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Stiff Vacuum Extrusion for Agglomeration of Natural and Anthropogenic Materials in Metallurgy

Ivan Kurunov and Aitber Bizhanov

Abstract

Recently developed concept of stiff vacuum extrusion (SVE) agglomeration for iron and steel making helps to innovate the briquetting technology and make it competitive with sintering. The results of the R&D in this field show that extrusion attributes very specific properties to the agglomerated products—BREX (extrusion briquettes), which favors their wide utilization in metallurgy—among them are quick strengthening of the BREX, their high hot strength, very low self-cost, and maintenance values. A set of the successful projects have been realized in iron making, ferroalloy production, and direct-reduced iron (DRI) production.

Keywords: extrusion briquettes (BREX), stiff vacuum extrusion (SVE), agglomeration, recycling, blast furnace, ferroalloys

1. Introduction

Most of the world's major metallurgical plants have accumulated millions of tons of blast furnace (BF) sludge during production. These wastes are typically recycled as a charge component for production of sinter in quantities limited by the allowable zinc input for the blast furnace (partial replacement of iron ore concentrate with low-cost sludge makes this recycling economically attractive). However, the addition of sludge in the sintering charge has a negative effect on sinter stability and quality.

Briquetting, and the subsequent use of briquettes in the blast furnace, offers a more promising and environmentally friendly way of recycling this sludge. In addition to improving sinter stability and quality, the carbon in blast furnace sludge in the briquettes is used as the reducing agent, whereas in the sinter process, it almost does not work. By briquetting sludge is removed from the sintering charge and directed into the blast furnaces to the extent that the zinc inputs to the blast furnaces do not exceed the established limits. Economic efficiency comes from replacing more expensive merchant ore pellets, reducing coke consumption by smelting the carbon-containing briquettes, and improving sinter quality after sludge is removed from the sinter plant's charge. Briquetting was widely used for agglomerating iron ore fines and waste in the 1920s. At one point, briquettes constituted between 30 and 40% of the charge for the West blast furnace plant in the Calbe (Germany). Briquettes also constituted 100% of the charge for a low-shaft blast furnace plant in Maxhütte, Germany. These briquettes were made from iron ore fines, coke, and limestone dust [1]. However, the advent of high-productivity iron ore and concentrates sintering method meant that briquetting was no longer competitively priced, due to the low capacity of the briquetting equipment.

Today, agglomeration of anthropogenic and natural metal-containing substances by cold briquetting, using mineral or organic binders, is becoming more prevalent. There are three basic technologies—roller pressing, vibropressing, and stiff extrusion with vacuum. Stiff extrusion with vacuum entails forcing a homogeneous wet mix (typical moisture content ranging from 12 to 18% of bulk material under 2.5–4.5 Mpa pressure through die holes.

Extrusion for agglomeration of ore and metallurgical wastes first occurred in the 1990s, when Bethlehem Steel commissioned a stiff extrusion line for briquetting 20 tons per hour of sludge and flue dust [2]. These briquettes were melted in Bethlehem Steel blast furnaces. The line operated until 1996, when it ceased due to the closure of the plant. This milestone was not thoroughly investigated by metallurgists until 2010, when the authors of the present paper began to study the characteristics of stiff extrusion and their influence on the metallurgical properties of extrusion briquettes (BREX) [3]. By April 2011, more iron-making specialists were evaluating industrial briquetting plant production, along with the use of stiff extrusion briquettes as a major component of the blast furnace charge.

Extrusion characteristics and the properties of briquettes are consolidated in the following comparative table (**Table 1**). Entries are based on the results of briquetting plants and data published online by the producers of briquetting equipment, including roller presses and vibropresses.

One can see that stiff vacuum extrusion (SVE) offers clear advantages over other briquetting technologies. Stiff vacuum extrusion requires significantly less cement binder than roller-pressed briquettes and is less dependent on the moisture content of the charge for briquetting. It also allows production of briquettes with a minimum size (diameter) comparable to the size of the sinter and pellets.

Characteristics of the process and properties of briquettes	Machines for briquetting and their characteristics		
	Vibropress	Roller press	Extruder
Maximum output (Mt/h)	30	50	100
Cement binder content (%)	8–10	15–16	4–8
Thermal processing of raw briquettes	80°C (16–20 h)	–	–
Waste generation	–	30% of production	–
Shape of briquette	Cylinder, prism	Pillow	Any
Dimensions (mm)	80 × 80	30 × 40 × 50	5–35
Moisture content of charge (%)	<5%	<10%	12–18%
Possibility of immediate stockpiling of raw briquettes	–	Possible	Possible

Table 1. Briquetting technology comparison.

2. Specific features of stiff vacuum extrusion (SVE) agglomeration

According to the classification adopted in the brick industry, "stiff extrusion" means the extrusion process, carried out at pressures of 2.5–4.5 Mpa and moisture contents of the formable mass going from 12 up to 18% (**Table 2**, Ref. [4]).

The process starts with the mixing of BREX constituents together with a plasticizing binder (bentonite) and water and further preparation of the mix for homogenization (souring). To

Type of extrusion	Low-pressure extrusion	Medium-pressure extrusion	High-pressure extrusion	
Designation used in structural ceramic industry	Soft extrusion	Semi-stiff extrusion	Stiff extrusion	High-pressure stiff extrusion
Extrusion moisture (%)	10–27	15–22	12–18	10–15
Extrusion pressure (MPa)	0.4–1.2	1.5–2.2	2.5–4.5	Up to 30
Penetrometer (N/mm²)	<0.20	0.20–0.30	0.25–0.45	>0.30

Table 2. Types of extrusion and approximate values of the most important parameters.

achieve this process, all constituents and additives are removed from their bunkers or silos and loaded into feeding devices that precisely proportion each of them into a primary mixer where water is added. The mix is thoroughly mixed under high shear conditions. The next step is transportation of the moistened mix to the area of homogenization and curing of the mix for 24 h. After 24 h of souring, the material is loaded into Even Feeders, which feed the material in a regular way to the stiff vacuum extrusion briquetting line. This is followed by the secondary mixing of the moistened mix and binder, transportation of the prepared homogeneous mix to the extruder, and extrusion of the finally prepared mix to produce green BREX of a given strength.

