

# Mechanical Strength of Extrusion Briquettes (Brex) for Blast-Furnace and Ferroalloy Production: I. Dependence of the Strength Properties of Extrusion Briquettes on the Binder

A. M. Bizhanov<sup>a</sup>, I. F. Kurunov<sup>b</sup>, and V. Ya. Dashevskii<sup>c</sup>

<sup>a</sup>Russian Office, J.C. Steele&Sons, Inc., Russia  
e-mail: abizhanov@jcsteele.com

<sup>b</sup>JSC Novolipetsk Metallurgical Works, Lipetsk, Russia

<sup>c</sup>Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences,  
Leninskii pr. 49, Moscow, 119991 Russia  
e-mail: vdashev@imet.ac.ru

Received July 15, 2014

**Abstract**—The efficiency of preliminary homogenization of a briquetted charge using bentonite is shown. The dynamics of increasing the strength of commercial extrusion briquettes (brex) during storage under natural conditions is studied. A combined cement–bentonite binder is used to reveal a new effect of local maximum of the cold strength of brex at the third day of hardening, which is accompanied by a change in the character of its fracture.

DOI: 10.1134/S0036029515030039

The agglomeration of disperse natural and anthropogenic materials in metallurgy by briquetting becomes a widely used technology. One of the promising methods of briquetting is stiff vacuum extrusion: it ensures a high capacity of briquetting lines and the correspondence of the metallurgical properties of extrusion briquettes (brex) to the requirements of blast-furnace production, steelmaking, and ferroalloy production [1–3].

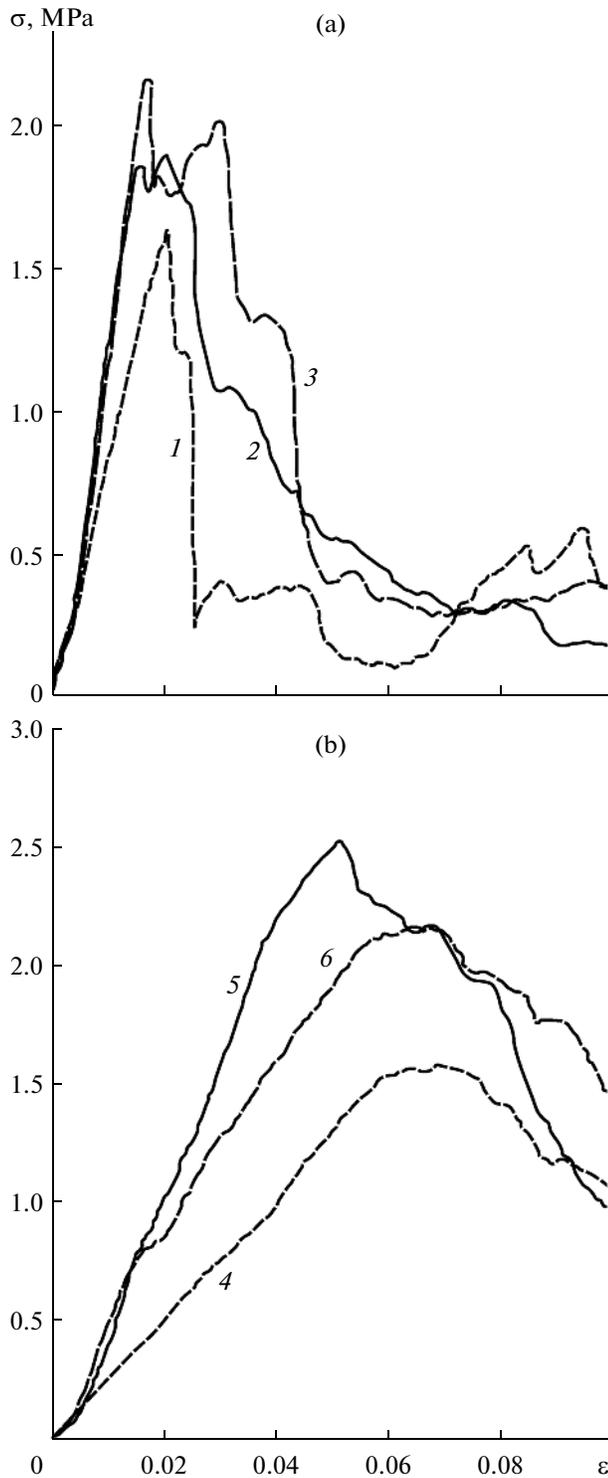
The properties of a mixture to be briquetted that make it suitable for extrusion are most often achieved by the addition of a plasticizing agent, mainly bentonite, to a charge. The fraction of bentonite required to ensure the extrusion of a mixture oscillates in the range 0.25–1.0% of the briquetted material density.<sup>1</sup> An important consequence of the plasticized mixture is an increase in the mechanical strength of brex and a change in the character of its fracture from brittle to viscoplastic fracture.

