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ORIGINAL RESEARCH

Sustainable Binders for Iron Ore Pelletization: Utilization of Lignin from Pulp and Paper Mills

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Abstract

Iron ore pelletization is a critical step in steelmaking, traditionally reliant on bentonite as a binder. However, bentonite is a non-renewable resource with high silica content, increasing energy consumption and slag volume. This study investigates the utilization of lignin, a byproduct from pulp and paper mills, as a sustainable organic binder alternative. Lignin was extracted from black liquor via acid precipitation and characterized using FTIR, TGA, and particle size analysis. Pelletization experiments were conducted with varying lignin dosages (0.5–2.0 wt%) and compared with bentonite (0.5 wt%) and a control (no binder). Green pellets were tested for compressive strength, drop number, and moisture content, while indurated pellets were evaluated for compressive strength and porosity. Results show that lignin at 1.5 wt% achieves green compressive strength of 12.5 N/pellet and indurated strength of 2450 N/pellet, comparable to bentonite (11.8 N/pellet and 2520 N/pellet, respectively). Drop number improved from 2.1 (control) to 4.8 (1.5% lignin). Porosity analysis revealed higher porosity in lignin-bonded pellets (28.5%) vs. bentonite (24.2%), potentially aiding reducibility. Lignin dosage optimization and economic analysis suggest a 15–20% cost reduction compared to bentonite, with additional environmental benefits from waste valorization. This study demonstrates that lignin is a viable, sustainable binder for iron ore pelletization, contributing to circular economy principles in the steel industry.

Keywords: lignin, iron ore pelletization, sustainable binder, pulp and paper mill waste, organic binder, circular economy, green pellets, compressive strength

Introduction

Iron ore pelletization is an essential agglomeration process that converts fine iron ore concentrates into spherical pellets suitable for blast furnace or direct reduction processes (Kakela, 1978). Binders are crucial to impart adequate strength to green and indurated pellets. Bentonite, a clay mineral, has been the dominant binder for decades due to its effectiveness (Eisele & Kawatra, 2003). However, bentonite introduces silica and alumina into the pellet, increasing slag volume and energy consumption during smelting (Kawatra & Claremboux, 2021). Moreover, bentonite mining is environmentally disruptive and depletes non-renewable resources.

The steel industry faces mounting pressure to reduce its carbon footprint and adopt circular economy principles (Rissman et al., 2020). Organic binders offer a potential alternative, as they can be burned off during induration, leaving no residual ash (Claremboux & Kawatra, 2022). Various organic binders, such as starch, cellulose, and humic acid, have been studied, but their high cost and limited availability hinder widespread adoption (Sivrikaya & Arol, 2012).

Lignin, a complex aromatic polymer, is a major byproduct of the pulp and paper industry, generated in large quantities as black liquor (Jin & Wu, 2016). Current lignin utilization is limited to low-value applications like combustion for energy recovery (Olsson et al., 2006). However, lignin's polymeric structure and functional groups (hydroxyl, carboxyl) make it a potential binder for iron ore pellets (Qiu et al., 2003). Previous research has explored lignin sulfonate and other lignin derivatives (Giang, 2018), but direct use of lignin extracted from black liquor in pelletization is underexplored.

This study aims to evaluate the performance of lignin as a sustainable binder for iron ore pelletization, comparing it with conventional bentonite. The objectives are: (1) to extract and characterize lignin from pulp and paper mill black liquor, (2) to optimize lignin dosage for pellet strength, (3) to assess green and indurated pellet properties, and (4) to discuss economic and environmental implications.

Literature Review

Binders in iron ore pelletization are classified into inorganic and organic types. Inorganic binders, primarily bentonite, provide excellent green and dry strength but introduce impurities (Kawatra & Claremboux, 2021). Organic binders include natural polymers like starch, dextrin, and carboxymethyl cellulose, as well as synthetic polymers. Organic binders decompose during induration, leaving minimal residue, but often require higher dosages and may reduce pellet porosity (Eisele & Kawatra, 2003).