The first step of the extrusion process is to blend cement binder and additional water with the soured mix. This is done via a secondary mixer that sits on top of extruder and discharges the mixed material into it (**Figure 1**). This mixer is designed to seal for vacuum as well.

The mixture enters the vacuum chamber and is partially agglomerated there due to the presence of high vacuum inside the chamber and removal of the air and moisture. The mixture is immediately crumbled, and its isolated particles fall down on blades of extruder auger. It is known [5] that the air adsorbed by surface of the particles of the plastic material in the form of multimolecular layers held by van der Waals bonding delays wetting them with water, even prevents compaction of mass, and contributes to the elastic deformation in plastic forming, contributing the lamination and microcracks detected during the drying and sintering of the extrusion products. Filling the pores, the air also prevents moisture penetration and separates particles. Vacuum removes the air from the pores and promotes closer contact of particles. The vacuum is maintained throughout the working volume up to the extruder dies. The vacuum level is at least 100 mm Hg (in absolute values). The combination of high mechanical values of auger pressure and the presence of vacuum, which deletes almost all compressible air from the material before it is subjected to pressure, leads to high values of the strength of the

Figure 1. General view of the extruder (bottom) and pug sealer.

green BREX, which allows their immediate transportation by conveyors and their stacking, practically without generation of any fines. In addition, it is known that under vacuum the viscosity of the cement paste decreased. This simplifies its uniform distribution and improves their interaction with water [6]. In combination with higher density of extruded mass, due to the removal of air, this leads to a decrease in consumption of cement binder.

BREX production ends with the exit of the elongated rods through the holes of the extruder die. These rods spontaneously break down during transportation by conveyors and further stockpiling into shorter fragments without generation of any dust (**Figure 2**). The decomposition of the elongated BREX during transportation by conveyors and discharge on the floor was described by Bizhanov et al. [7]. The reason for this is the bending of elongated BREX due to the gravity at the exit from the extruder that resulted in generation of 2–3 concentrators of the strain in the areas of future decomposition of this BREX.

Figure 2. Raw BREX at the exit of extruder and in the pile.

3. Investigation of BREX physical and metallurgical properties

We studied the process of strengthening of the BREX with combined binder (bentonite and cement) under natural conditions. For tests, we have chosen the BREX produced by industrial stiff vacuum extrusion briquetting line. The BREX contained (%) 47.2 of converter sludge, 28.3 of blast furnace dust, 18.9 of iron ore fines, 4.7 of Portland cement, and 0.9 of bentonite. Portland cement and bentonite were manually mixed in a dried state and added to a mixture before a pug mill with vacuum seal. For BREX samples, we daily measured compressive strength (on Tonipact 3000 (Germany) according to standard DIN 51067, open (apparent) porosity (vacuum method of liquid saturation according to standard DIN 51056), and density (on Mettler balance (the United States)). **Table 3** gives the results of daily measurements during 7 days. Apparent porosity and compressive strength values are given also in comparison in **Figure 3**.

A pronounced local peak is clearly visible in the BREX strength curve at the third day. The next day it changes into softening. During further storage, the strength increases. Note that, before softening, the BREX strength accounts for ~84% of the BREX strength after strengthening storage for 1 week. The change of open porosity almost follows the change in strength,

Strengthening time (days)	Apparent porosity (%)	Density (g/cm³)	Compressive strength (kgF/cm²)
1	31.5	2.42	24
2	25.4	2.66	45
3	32	2.43	63
4	27	2.44	52
5	27.2	2.45	56
6	26.2	2.45	57
7	26.8	2.46	59

Table 3. Change of physical properties of industrial BREX during strengthening.
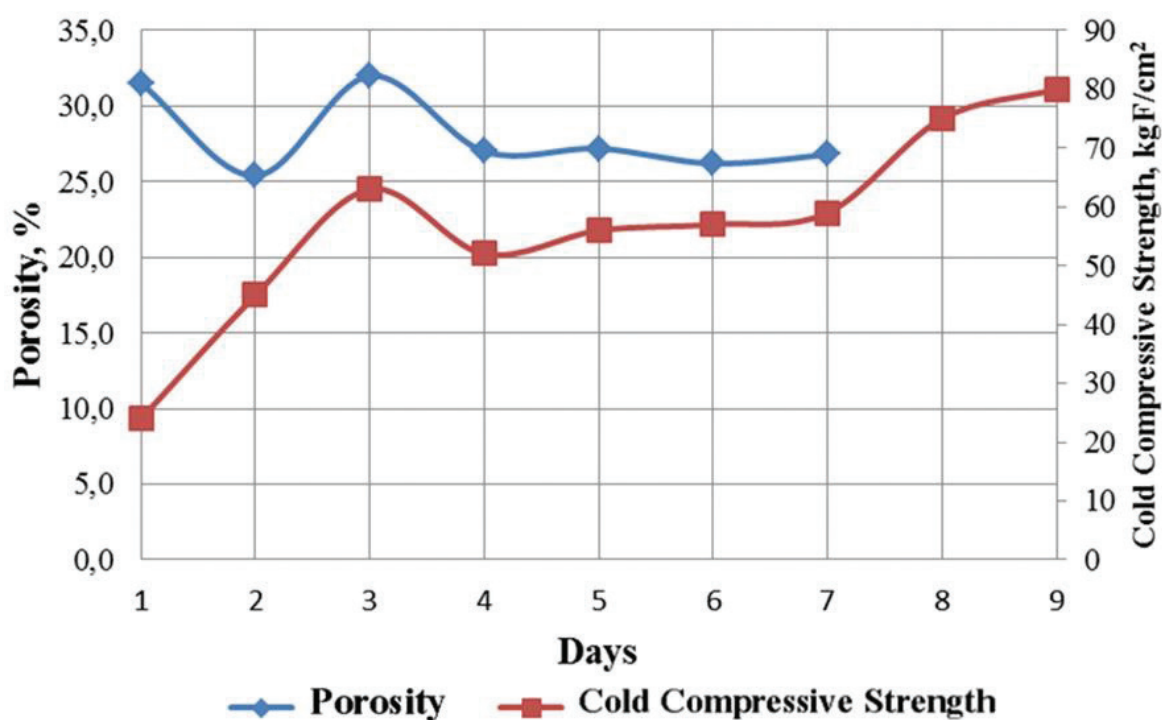

Figure 3. Change in strength and porosity of BREX during strengthening.

except for the first day of strengthening. The decrease in the porosity at that time is obviously related to the swelling of bentonite, which fills the pore space [8].