As an example, we present the results of axial compression tests of the brex of the first series made of a charge of a base composition ((in %), 67 dust of the aspiration of ferrochrome production, 15 chromium ore concentrate, 15 coal, 3 Portland cement) and the brex of the second series made of the same charge with an addition of 0.5% bentonite that were performed in a laboratory extruder. The axial compression tests of

the brex of both series were carried out on a bench-type one-column electromechanical Instron 3345 tensile-testing machine at a load up to 5 kN. Figure 1 shows the stress–strain curves that demonstrate the change of the character of fracture of bentonite-containing brex from pronounced brittle to viscoplastic fracture. This change is also illustrated in Fig. 2: it is seen that, in the case of fracture of bentonite-containing brex, the compression surfaces of the tensile-testing machine should be much closer than in the case of bentonite-free brex. A comparison of the strengths of the brex of two series showed that the average ultimate compressive strength of the brex made of a bentonite-free mixture is 1.88 MPa and that of bentonite-containing brex is 2.08 MPa (which is higher by 10%).

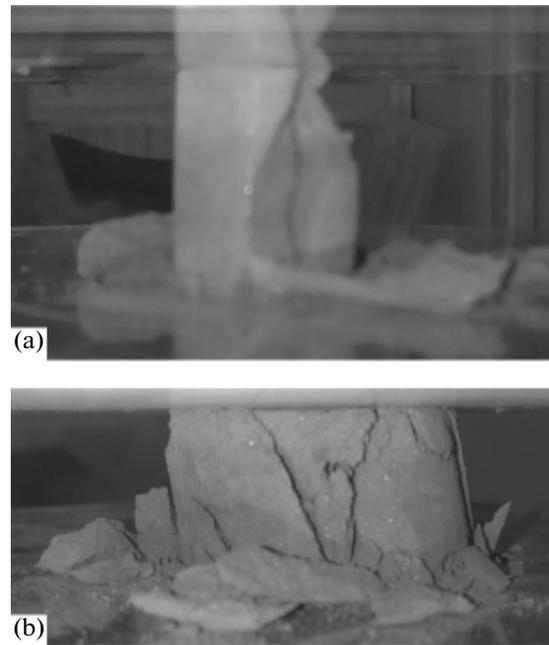
The change in the properties of brex induced by the addition of bentonite to the composition of the mixture to be briquetted also manifests itself after preliminary homogenization of the mixture to be briquetted during its “souring” (storage of the mixture for 1 day). We studied the effect of souring on the strength properties of brex of various compositions (Table 1). Table 2 gives the results of tensile splitting tests of brex 1 week after their manufacture. These results demonstrate that the use of bentonite in combination with Portland cement improves the strength properties of brex. The strength of brex increases substantially in some cases. In addition, the character of their fracture also changes and signs of viscoplastic fracture appear. In

<sup>1</sup> Hereafter, the component contents are given in wt %.



**Fig. 1.** Stress  $\sigma$ —strain  $\varepsilon$  curves for brex based on aspiration dust (a) without and (b) with 0.5% bentonite.

this case, brex can better withstand the impact loads that appear during their transportation to the sites of their application.



**Fig. 2.** Fracture of brex based on aspiration dust: compositions (a) without and (b) with 0.5% bentonite. The initial brex sizes are 50 mm in height and 25 mm in diameter.

