Recycled Arabic Gum as Binder for Self-Reducing Briquettes Made by Steelmaking By-Products

Sara Scolari[1], Davide Mombelli[1], Gianluca Dall'Osto[1], Carlo Mapelli[1]
[1]Dipartimento di Meccanica, Politecnico di Milano, Via La Masa 1, 20156 Milano, Italy
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Corresponding author email: sara.scolari@polimi.it

Despite the strong encouragement of the electric steelmaking, 70% of the 1 888 Mt of crude steel in 2023 was produced by integrated cycle steel plants. Blast furnaces (BF) and basic oxygen furnaces (BOF) generate significant amounts of by-products, including about 34 Mt of dust and 25 Mt of sludge annually. Current management strategies include internal reuse (53%), external recovery (29%) and landfill (18%) (Remus & Europäische Kommission Gemeinsame Forschungsstelle Institut für Technologische Zukunftsforschung, 2013; World Steel Association, 2023). However, the environmental and economic drawbacks associated with disposal and the limitations of existing recycling methods highlight the urgent need for innovative and sustainable solutions. Among these wastes, blast furnace sludge (BFS) and basic oxygen furnace dust (BOFD) pose significant challenges due to their complex composition, containing valuable iron and carbon as well as harmful elements, such as zinc and alkalis (Remus & Europäische Kommission Gemeinsame Forschungsstelle Institut für Technologische Zukunftsforschung, 2013).

The authors have already presented the agglomeration of BFS and BOFD into self-reducing briquettes as a promising approach to valorise these by-products, reduce waste, and improve the circularity of the steelmaking [(Proceedings - 11th International Conference on Sustainable Solid Waste Management (Uest.Gr), 2024)]. However, the choice of binder plays a critical role in determining the mechanical stability and metallurgical performance of the briquettes. The use of conventional corn starch as binder has shown limitations in the mechanical strength and thermal stability of briquettes containing fine integrated steelmaking by-products. Natural Arabic gum has shown significant potential as a binder highlighting the possibility of introducing a novelty to metallurgical field. It has enhanced particle densification resulting in improved mechanical properties. Specifically, Arabic gum increased the impact resistance of briquettes by 700%, increased the resistance to 10 drops instead of 5, achieved an improvement of 4.36% in the reduction degree and overcame the disruptive forces generated during the thermal treatments in briquettes containing corn starch guaranteeing instead the self-stand capacity to the agglomerate. Despite these important advantages, the industrial application of natural Arabic gum is limited by some drawbacks: high cost (up to 4000 € ton^{-1}) and environmental concerns related to its import from Senegal, make it unsustainable for industrial scale-up.

To address these challenges, this study investigates the use of a recycled solution of Arabic gum, sourced as a by-product of the wine industry, as a more cost effective and environmentally friendly alternative. The mechanical and metallurgical properties of the briquettes bound with the two different binders (Natural Arabic Gum – NAG and Recycled Arabic Gum – RAG) were compared to evaluate the feasibility of using RAG.

Briquettes were prepared by combining BOFD and BFS in a mass ratio of 2.1:1, with 5% solid binder content relative to the total dry powder mass. Briquettes of 20 mm in height and 20 mm in diameter were produced by pressing the powders at a constant speed of 20 mm min^{-1} until 40 MPa and maintained for 2 min, using a modified uniaxial tensile test (Mombelli et al., 2021). After 15 days of curing, the briquettes were mechanically characterized by means of drop test (ASTM D440−07 (2019)) and compression test (BS ISO 4700:2015). After thermal treatment at 1200 °C, the briquettes were metallurgically characterized by means of degree of reduction (DoR) (BS ISO 11258:2015) and swelling (BS ISO 4698:2022). The density of the briquettes, their mechanical and metallurgical properties are summarized in **Table 1**.