This behavior of BREX can be explained by the properties of a cement-bentonite binder and is related to the formation of coagulation structures in the cement-bentonite-water system, which leads to the modification of properties of the binder. Such structures are known to form in the gel-cement solutions used for the cementation of boreholes. The properties of the gel-cement solutions and the theoretical and practical aspects of formation and fracture of cement-bentonite systems are well known and systematized in, e.g., Ref. [9]. The driving force of the formation of such structures is the attraction of negatively charged bentonite particles to

positively charged Portland cement particles, which results in their rapid coagulation and formation of a structure with suspended cement particles. Hydrated cement particles are gradually coated with an impermeable shell of flaky bentonite particles. The number of adsorbed bentonite particles is proportional to the activity of cement. During hydration, Portland cement particles grow in size, which leads to tension, break in the integrity of bentonite shells, and penetration of water into cement particles (i.e., to further hydration of cement and, apparently, adsorption of a larger amount of bentonite).

In order to identify possible impact of shear stress on the change of particle size distribution occurring in conditions of stiff vacuum extrusion, we have compared the results of pulverization of coke in three different ways: in a hammer mill, smooth roller crusher, and double shearing through the shearing plate of the extruder (**Figure 4**).

The degree of grinding of coke breeze appeared to be maximal after double shearing through a shearing plate in an extruder. The effect of deep grinding in this case is reached due to the application of high shear stresses. The use of a hammer mill for such a material was found to be ineffective, and the granulometric composition of the ground material differed weakly from that of the initial coke breeze.

Based on this we decided to compare the compressive strength values of the BREX produced from these three differently processed materials. Three sets of BREX were manufactured using laboratory extruder with the same composition: 94% of coke breeze, 5% of cement, and 1% of bentonite. The only difference is being how the coke breeze has been pulverized. Those were the BREX #1 (smooth-rolled coke breeze), BREX #2 (hammer-milled coke breeze), and BREX #3 (double-sheared coke breeze). The BREX samples were subjected to tensile splitting tests on a bench-type one-column electromechanical Instron 3345 tensile testing machine at a load of 5 kN. **Figure 5** shows the results of testing the specially prepared cylindrical specimens of BREX with 25 mm diameter and 20 mm height. It is seen that, for an approximately the same load-bearing capacity of BREX specimens, their reactions to an applied load are different. The difference in maximum loads can be due to defects in the specimens. However, the difference in the characters of behavior may have radically different causes. BREX #2 demonstrates ductile fracture, which is indicated by existence of a yield plateau, i.e., horizontal component of
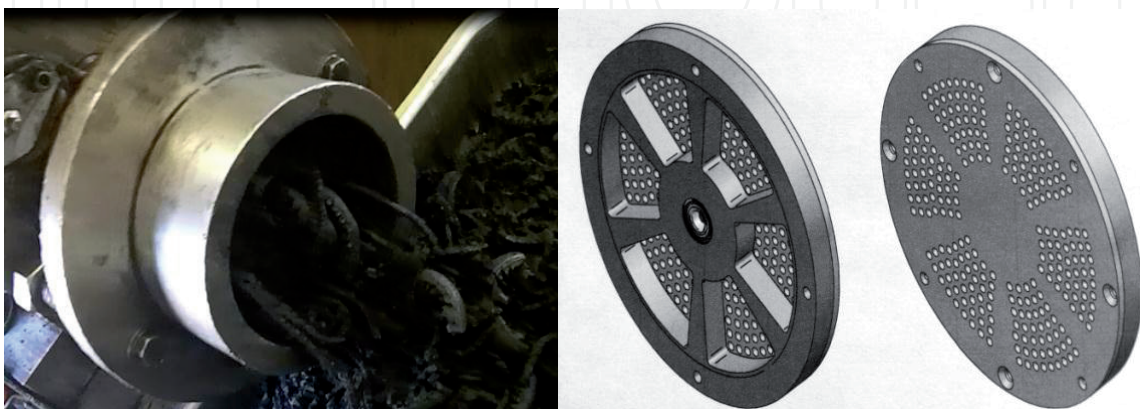
Figure 4. Shearing through the shearing plate extruder; view of shearing plate.
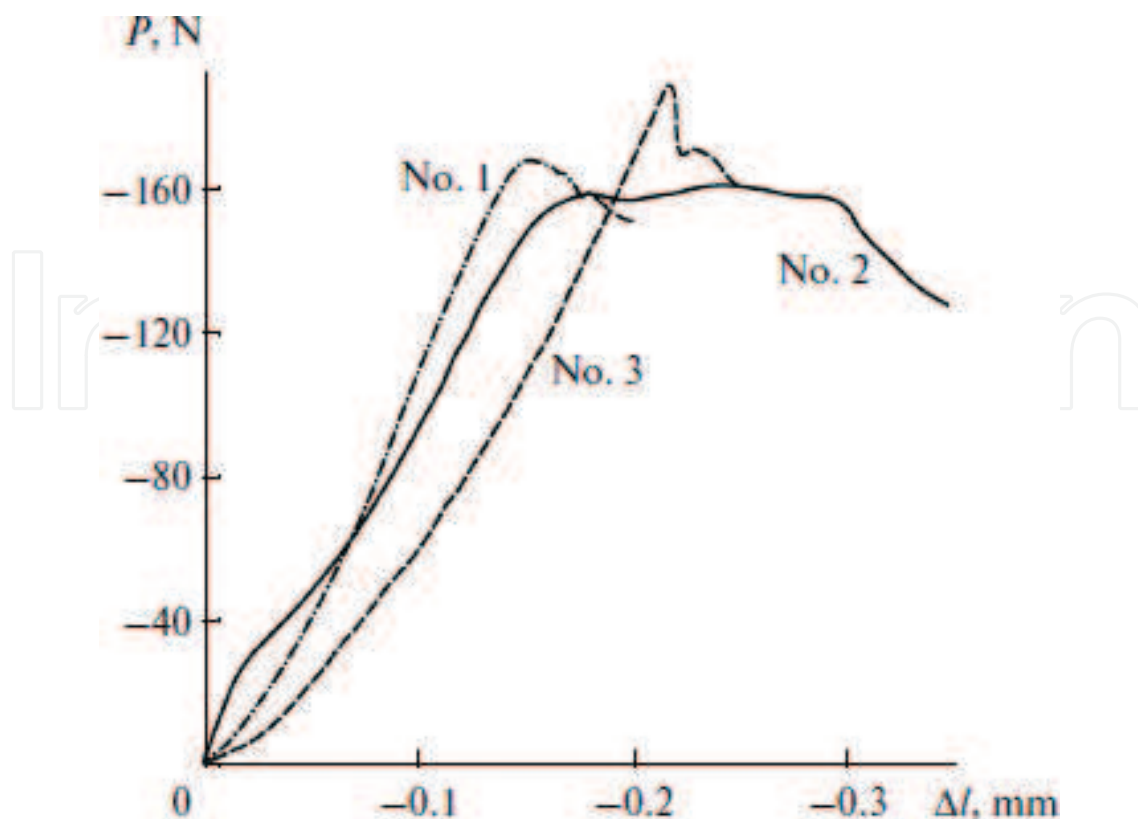
Figure 5. Results of the tensile splitting test of BREX; *P*, load; Δ*l*, displacement.