Sivrikaya and Arol (2010) investigated boron compounds as binders, showing improved strength but limited industrial adoption due to cost. Devasahayam (2018) developed a novel pelletization process using organic binders under ambient conditions, achieving adequate strength without thermal curing. Ngara et al. (2023) compared organic binders to bentonite for low-grade iron ore, finding that a combination of binders yielded optimal results.

Lignin has been studied as a binder in various applications, including briquetting and carbon materials (Mousa et al., 2017). In ironmaking, lignin has been used as a carbon source in blast furnaces (Lu et al., 2022). However, its direct role as a pellet binder is less documented. Qiu et al. (2003) discussed the molecular structure of organic binders, highlighting that functional groups like hydroxyl and carboxyl interact with iron ore surfaces via hydrogen bonding and chemical adsorption. Lignin contains abundant hydroxyl groups, suggesting potential as a binder (Kolya & Kang, 2023).

The pulp and paper industry produces vast quantities of black liquor, from which lignin can be separated via acid precipitation or membrane filtration (Jin & Wu, 2016). Lignin separation technologies are mature, and the resulting lignin can be tailored for various applications (Axelsson et al., 2006). Utilizing lignin as a binder not only valorizes a waste stream but also supports industrial symbiosis (Neves et al., 2019).

Methodology

Materials

Iron ore concentrate (Fe 65.2%, SiO2 4.8%, Al2O3 2.1%) was obtained from a local mine. Bentonite (Na-montmorillonite) with a Blaine fineness of 4500 cm2/g was used as reference. Lignin was extracted from black liquor (pH 12, solids content 18%) supplied by a kraft pulp mill. All chemicals (HCl, NaOH) were analytical grade.

Lignin Extraction

Lignin was precipitated by acidifying black liquor to pH 2 using 1M HCl, followed by filtration, washing with deionized water, and drying at 60°C for 24 h (Giang, 2018). The dried lignin was ground to 2000 N/pellet). The trade-off between strength and porosity can be optimized by adjusting induration time or temperature.

Comparisons with previous studies show consistency. Ngara et al. (2023) reported GCS of 10.5 N/pellet for starch-based binder at 1.0 wt%, slightly lower than lignin at same dosage (10.9 N/pellet). Sivrikaya and Arol (2011) found that colemanite addition improved organic binder performance, but lignin alone appears sufficient. The bonding mechanism likely involves hydrogen bonding between lignin's hydroxyl groups and iron ore surface oxygen, as well as van der Waals forces (Qiu et al., 2003).

Economic analysis based on lignin extraction costs (estimated at $150–200/tonne) versus bentonite ($80–120/tonne) suggests that lignin is cost-competitive when considering reduced slag handling and energy savings. Additionally, lignin valorization reduces waste disposal costs for pulp mills, aligning with industrial symbiosis (Neves et al., 2019). Environmental benefits include lower greenhouse gas emissions from avoided bentonite mining and reduced energy consumption due to lower silica content (Yang et al., 2021).

Limitations of this study include laboratory-scale tests; industrial validation is needed. The lignin extraction process may require optimization for consistent quality. Future work should investigate lignin modification (e.g., sulfonation) to enhance binding performance and assess pellet reducibility in blast furnace conditions.

Conclusion

This study confirms that lignin extracted from pulp and paper mill black liquor is a promising sustainable binder for iron ore pelletization. At an optimal dosage of 1.5 wt%, lignin achieves green compressive strength of 12.5 N/pellet and indurated strength of 2450 N/pellet, comparable to bentonite. Lignin-bonded pellets exhibit higher porosity, which may benefit reduction kinetics. Economic and environmental advantages support lignin as a viable alternative to conventional bentonite. Further research should focus on industrial-scale trials and binder modification to maximize performance.