As for the traditional methods of briquetting, this favorable influence of bentonite or bentonite in combination with Portland cement on the strength properties of briquettes is well known [4, 5]. An attempt to determine the optimum ratio of the fractions of Portland cement and bentonite in a charge to be briquetted was described in patent [6]. It was stated that the addition of the binder consisting of bentonite (15–25%) and Portland cement (85–75%) enhances the mechanical strength of the corresponding briquette. For the briquettes consisting of converter sludge (24.3%), scale (23.4%), blast furnace dust (23.4%), iron ore fines (18.9%), and the binder (10%) consisting of 75% Portland cement and 25% bentonite, the result of a drum test (fraction of a size of >6.3 mm) increased to 76% (it was 67% for the briquettes of the same composition but without bentonite).

We studied the influence of this combined binder on both the compressive strength of brex and the rate of increase of strength during strengthening storage under natural conditions. For tests, we chose the brex that were produced in the production line of stiff vacuum extrusion located at Suraj Products Ltd. (India) and contained (%) 47.2 converter slime, 28.3 blast furnace dust, 18.9 iron ore fines, 4.7 Portland cement, and 0.9 bentonite. Portland cement and bentonite were manually mixed in a dried state and added to a charge mixture before a pug mill with vacuum seal. For brex samples, we daily measured compressive strength  $\sigma$  (on Tonipact 3000 (Germany) according to standard DIN 51067), open (apparent) porosity  $\eta$  (vacuum method of liquid saturation according to standard

**Table 1.** Compositions of the charges of brex 1–6 for souring efficiency (%) tests

Charge component	1	2	3	4	5	6
Blast-furnace slime	42.8	41.8	41.8	41.2	47.8	28.3
Converter slime	39.8	38.8	38.8	38.2	43.7	25.4
Iron ore concentrate	—	—	—	—	—	29.3
Scale	13.0	13.0	13.0	12.1		10.7
Portland cement	4.0	4.0	6.0	8.0	8.0	5.8
Bentonite	0.4	0.4	0.4	0.5	0.5	0.5
Silica microgranules	—	2.0	—	—	—	—

DIN 51056), and density  $\rho$  (on Metler (United States) balance). Table 3 gives the results of daily measurements during 9 days.

Figure 3 shows the brex porosity and strength curves measured during strengthening storage. A pronounced local maximum is clearly visible in the brex strength curve at the third day. In the next day, it changes into softening. In the course of 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 repeats the change of strength, 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 [7].

We obtained similar results on the strength of brex during compressive strength and splitting strength tests performed on a strength-testing machine, which consists of a hand-power press, a strain gage, and a recording secondary device (Fig. 4). At the third day of increasing strength, the brex samples retained their integrity up to the end of testing and demonstrated a viscoplastic character of fracture during compressive and tensile splitting tests. At the third day of strengthening, both halves of the brex were connected despite almost complete development of a crack in the tensile splitting test. It is seen that compression and splitting of brex led to moisture release at the bottom. Moisture release was absent during compression at the seventh day of strengthening. When samples were subjected to compressive and tensile splitting tests at the seventh day of strengthening, a viscoplastic character of fracture was substantially lost.

This effect of nonmonotonic strengthening of briquettes with a cement binder, which is characterized by a local strength maximum and is accompanied by viscoplastic behavior at a breaking load, has not been detected and described earlier. The strengthening of monomineral cement stone and concrete is known to have a monotonic character [8]. A nonmonotonic character of increasing strength of brex having an alternative (noncement) binder or having no binder is well known. Ozhagin [9] presents data on the impact

fracture (analog of dropping strength) oscillations of briquettes having no binder and having different compositions upon drying under natural conditions (at a temperature of 20°C). The detected softening was thought to be caused by recrystallization, and it was recommended to limit the transportation and transfer of briquettes at this time and to store briquettes in closed vessels.