the curve of BREX #2. This phenomenon may be explained by a "relay race" transfer of gliding from grain to grain in terms of the Hall-Petch relation [10]. In this case, a grain boundary is a barrier to dislocation motion, which causes dislocation nucleation and development in a neighboring grain. In other words, the larger is the number of barriers to be overcome, the lower is the dislocation motion dynamics, and the higher is the crack development resistance.

One of the most compelling advantages of BREX with combined bentonite-cement binder is the possibility of their accelerated strengthening in comparison with the traditionally produced briquettes without addition of plasticizers. Composition of the BREX which we have subjected to three drops on the steel plate from 2 m height was as follows: A and B iron ore-sludge mixture (62.5%), mixture of flue dust and aspiration dust (30.5%), Portland cement (6%), and bentonite (1%); C- iron ore-sludge mixture (62.4%), mixture of flue dust and aspiration dust (30.1%), Portland cement (7%), and bentonite (0.5%); and D- iron ore-sludge mixture (62.2%), mixture of flue dust and aspiration dust (30.3%), Portland cement (6%), and bentonite (1.5%). Two modifications of BREX C were covered by tests using the addition of different amounts of water during mix preparation (50 and 100 ml). Components for all considered BREX were subjected to preliminary homogenization for 24 h in the form of hydrated mixture with the addition of bentonite. This method allows achieving a high degree of homogeneity of mixture properties for subsequent agglomeration. In some cases, the mechanical strength of BREX made of preliminary homogenized mix can significantly increase. Plasticizer's consumption can be considerably decreased during agglomeration of the preliminary homogenized substances.

Results of drop tests of the BREX after only 48 h of strengthening are presented in **Table 4**. It is known that the same strength level for the vibropressed briquettes on the cement binder can be achieved only after heat treatment at 80°C for 16–20 h or under the natural conditions (at a temperature of not less than 20°C) for 7 days [11].

For the assessment of the metallurgical properties of BREX, we have considered their low-temperature reduction disintegration indices (RDI). We have compared these values for two different types of BREX (**Table 5**)—blast furnace (BF) and basic oxygen furnace (BOF) sludge mixture with cement binder (BREX #1) and magnetite iron ore and coke breeze with cement and bentonite binders (BREX #2).

Testing of these two BREX types based on ISO 4696-1:2015 revealed a big advantage of BREX #2 compared with BREX #1 (**Table 6**). This can be attributed to the lack of any hematite phases in BREX #2 and to the presence of the secondary hematite in BREX #1. Crystal lattice of hematite is known to be subjected to the restructuring during reduction at low temperature causing mechanical stresses and disintegration of pieces of material that contain hematite. For comparison at the same time, we have measured following the same standard of the hot strength of sinters with basicity [$(CaO + MgO)/(Al_2O_3 + SiO_2)$] 1.2, 1.4, and 1.6. Hot strength of BREX #1 is comparable to the hot strength of sinters with basicity 1.2 and 1.4 (64 and 60%), which is due to practically the same content of secondary hematite. Hot strength of sinter with basicity 1.6 (77%) is larger than the hot strength of BREX #1 because of the presence in the sinter of this basicity of a new phase—calcium ferrites, which help to strengthen the sinter structure and to prevent its disintegration during low-temperature reduction. At the same time, the hot strength of BREX made of iron ore concentrate and coke breeze far exceeds the relevant indicators of all tested agglomerates.

For comparison we have studied the metallurgical properties of the hematite iron ore and coke breeze BREX (iron ore, 79%; coke breeze, 15%; cement, 5.55%; bentonite, 0.45%). Particles of this rich ore (Fe_{total}, 67.5%; SiO_2, 1.5%; Al_2O_3, 0.3%; CaO, 0.2%; MgO, 0.3%; S, 0.05%; P_2O_5, 0.05%) have a plate shape, which prevents their lump-forming capacity and makes the quality of the sinter lower. But this property of ore does not adversely impact on the quality of BREX and allows treating this ore as a promising raw material for the BREX

BREX parameters	A	B	C		D
Cement content (%)	6	6	7		6
Bentonite content (%)	1	1	0.5		1.5
Moisture content (%)	13.5	12.8	12.1	13.2	13.4
Drop strength testing (48 h) (%) of fines with size less than 5 mm	4.1	5.6	4.0	4.3	6.1

Table 4. Drop test results for the BREX after 48 h of strengthening.

BREX components	Mass share (%)	
	BREX #1	BREX #2
Portland cement	9.1	9.0
Coke breeze	–	13.5
Bentonite	–	0.9
BF sludge	54.5	–
BOF sludge	36.4	–
Iron ore concentrate	–	76.6

Table 5. BREX for RDI testing compositions.

