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Softening-Melting Properties of Hot Briquetted Iron and Its Application in Blast Furnace Ironmaking

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Laboratory softening–melting (SM) experiments, complemented by a commercial blast-furnace (BF) trial, demonstrate that hot briquetted iron (HBI) is a robust low-carbon substitute for part of the BF burden at China Steel Corporation (CSC). Three industrial HBI grades (TFe > 90 wt.%) exhibited negligible pressure-drop peaks (< 30 mm H_2O) and melt-down ratios above 92%, confirming excellent permeability throughout the cohesive zone. In contrast, high-basicity sinter (B_2 = 2.2) generated severe resistance and a meltdown ratio of only 8%. Blending HBI with this sinter cut the peak pressure by roughly 30%, advanced dripping onset by ~50°C, and restored melt-down behaviour, illustrating HBI's capacity to reopen gas channels and dilute high-resistance phases. Particle-size studies further revealed that finely cut HBI (10–15 mm^3) lowered the initial dripping temperature by nearly 200°C compared with blocky pieces, offering an additional lever for process control. A full-scale trial, charging 100 kg HBI t^{-1} hot metal reduced the coke rate by 36 kg tHM^{-1}. Model predictions and international benchmarks indicated that this was achieved without adverse effects on hot-metal chemistry. These findings confirm that integrating HBI can simultaneously curb CO_2 emissions, enhance cohesive-zone permeability, and deliver operational flexibility, especially when counterbalancing high-basicity burdens.

Keywords: Hot briquetted iron, Softening–melting, Cohesive zone, Blast furnace, Decarbonization

1. INTRODUCTION

Climate change has compelled the global steel industry to accelerate its transition toward deep decarbonisation. In response, China Steel Corporation (CSC) has formulated a phased carbon-reduction roadmap, targeting a 7% reduction in CO_2 emissions by 2025, 25% by 2030, and net-zero emissions by 2050.

Within the ironmaking domain, CSC is advancing three complementary strategies:

(1) Partial substitution of traditional sinter and coke burden with hot briquetted iron (HBI);

(2) Injection of hydrogen-enriched reducing gas into the lower zones of the blast furnace to enhance indirect reduction reactions.

(3) Deployment of carbon-utilization modules to convert blast-furnace off-gases into platform chemicals, while simultaneously recovering sensible heat and carbon monoxide.

Despite these efforts, achieving deep decarbonisation in the blast-furnace–basic-oxygen-furnace (BF–BOF) route—which remains responsible for ~70% of global crude steel output—poses substantial technical and operational challenges. HBI, a low-carbon solid metallic feedstock, is produced by compressing direct reduced iron (DRI) at high temperature and pressure into dense, pillow-shaped briquettes, with metallic Fe content typically exceeding 80%. Its high mechanical strength and resistance to oxidation or self-heating during storage and transport make it a stable and reliable burden material. Historically, HBI has been used primarily in electric arc furnaces (EAF), but its integration into BF operations is gaining attention owing to the growing maturity of hydrogen-based direct reduction technologies[1].

Replacing part of the sinter burden with HBI not only curtails carbon emissions from sintering but also reduces coke consumption required for iron-oxide reduction, thereby contributing to blast furnace decarbonisation. However, changes in burden structure inevitably influence the formation and stability of the SM zone. Due to its high metallic content and low gangue, HBI can be readily used to reduce coke dependency. Industrial trials—such as those conducted in Linz—have shown that charging 100–300 kg HBI per ton of hot metal can reduce coke rate by 25–85 kg t^{-1} [2-4].

Nevertheless, the precise SM behavior of HBI under blast furnace conditions, and its interaction with high-basicity sinter, remain insufficiently understood. This study aims to address this knowledge gap through systematic laboratory-scale SM testing combined with a commercial-scale BF trial, with results benchmarked against international best practices.

2. METHODOLOGY

The HBI samples used in this study were sourced from three different manufacturers, designated as brands A, B, and C. These samples had an average total iron content of over 90 wt.%, an average metallic iron content of 79 wt.%, and carbon content ranging from 0.65 to 1.25 wt.%. The major gangue components were all below 5 wt.%. The sinter samples used in this study were produced by China Steel Corporation's own sinter plant, with detailed chemical compositions summarized in Table 1.

In terms of sample sizing, the HBI was cut into basic dimensions of 10–15 mm³, and sinter was screened to a particle size of 10–15 mm. These were used in single-material, mixed-material, and small-group tests. Additionally, HBI was cut into larger pieces, approximately one-third the original size (about 30 × 50 × 15 mm, approximately 250 g per piece) for the Big Size group tests. All test samples were dried at 105°C for 12 hours before use.