It is substantial in the phenomenon described above that the application of a cement–bentonite binder changes the behavior of brex during a braking

**Table 2.** Strength\* of brex 1–6 (see Table 1) in tensile splitting tests (MPa) and the souring efficiency\*\* of a briquetted mixture

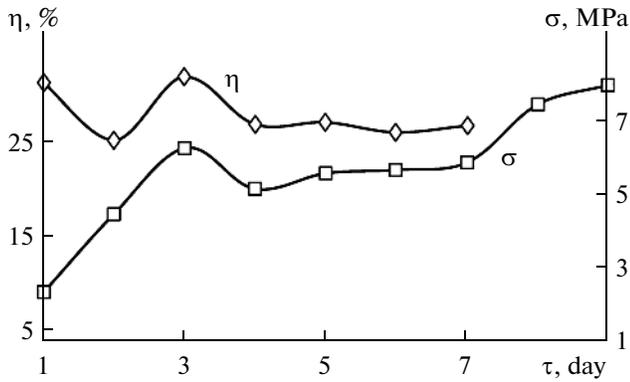
1	2	3	4	5	6
0.86	1.93	2.08	1.00	1.01	0.77
2.45	3.83	5.76	1.88	1.29	1.26
2.85	1.98	2.76	1.88	1.28	1.64

\* Numerator, the strength of brex without souring of the mixture to be briquetted; denominator, the same after souring.

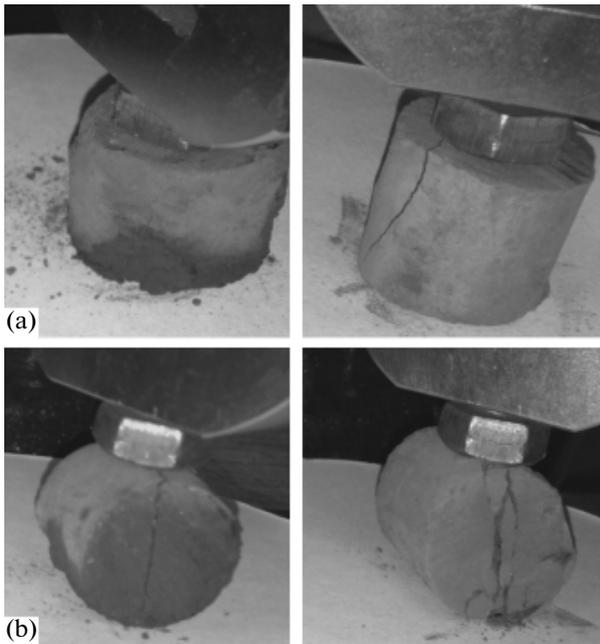
\*\* It is estimated as the ratio of the strengths of brex after souring and without it.

**Table 3.** Changes in the physical properties of the brex produced at Suraj Products Ltd. during strengthening 9-day storage

$\tau$ , day	$\eta$ , %	$\rho$ , g/cm <sup>3</sup>	$\sigma$ , MPa
1	31.5	2.42	2.35
2	25.4	2.66	4.4
3	32.0	2.43	6.2
4	27.0	2.44	5.1
5	27.2	2.45	5.5
6	26.2	2.45	5.6
7	26.8	2.46	5.8
8	—	—	7.4
9	—	—	7.8



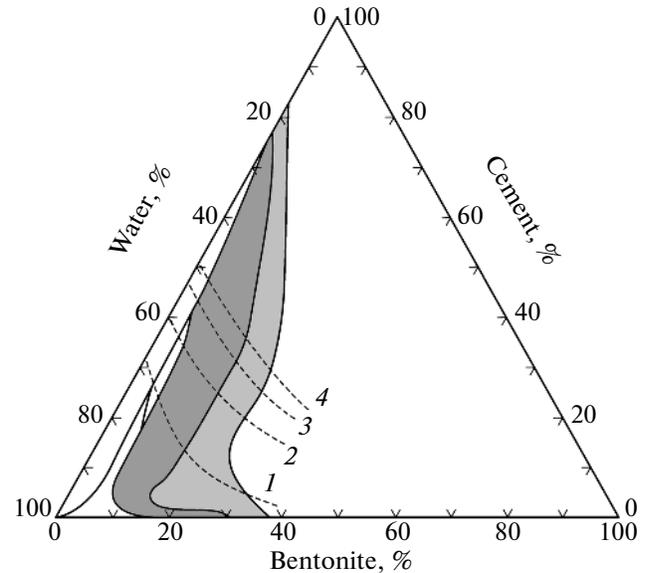
**Fig. 3.** Changes in compressive strength  $\sigma$  and porosity  $\eta$  of brex during strengthening 9-day storage.