Test material	RDI (%)
BREX #1 (1.93)	**61.9**
BREX #2 (basicity 0.75)	**96.5**
Sinter (basicity 1.2)	64
Sinter (basicity 1.4)	60
Sinter (basicity 1.6)	77

Table 6. Comparison of the RDI indices of BREX and sinter.

making. Mineralogical studies have shown that ore minerals are represented by hematite (Fe_2O_3) and rarely by splices of hematite with magnetite (Fe_3O_4). Silicates are most often observed in splices with iron minerals. To estimate the reduction process, polished sections of BREX samples were examined after their heating in a reducing atmosphere to temperatures: 900, 1100, and 1200°C. For the core of the BREX reduced by heating to a temperature of 900°C, the iron-containing phase is primarily represented by Wustite and magnetite (**Figure 6**, left), and the peripheral part contains linked metal iron particles with small inclusions of silicate phases (**Figure 6**, right).

In the peripheral part of the BREX heated to 1100°C, iron oxides have been fully reduced to the metal, and the metallic frame can be clearly visible (**Figure 7**).

Further heating to a temperature of 1200°C completes the process of BREX reduction of iron in its entire volume. In the core of BREX, iron is represented by metal and only partially in the form of Wustite. A small amount of inclusions of the unreacted particles of coke breeze (**Figure 8**) testifies to its abundance in the mix for BREX production even for the rich iron ore (67.5% Fe).
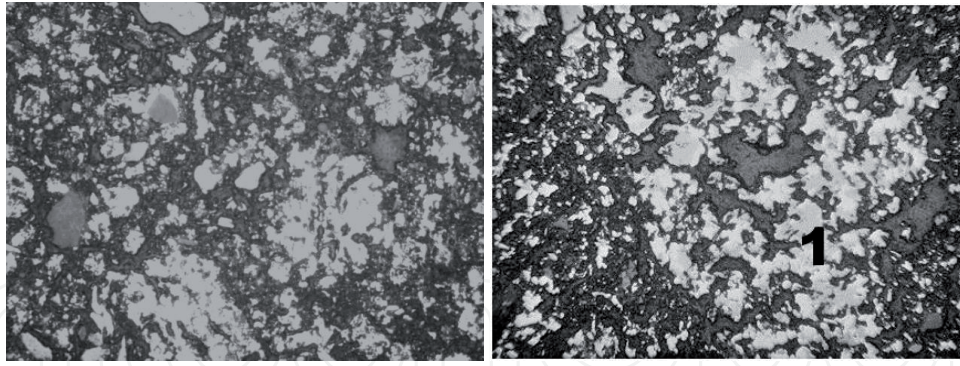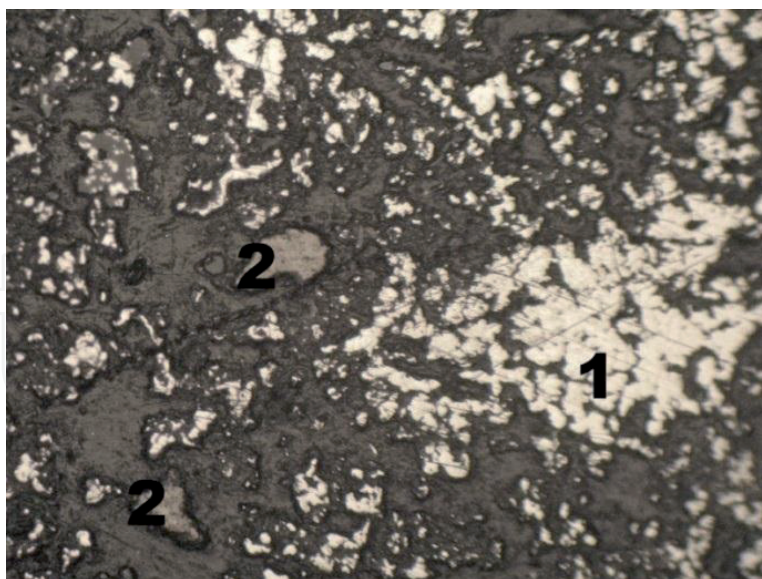
Figure 6. At left: microstructure of the core of the BREX reduced at a temperature of 900°C; reflected light, magnification × 100. At right: the formation of the metal frame by hematite grains (1) on the periphery of BREX (T = 900°C), the reflected light, magnification × 200, light gray-separate plots of the reduced Wustite and magnetite, and gray silicate phase.
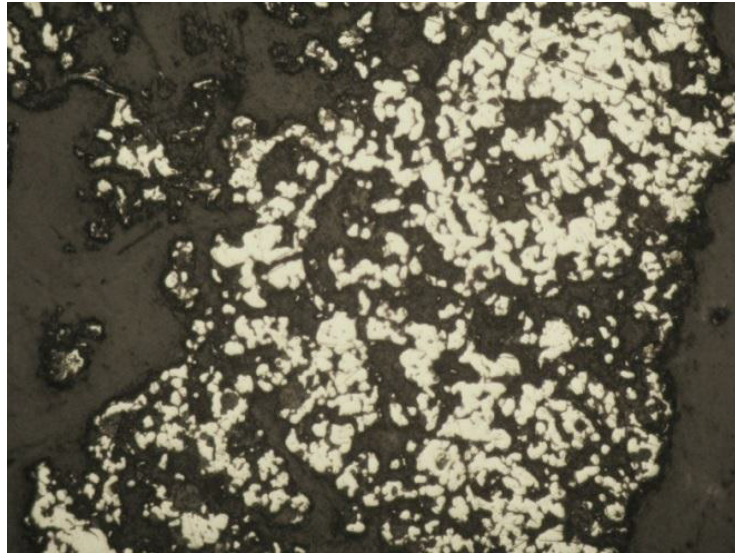
Figure 7. Microstructure of the periphery of the reduced BREX at a temperature of 1100°C: white, metal; gray, transformed mineral phases of the cement binder; reflected light, magnification × 200.

Thus, with increasing temperature above 900–1000°C, a major role in the reduction of the iron oxides in the body of the BREX is played by carbon of the coke breeze; in the peripheral part of the BREX the metallic frame is being developed at this stage resulting from the oxide reduction by gas.. The presence of coke breeze particle in BREX after its heating in reducing atmosphere until 1200°C leads to the conclusion that it is necessary to maintain the carbon content of BREX in accordance with the stoichiometric ratio of C/O equal to or slightly greater than 0.3–0.5 relative to atomic oxygen content in iron oxides of BREX after their reduction to Wustite [12].

Figure 8. Microstructure of the core of the reduced BREX at a temperature of 1200°C. (1) metal, (2) coke breeze, gray, transformed mineral phases of the cement binder; reflected light, magnification × 200.

