard clinkering processes, provided that the TiO₂ concentration in the final clinker is maintained near the 1% threshold. The mineralizing effect of TiO₂ allows for a reduction in burning zone temperatures, aligning with national goals for energy efficiency and CO₂ reduction.

Logistically, the proximity of the Dodola deposit to the central industrial corridor of Ethiopia provides a significant advantage over kiln efficiency, reducing energy costs and emissions. In the post-birr-float economic environment, the transition to local sourcing is no longer merely an environmental preference but a macroeconomic necessity. By integrating Dodola iron ore into the national supply chain, Ethiopia can strengthen its industrial resilience, support its climate commitments, and ensure the continued expansion of the infrastructure that is vital to its future prosperity.

Abbreviations

LSF	Lime Saturation Factor
SR	Silica Ratio
AM	Alumina Modulus
GERD	Great Ethiopian Renaissance Dam
Abgn	Augen Biotite Gneiss
Mg	Meta-Gabbro
C3S	Alite (Tricalcium Silicate)
C2S	Belite (Dicalcium Silicate)
C3A	Aluminate (Tricalcium Aluminate)
C4AF	Ferrite (Tetracalcium Aluminoferrite)

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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