Table 1 Mechanical and metallurgical properties of briquettes and relative benchmarks

Binder used	Density [g cm^{-3}]	N° of drop	IRI	UCS [MPa]	DoR [%]	Swelling [%]
Natural Arabic Gum	2.51	10	1000	15.86	89.71	-10.10
Recycled Arabic Gum	2.45	10	1000	13.98	91.36	5.60
Benchmark	>1.3	>4	>97.7	>9.5	n.d.	<20

Both the briquettes showed good mechanical resistance at first sight, without the presence of dangerous cracks on their surface. Although both the densities were higher than the benchmark imposed for direct reduced iron making (Adeleke et al., 2021), they were lower than the density of electric arc furnace (EAF) slag (2.9 g cm^{-3}) (Seetharaman et al., 2013). Hence, by considering the briquettes' introduction in the EAF (after evaluation of chemical compatibility), they should be charged in the lowest layers of the first charging bucket, otherwise they will float on the slag and avoid the iron recover (Seetharaman et al., 2013).

Mechanical evaluations showed that briquettes bonded with recycled Arabic gum had comparable performance to those made with natural gum. Both briquettes survived up to 10 drops without releasing large amounts of fines (0.75 wt.% and 0.83 wt.% below 500 µm with NAG and RAG, respectively) and their Impact Resistance Index (IRI) largely was above industrial benchmarks (Adu-Poku et al., 2022), demonstrating resilience during handling and transport. Although the Ultimate Compression Strength (UCS) of the briquettes with recycled Arabic gum was a slightly lower than that of the NAG, it still exceeded the benchmark ((Barisetty et al., 2020)) by 47%, confirming the robustness of the briquette under compressive forces.

Metallurgical evaluations further confirmed the suitability of RAG binder. Reduction degree tests showed that the recycled Arabic gum not only did not alter reduction behaviour of the briquettes, but also slightly increased the reduction capacity of the agglomerate. To ensure that the reduced purity of the recycled Arabic gum did not affect the reduction behaviour, the XRD patterns of the two agglomerates were compared after the reduction at 1200 °C. The patters showed no difference and confirmed the metallization of the agglomerates by the presence of iron peaks and the absence of more oxidized iron-phase than wustite. The swelling behaviour was analysed by comparing the initial volume of the briquettes, assumed to be a perfect cylinder, and the volume after the thermal treatment, calculated after a 3D reconstruction of the briquette. The two briquettes showed an opposite swelling behaviour showing the predicted shrinkage in the presence of natural Arabic gum (Singh & Bjorkman, 2004) and swelling with the recycled one. In order to define the reason for this different behaviour, scanning electron microscopy (SEM) provided detailed insights into the briquettes highlighting the presence of a large number of iron whisker nucleation sites in presence of natural Arabic gum, while a larger number of elongated iron whiskers with the recycled one. Since the mixture of the briquettes was composed of the same raw materials, the difference in morphology could only be related to the binder used. After an overnight treatment of the two binders at 105 °C, the SEM-EDS revealed only carbon and calcium oxide (CaO) in briquettes bound with natural Arabic gum, while the agglomerate with recycled Arabic gum contained a high amount of silicon oxide (SiO_2). CaO increased the number of nucleation sites for iron whisker formation during thermal reduction, while the presence of SiO_2 contributed to the clustering of these whiskers (Wang & Sohn, 2011) explaining the presence of longer whiskers leading to volume increase. However, the swelling observed in the briquettes with natural Arabic gum remained within acceptable limits (Andersson et al., 2019), thus ensuring the mechanical stability and self-standing capacity of the briquettes during exposure to high-temperature.

In conclusion, the results demonstrated the feasibility of using recycled Arabic gum as a sustainable and cost-effective binder for steelmaking by-products, with comparable results in both mechanical and metallurgical performance. This innovative approach is in line with the circular economy principles, allowing the recovery of up to 3.5 kg of BFS and 7 kg BOFD while reducing CO_2 emissions by 5%, creating new synergies between steelmaking and food industry for by-product valorisation.

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