4. Application of stiff vacuum extrusion for the production of blast furnace charge components

Based on these results, the decision was made to achieve the maximum possible share of BREX in the charge of an industrial small-scale blast furnace with a volume of 45 m³ (working volume 40.01 m³) [13]. The blast furnace is equipped with a skip hoist with a skip volume of 0.5 m³, double-cone charging device, hydraulic equipment for notch service, hot blast stoves, and a two-stage dry gas-cleaning system (dust collector and seven modules of bag filters). The blast furnace has eight air nozzles and one iron notch. External watering cools the furnace. Produced cast iron is immediately poured by the casting machine, and slag is granulated. Cast iron and granulated slag are shipped to customers by truck.

With two shifts working, the extrusion line produces 200 tons of BREX per day (12 castings per day). A required amount of the so-called washing BREX, made of manganese ore fines (−3 mm size) with 5% of Portland cement for binder, is also produced with stiff extrusion according to the operation schedule. It is known that in some cases, technologists were faced with "cluttering" of the hearth of the furnace due to the deterioration of coke's ability to filter when filling the voids between its particles by the pieces of slowly moving smelting products. It can result in combustion of air tuyeres, decrease of hearth heating, and other phenomena, which reduce the melting performance. One of the most effective means of combating this phenomenon is "flushing" the hearth by liquid slag containing FeO or MnO. Typically, the special sinter made with the use of mill scale is used as the "washing" material. Manganese briquettes can also be used for such purposes. The blast furnace melts 100–135 tons of BREX a day.

Operations began in May 2011 with BREX forming 10% of the charge, a percentage that gradually increased. When operating on a charge of 80% BREX and 20% iron ore, coke consumption decreased by 150 kg/t of cast iron (22%). This resulted from the decrease of carbon content in the BREX and withdrawal of the charge of raw fluxes. Lowering blast furnace performance by 15%, while switching to the new charge with BREX, was due to lower iron content in this charge (7.2%) compared to the charge consisting of iron ore and raw fluxes. Further increasing the share of BREX in the charge was not possible, due to an excessive increase in basicity of slags caused by the high basicity of BREX, which resulted from the presence of Linz-Donawitz sludge. During the development of the blast furnace regime with this new type of briquetted charge, we had to go to the new lower level of the furnace stockline because of difficulties with the dry gas-cleaning system. Gradually increasing the percentage of BREX in the blast furnace charge resulted in a lower temperature of furnace top gas and increased moisture content. As a result, bag filters become clogged with the wetted dust, and their regeneration by reverse pressure pulses had not reached the positive effect. Lowering the stockline helped increase the furnace top gas temperature, and the bag filter sticking stopped. Lowering the stockline had virtually no impact on the performance of blast furnace, primarily because iron oxides in the BREX are reduced by the dispersed carbon in the briquettes.

At the same time, the decision was made to increase the percentage of iron ore fine share in the BREX from 9.45 to 18.9%. This contributed to better blast furnace performance, due to better sintering and higher value of the activity of the "virgin" iron ore substance compared to the sludge and dust which have already undergone high-temperature processing. For more than two and a half years, the blast furnace worked successfully with a charge containing 80% of BREX. This blast furnace has worked with a 100% briquetted charge for the past 3 years.

Using BREX first as the primary and then as the only component of the blast furnace charge was possible because of their sound metallurgical properties and compatibility with the requirements of the iron-making process. This compatibility spans the life cycle of these briquettes, from the moment they exit the extruder die through the formation of cast iron in the blast furnace. BREX generate no fines moving from the extruder to the stockpile to the ready goods warehouse (loading these briquettes by forklift generates negligible amounts of fines). This eliminates the need for fines screening before charging, without any damage to the blast furnace. Skips with BREX do not contain any fines—pouring from the bunker to the skip and from the skip to the blast furnace-charging device of blast furnace generates no dust. Inside the blast furnace, BREX do not collapse when lowered from the top, preserving their integrity through softening and further melting in the cohesion zone. Results from various high-temperature tests, using BREX of different compositions in reducing atmospheres to investigate their mineralogical structure, confirm this conclusion [4]. All of the BREX kept their shapes when heated at a speed of 500°C/h up to 1150°C with a half-hour soak at that temperature and then cooled in an inert atmosphere.

The blast furnace operation parameters with different shares of BREX in the charge are given in **Table 7**.

Performance of blast furnace	100% iron ore	80% BREX	100% BREX
Consumption, kg/ton:			
Iron ore	1500	372	–
BREX	–	1425	1960
Limestone	150	–	–
Dolomite	144	–	29
Scrap	132	–	–
Quartzite	–	–	13
Mn ore BREX	–	19	75
Coke[*]	680	530	490
Fe_{total} in fluxed charge (%)	57.6	50.4	45.5
Capacity (ton/m^3 per day)	1.9	1.62	2.0
Blow temperature (°C)	925	900	1000
Blow pressure (kg/cm^2)	0.5	0.34–0.38	0.38–0.42
[Si] (%)	1.0–1.8	1.0–1.5	0.8–1.1
[Mn] (%)	0.2	0.4–0.5	0.7–0.8
[C] (%)	3.8–4.0	3.75–3.90	3.80–3.95
[S] (%)	0.050–0.060	0.038–0.050	0.038–0.042
Hot metal temperature (°C)	1380–1440	1400–1450	1410–1450
(CaO) (%)	34.86	33.12	38.0–39.0
(SiO$_2$) (%)	31.98	30.23	30.0–32.0
(Al$_2$O$_3$) (%)	23.87	17.98	16.0–18.8
(MgO) (%)	9.46	9.48	8.0–9.5
(FeO) (%)	1.01	1.26	0.6–1.15
(MnO) (%)	0.35	0.75	1.3–1

[*]It means the size of coke lumps 15-25 mm.

Table 7. Operation parameters of blast furnace with BREX in charge.