The high-temperature load softening–melting (SM) testing equipment used in this study is shown in Figure 1. It comprises several key components and functionalities. First, it includes a graphite tubular furnace capable of reaching temperatures above 1600°C, with precise temperature control. The system is equipped with a sample-loading device that incorporates a pneumatic system to regulate the applied load on the sample. Gas supply and flow-control units are provided for CO_2, CO, and N_2, enabling accurate atmospheric control during testing. For real-time monitoring, the equipment features a displacement gauge to measure sample height changes and a differential pressure system to detect pressure variations above and below the sample. A rotary-type collector is used to gather molten slag or metal droplets during the melting phase. The samples are placed in a graphite crucible with vented top and bottom covers to allow for adequate gas flow. All experimental data are recorded and processed through an integrated data-acquisition and analysis system.

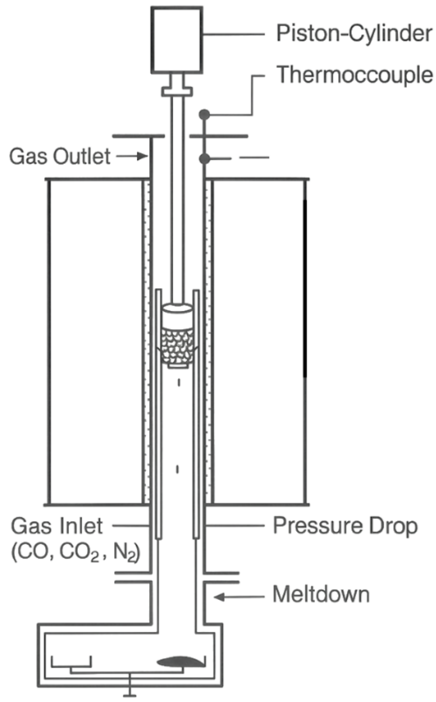

Fig.1. High-Temperature Load-Softening and Melting-Testing Equipment.

3. RESULTS AND DISCUSSION

3.1 Analysis of High-Temperature Softening–Melting Characteristics of HBI

Figure 2 shows the shrinkage curves and pressure-drop curves of the three HBIs. All grades began shrinking gradually at approximately 1000°C, with pronounced

Table 1 Chemical Composition and Basicity (B2) of the Samples.

Sample	HBI-A	HBI-B	HBI-C	Sinter
TFe	91.47	93.32	90.70	55.50
C	0.65	1.07	1.25	0.02
CaO	1.05	1.22	1.08	11.40
MgO	0.03	0.50	0.36	1.90
Al_2O_3	1.16	0.43	0.46	1.70
SiO_2	2.48	1.96	2.34	5.10
B2 (CaO/SiO_2)	0.42	0.73	0.46	2.24

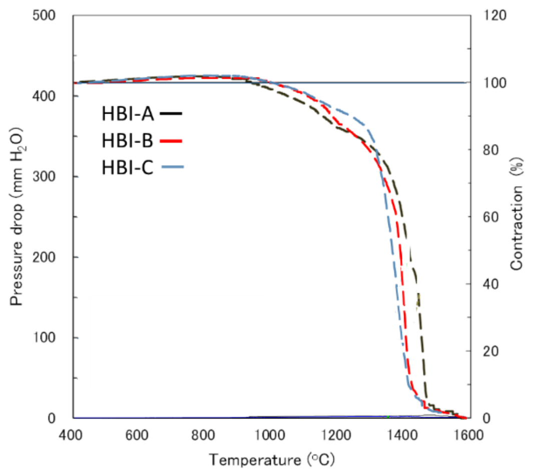

Fig.2. High-temperature shrinkage and pressure-drop curves for three HBI grades (A, B, and C).

contraction occurring above 1250°C, although the pressure build-up remained < 30 mm H_2O. Melting commenced between 1310°C and 1340°C, and final melt-down ratios exceeded 92%. These features confirm that HBI forms an open, permeable structure in the cohesive zone.

The chemical composition of the HBI materials differs substantially from that of sinter, while the variation among the three HBI brands is minor (Table 1). As a result, their SM pressure-drop profiles are comparable, though their shrinkage behaviors differ. Unlike sinter, which undergoes a distinct softening followed by melting, HBI primarily transitions from solid to molten metallic iron, yielding an extremely low pressure drop that precludes precise determination of softening onset.

For instance, HBI-A shows slow deformation between 940°C and 990°C. Nevertheless, metallic Fe within the briquettes preserves voids and gas permeability (S-value ≈ 0). At ~1330°C, the carbon-saturated melting point is reached, triggering the rapid formation and release of pure iron melt droplets. At this stage, burden height decreases by only ~25%, indicating initial deformation. As temperature increases, rapid burden descent ensues due to large-scale liquefaction.

Compared with HBI-A, both HBI-B and HBI-C exhibit earlier onset of shrinkage and higher dripping rates. In general, due to their minimal slag-forming constituents and high metallization, HBI samples melt predominantly via iron liquefaction, producing negligible gas-flow resistance throughout the test. The average meltdown ratio exceeds 92% across all brands (Fig.3). Minor discrepancies in impurity and carbon content explain subtle differences in melting behavior. Notably, HBI-A, having the lowest carbon content (0.653 wt.%), exhibited the slowest dripping rate, though this did not significantly influence other SM characteristics.

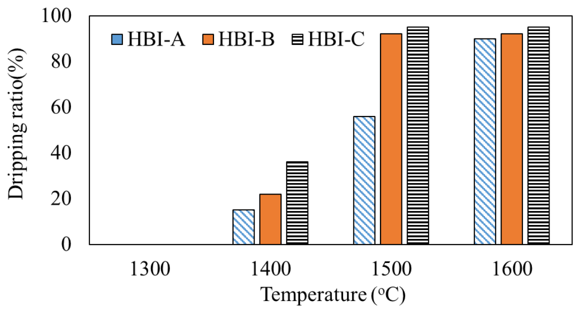

Fig.3. Dripping ratios of HBI-A, HBI-B, and HBI-C at different temperatures.

3.2 Influence of HBI with High-B_2 Sinter

To stabilize the final slag composition during blast furnace (BF) operation with hot briquetted iron (HBI), a high-basicity sinter burden with $B_2 = 2.2$ was adopted in the experimental burden design. Previous studies have shown that increasing sinter basicity elevates the softening–melting (SM) transition temperatures. Specifically, high-B_2 sinter exhibits higher shrinkage onset, softening, and melting temperatures compared with conventional sinter. The melting temperature was estimated to exceed 1600°C, while the dripping onset shifted from 1510°C to 1555°C. These elevated transition temperatures led to markedly increased gas-flow resistance in the cohesive zone. The high-temperature ΔP also increased significantly, indicating poor permeability. Moreover, the meltdown ratio at 1600°C dropped sharply from 38% for standard sinter to just 8% for high-B_2 sinter (Fig.4), suggesting that the burden failed to adequately soften and drain slag-metal melt under standard operating temperatures. This behavior implies that overly high basicity—though beneficial for slag fluidity and desulphurization—may compromise cohesive-zone permeability and operational stability. To mitigate this adverse effect, HBI was blended with the high-B_2 sinter, and the resulting mixture was subjected to SM testing. The combined burden showed significantly improved permeability characteristics. Specifically, the peak pressure drop decreased to ~140 mm H_2O, and the dripping onset occurred at a lower temperature relative to high-B_2 sinter alone. Furthermore, the meltdown ratio at 1600°C increased appreciably. These results clearly indicate that HBI contributes to opening gas channels, thereby enhancing permeability and facilitating melt drainage. The beneficial effect arises from HBI's intrinsic properties: low gangue content, high metallic Fe content (> 80%), and its tendency to undergo direct melting without forming a significant semi-molten zone. By diluting the high-resistance portion of the burden, HBI effectively offsets the permeability penalties associated with elevated B_2. Therefore, the integration of HBI into high-basicity sinter mixtures

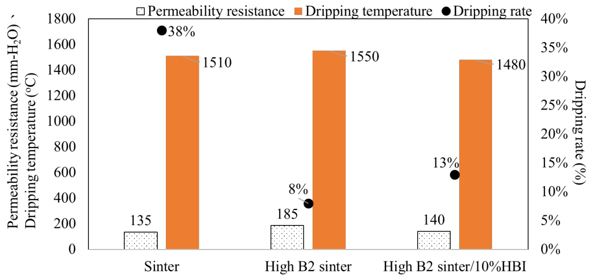

Fig.4. High-Temperature Permeability and Melting Behavior of Standard Sinter, High-B_2 Sinter, and HBI-Enhanced Burden.

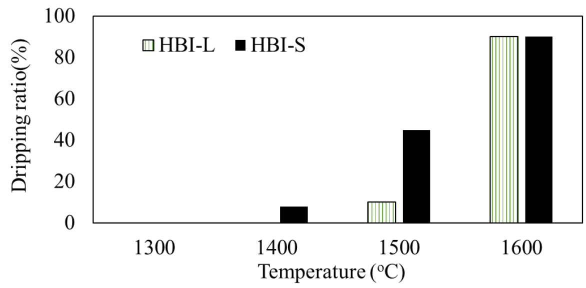

Fig.5. Sinter blended with HBI of different particle sizes.

represents a promising operational strategy to balance slag chemistry requirements with cohesive-zone performance, enabling more robust and flexible BF operation under decarbonisation-oriented burden schemes.