The data show that when working on a charge of 80% of BREX and 20% of ore, coke rate decreased by 150 kg/t of iron (22%) compared to furnace operation using 100% of iron ore. Coke rate reduction occurred because of carbon contained in the BREX, as well as the withdrawal of limestone and dolomite from the charge. Lower performance with a charge of 80% of BREX results primarily from decreasing iron content in this charge by 7.2% compared to the charge with the iron ore and raw fluxes. Working with a charge of 100% of BREX ultimately led to further reduction in the coke rate, due to the additional carbon of BREX, raising the blast temperature by 100°C. In addition, the use of the so-called washing manganese ore BREX reduced viscosity of slags and improved refinement of smelting products. As a result,

furnace productivity increased by improving the structure of stock column, reducing primary slag viscosity and raising the overall pressure drop.

As can be seen, despite the high specific heat loss (due to the small size of the blast furnace and low blast temperature), the consumption of coke in the blast furnace at 100% of BREX does not exceed 500 kg/t, which corresponds to the modern high-efficiency furnaces with iron content of 58–59% in charge with a temperature of 1200°C and with the blast overpressure of gas on furnace top equal from 180 to 250 kPa. This is the consequence of the self-reducing nature of BREX (due to the presence of carbon in flue dust), as well as their basicity, which provides the necessary basicity of blast furnace slag. The latter allowed elimination of limestone use. Additions of quartzite and dolomite were applied to adjust slag basicity and magnesia content in the slag. As a result, coke consumption for the 100% of BREX charge fell by approximately 200 kg/t compared to the 100% of rich iron ore charge operation of the blast furnace. It can also be seen that Si content in pig iron has approached the level typical for large blast furnaces.

Five years of industrial operation, producing agglomerated products for a blast furnace, show that BREX obtained from natural and anthropogenic dispersed raw materials have optimal and adjustable dimensions, manageable chemical composition, and high metallurgical properties. Thus, these BREX can be seen as a new type of agglomerated and fluxed furnace charge component for blast furnaces. Unlike sinter and pellet production, stiff extrusion is environmentally friendly and completely waste-free, with neither gaseous nor solid emissions.

Results of investigation of the metallurgical properties of BREX, together with the unique experience of small blast furnaces using 100% of BREX in the charge, served as the basis for research for the feasibility and efficiency of stiff extrusion for large-scale modern blast furnaces. Research performed with mathematical modeling of the blast furnace used a simulation of the process and DOMNA software developed in the National University of Science and Technology MISiS. Blast furnace smelting was evaluated under the existing conditions of the industrial blast furnace of PJSC "NLMK" (volume 4297 m^3) [14].

Modeling was conducted for the equal composition of cast iron and its temperature ([Si] =0.4%; [C] = 4.8%; T = 1500 °C) and for equal reduction efficiency (degree of approximation of the composition of the gas to the equilibrium in the Wustite reduction zone). Results showed that carbon contained in BREX reduced the consumption of coke by smelting compared with the base option by 10%. When working with a pulverized coal injection (PCI) furnace with 160–284 kg/ton coke consumption, injecting natural gas at the rate of 125 m^3/ton coke consumption reaches 354 kg/ton (**Table 8**).

Results of mathematical modeling of a blast furnace, using a charge containing BREX made of iron ore concentrate and coal, have shown high efficiency of the partial (50%) substitution of the sinter production by BREX production, along with a 10% reduction of coke rate and 50% decrease in gas and dust emissions during sinter production. Calculations show that, in view of the increased basicity of sinter produced (after the substitution of 50% of sinter production by BREX making), CO_2 emissions at the sinter plant will decrease by 32%, dust emissions by 50%, and sulfurous gas emissions by 43%.

The performance of the furnace	Traditional charge	Option 1	Option 2
Sinter consumption B2 = 1.7 kg/ton	1109	–	–
Sinter consumption B2 = 3.0 kg/ton	–	557	575
Pellets consumption (kg/ton)	546	557	541
BREX consumption (kg/ton)	–	557	575
Iron ore consumption (kg/ton)	–	17	–
Fe content in charge (%)	58.2	57.45	57.15
Coke rate (kg/ton)	391	354	284
Natural gas consumption (nm^3/ton)	125	125	35
Pulverized coal consumption (kg/ton)	–	–	160
Blow rate (m^3/min)	7483	7568	7340
Blow temperature (°C)	1240	1240	1240
O_2 content in blow (%)	30.5	30.5	30.5
Blast humidity (g/m^3)	10	10	20
Top gas (m^3/ton)	1545	1540	1470
Top gas pressure (kPa)	240	240	240
CO content (%)	24.4	24.9	26.2
CO_2 content (%)	23.2	22.6	23.9
H_2 content (%)	9.7	9.9	8.2
Slag ratio (kg/ton)	318	314	323
Slag basicity (B2)	1.01	1.01	1.02
Capacity (ton/day)	12,465	12,624	12,708
Capacity (ton/m^2 day)	92.48	93.66	94.3
Reduction efficiency (%)	94.2	94.2	94.2

Table 8. Blast furnace smelting simulation results (traditional charge and charge with iron and carbon containing BREX (one third of charge).

5. Application of stiff vacuum extrusion for manganese ferroalloy production

An industrial extrusion line in Ragland, Alabama, produced 2000 tons of BREX to investigate the applicability of stiff extrusion for ferroalloy production. A 1400 tons of manganese ore

fines were shipped from the Republic of Georgia (Chiatura), with 600 tons of baghouse dust shipped from a ferroalloy plant in West Virginia to make the BREX. The bulk raw material was blended and then transferred to the extrusion plant feed tanks. The blend was fed into a Steele 75ADC extruder, where it was mixed with water and 3–5% of cement. The extruder and vacuum mixer had a combined 338 KW capacity. The extruder was equipped with multi-hole extrusion die with round openings of 25 and 30 mm diameter. Typical production parameters were a production rate of 55 metric tons per hour, moisture content of the green BREX 10.5%, and vacuum level of 100 mm Hg absolute. **Figure 9** shows the production of the BREX and their immediate loading onto truck and further discharge within 5–10 min after production.

Next, the BREX were shipped to the smelter by barge and were discharged at a pier. Trucks provided transportation from the pier to an open-batch stockyard, followed by a conveyor directly to the furnace bunkers. In total, transportation of the BREX to the ferroalloy (2000 km) entailed 20 handling operations over 30 days. Total fines generated during these operations (less than 6 mm) did not exceed 10%.

To initiate a full-scale industrial trial, a stable 27MVA capacity and 85-Mt/day average production of industrial submerged electric arc furnace (SEAF) was selected to run with the specific average energy consumption at 4200 kWh/Mt, manganese recovery rate at 80%, and manganese content of dump slag at 12–14%.