3.3 Effect of HBI Particle Size

This study also investigated the influence of HBI-A particle size on softening–melting (SM) behaviour by comparing two configurations. In the Small group, standard-sized HBI-A samples (10-15 mm³) were uniformly blended with sinter at a 50 wt.% ratio (≈ 250 g HBI). In contrast, the Large group used a single bulk HBI sample, cut from the original-thickness material, also weighing ≈ 250 g. In the latter case, sinter was layered above and below the HBI block to mimic inhomogeneous burden distribution.

Results showed that the Small group, due to its finer particle size, enabled better dispersion of HBI throughout the sinter matrix. Given HBI's high mechanical integrity at elevated temperatures, this distributed configuration offered superior structural support while creating multiple flow paths for both gas and molten material. Consequently, during initial iron melting, molten droplets drained more readily through these channels. The onset of dripping occurred at 1303°C in the Small group, which was 194°C lower than in the Large group.

In later heating stages, the small-sized HBI, benefiting from a greater specific surface area, absorbed heat more rapidly. Upon surpassing the Fe melting point, rapid liquefaction ensued, producing a large volume of melt that drained efficiently through the established channels.

Overall, particle size directly influenced burden dispersion, thermal response, and interparticle contact with the surrounding matrix. These factors primarily governed the initial dripping temperature and rate. However, final melt-down ratios and gas-flow resistance were similar across both groups, as shown in Figure 5, indicating that size had a limited effect on late-stage permeability and melt evacuation.

3.4 Results of HBI Trials in Blast Furnace Operation

Theoretical calculations based on the Rist diagram model suggest that using HBI at a rate of 10 wt.% (approximately 155 kg/tHM) can reduce the coke rate by 36 kg/tHM. In practice, China Steel Corporation's (CSC) No. 3 blast furnace trial, charging 100 kg HBI per tonne of hot metal, achieved a coke rate reduction of 36 kg/tHM. This indicates that the decarbonisation effectiveness observed in CSC's trial is on par with or even exceeds international benchmarks, demonstrating the technical feasibility and competitiveness of domestic HBI-based burden optimisation strategis.

4. CONCLUSIONS

This study investigated the high-temperature softening-melting (SM) behavior of hot briquetted iron (HBI) and its interaction with high-basicity sinter under simulated blast furnace (BF) conditions. Key findings are as follows:

(1) All three HBI samples demonstrated excellent permeability within the SM zone, with low pressure-drop profiles and melt-down ratios exceeding 92%. Their transition from solid to molten iron occurred without significant formation of semi-molten phases, facilitating stable gas flow and efficient melt drainage. Minor differences in carbon and impurity content among brands resulted in subtle variations in shrinkage and dripping behavior but did not significantly affect overall SM performance.

(2) High-basicity sinter (B_2 = 2.2), although favorable for slag fluidity and desulphurization, showed poor SM permeability, with elevated pressure drops and drastically reduced melt-down ratios. When blended with HBI, however, the combined burden exhibited significantly improved cohesive-zone performance, including reduced pressure drop, earlier dripping onset, and higher melt-down ratios. These enhancements stem from HBI's inherent metallurgical properties and its capacity to dilute high-resistance burden components.

(3) Smaller HBI particles (10-15 mm³) dispersed uniformly within the sinter matrix were more effective in promoting early-stage liquefaction and melt drainage compared to larger, block-shaped HBI. Although particle size had a pronounced effect on initial dripping temperature and melt kinetics, it had minimal influence on final melt-down ratios and gas-flow resistance.

(4) Theoretical calculations based on the Rist diagram model suggest that using HBI at a rate of 10 wt% (approximately 155 kg/tHM) can reduce the coke rate by 36 kg/tHM. In practice, China Steel Corporation's (CSC) blast furnace trial, charging 100 kg HBI per tonne of hot metal, achieved the same 36 kg/tHM reduction in coke rate. This indicates that the decarbonisation effectiveness observed in CSC's test is comparable to, or even exceeds, international benchmarks, demonstrating the technical feasibility and competitiveness of domestic HBI-based burden optimisation strategies.

In summary, HBI represents a strategically valuable burden material for decarbonising blast furnace ironmaking. Its integration not only lowers carbon intensity but also improves SM-zone permeability and stability, particularly when offsetting the challenges posed by high-basicity sinter. Moreover, optimizing HBI particle size provides an additional operational lever to fine-tune melt dynamics. These insights support the broader implementation of HBI as part of low-carbon BF burden strategies and provide a technical foundation for its deployment in commercial-scale decarbonisation efforts.

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