To initiate a full-scale industrial trial, a stable 27MVA capacity and 85-tons/day average production of industrial submerged electric arc furnace (SEAF) was selected, using specific average energy consumption at 4200 kWh/Mt, manganese recovery rate at 80%, and manganese content of the dump slag at 12–14%. For the accuracy of comparison of results of the furnace operation, with and without BREX, the furnace operated for 1 month. A weeklong period of furnace operation, without BREX, immediately preceded the pilot operating period to serve as the reference. The results of the full-scale trial of the silicomanganese production with BREX in the charge of the industrial SEAF appear in **Table 9**. Their detailed description is given in Ref. [15].

The primary positive aspect of the full-scale campaign, using BREX in the charge for smelting of merchandise silicomanganese, is that the furnace operated in a smooth, stable regime. Furnace top operation was characterized by good gas permeability all over the surface, without any charge downslide. The current load was uniformly distributed among three electrodes.

Figure 9. Production (at left), loading (in the middle), and stockpiling of the green BREX for ferroalloy production.

Indicator		Pilot industrial operating period phase						
		Reference period 1	2	3	4	5	6
Actual metal production over a period of time (t)	ton	816.323	298.4	277.1	196.6	570.6	397.2	757.2
	b.t*	839.670	300.7	285.8	199.5	584.75	393.2	767.8
Actual furnace performance (%)		98.9	97.6	97.4	99.7	96.2	98.6	93.6
Power consumption (MW)		3.339.27	1.078.2	1.085.4	734.7	2.120.8	1.536.3	2.821.48
Specific power consumption (kW × h/b. Mt)		3.977	3.586	3.798	3.682	3.627	3.908	3.675
Ore-2	ton(29%Mn)/b.t	1.106	0.933	0.892	0.714	0.635	0.626	0.492
	ton(48%Mn)/b.t	0.668	0.563	0.539	0.431	0.383	0.378	0.297
Ore-1	ton(49.5%Mn)/b.t	0.565	0.505	0.482	0.509	0.480	0.524	0.484
	ton(48%Mn)/b.t	0.582	0.520	0.497	0.525	0.495	0.540	0.499
BREX	ton(31.37%Mn)/b.t	0	0.077	0.164	0.273	0.387	0.571	0.605
	ton(48%Mn)/b.t	0	0.050	0.107	0.178	0.252	0.373	0.395
The total consumption of raw manganese ore	ton/b.t	1.671	1.515	1.538	1.496	1.502	1.721	1.581
	ton(48%Mn)/b.t	1.250	1.133	1.143	1.134	1.130	1.291	1.191
Coke (ton/b.t)		0.432	0.341	0.420	0.400	0.381	0.418	0.404
Quartzite (ton/b.t)		0.419	0.499	0.524	0.465	0.529	0.456	0.475
Briquettes based on Ferrosilicon manganese screenings (ton/b.t)		0.158	0.082	0.103	0.092	0.120	0.110	0.094
Scrap (Mn content in scrap, %) (ton/b.t)		0.358 (23.3)	0.601 (29.9)	0.462 (33.0)	0.477 (35.3)	0.461 (32.0)	0.455 (25.8)	0.373 (38.6)
Electrode mass (ton/b.t)		0.034	0.032	0.030	0.035	0.028	0.033	0.028
Manganese extraction from the ore component (%)		80.1	79.8	80.7	80.7	83.6	79.1	79.9

Basis ton.

Table 9. Furnace operation parameters during reference and full-scale trial periods.

Electrodes were deeply submerged and stable. Melt tapping took place on schedule and chemical composition of metal, and slag showed no significant changes. Replacing a substantial part of the lumpy manganese ore with BREX based on ore fines and aspiration dust led to an overall improvement of technical and economic process indicators.

Specific energy consumption during the test period decreased significantly. In the reference period, consumption per basic ton of the alloy was 3977 kWh, with the share of BREX replacing ore in the charges equal to 40% and specific energy consumption decreased up to 3675 kWh per basic ton (–7.6%). Another positive result of the full-scale trial relates to the increased manganese extraction from the ore. At 29% of BREX in the ore part of the charge, the manganese extraction was 83.6% versus the average extraction of 80% in the reference period of the furnace operation without BREX in the charge. Decreased extraction in the period preceding the final phase was not associated with the presence of BREX in charge and was the result of furnace downtime and problems with the electrode.

It is also important to know the relationship of the BREX share in the ore part of the charge with the specific productivity of the furnace, expressed in the basis of ton per unit of electricity consumed. The best performance is achieved when percentage of briquettes in the ore part of the charge ranges between 30 and 40%. In general, results of the full-scale trials provide reason to consider BREX based on manganese ore fines and baghouse dust from gas cleaning as a viable charge component for silicomanganese smelting. Three more new stiff extrusion lines for briquetting were recently built for ferroalloy production.

Applicability of stiff extrusion for briquetting has also been studied for direct-reduced iron (DRI) production [16]. Results indicate that BREX could achieve a metallization degree comparable with metallization of traditional DRI. It has also been demonstrated that BREX may be considered as a charge component for rotary hearth furnaces (RHF) [17].

6. Conclusions

The main conclusions on the results of R&D of stiff vacuum extrusion applicability for metallurgy are as follows.

We have discovered the special nature of BREX strengthening curing due to the application of bentonite-cement binders, leading to the existence of a local peak of compressive strength after 48 h of a strengthening aging. The utilization of combined bentonite-cement binder promotes more rapid strength gain in comparison with traditional briquettes. We have found that stiff vacuum extrusion technology can be competitive as the technology of the fine iron ore containing material agglomeration, which is also able to serve as a partial or complete substitute for sinter production. Industrial experience of 3 years of continuous operation demonstrated the economically efficient operation of blast furnaces with 100% of BREX in their charge. Full-scale industrial trial confirmed the efficiency of BREX utilization as the charge components of submerged electric arc furnaces (up to 40% of the charge). Stiff vacuum extrusion is the only technology to agglomerate efficiently ore concentrates and aspiration dusts of

ferroalloy production. This conclusion has been confirmed by the practical experience of the recently commissioned stiff vacuum extrusion briquetting plants.

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