**Fig. 4.** (a) Axial compression and (b) tensile splitting tests of the brex produced at Suraj Products Ltd. at the third ((a), (b) on the left) and seventh (on the right) day of strengthening storage. The initial brex sizes are 25 mm in height and 25 mm in diameter.

action, increases its impact strength, and decreases the probability brittle fracture.

This behavior of brex can be explained by the properties of a cement–bentonite binder and related to the formation of coagulation structures in the cement–bentonite–water system, which leads to the modification of the 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 the formation and fracture of cement–bentonite systems are well known and systematized in, e.g., [10]. The driving force of the formation of such structures is the attraction of negatively charged ben-

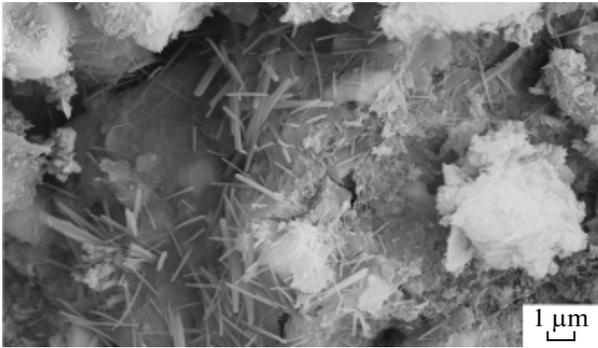


**Fig. 5.** Water–cement–bentonite phase diagram [11]. (light gray) Region of formation of a stable mastic suspension and (dark gray) region of a stable and mobile suspension. (1–4) Compressive strength of suspension: (1) 69, (2) 345, (3) 689, and (4) 1378 kPa.

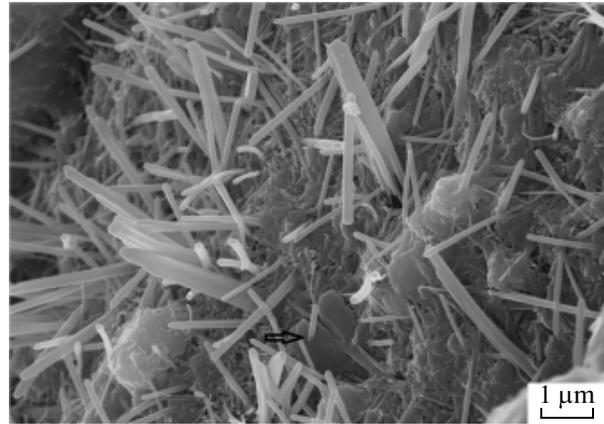
tonite particles to positively charged Portland cement particles, which results in their rapid coagulation and the formation of a structure with suspended cement particles. Hydrated cement particles are gradually coated with an impermeable shell of flaky bentonite particles. The number of adsorbed bentonite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

The fracture intensity of such a coagulation structure depends on the cement activity. The application of slag Portland cement is likely to retard this process. The coagulation structure begins to fail gradually as a result of the coagulation effect of calcium ions and changes into the structure of a hardening cement stone. The decrease in the strength after the peak at the third day is explained by the decomposition of the coagulation structure (see Fig. 3). The further increase in the strength is completely controlled by the hydration of cement stone.

The possibility of formation of such a stable structure is supported by the conclusions of work [11]. The range of the relative content of bentonite and Portland cement in the binder used for the production of brex (80% Portland cement, 20% bentonite) corresponds to the dark gray region in the water–cement–bentonite phase diagram (Fig. 5 [11]). Note that the local humidity near coagulated particles substantially (by



**Fig. 6.** SEM micrograph of acicular aggregates (ettringite particles) in cement in the structure of the brex produced at Suraj Products Ltd.



**Fig. 7.** SEM micrograph of acicular aggregates (ettringite particles) surrounded by bentonite plates in cement in the structure of the brex produced at Suraj Products Ltd.

11–12%) exceeds the humidity of the as-prepared brex due to differences in the permeabilities of minerals. An increase in the fraction of bentonite in the binder up to 30–40% favors the formation of a stable mastic suspension. The changes of the strength of the forming cement–bentonite compositions are also shown in the phase diagram. The strengths of the compositions are seen to decrease as the water content increases or the cement content decreases.

The effect revealed in this work can be important for practice: brex based on a cement–bentonite binder can be used as a charge component for a metallurgical furnace within 3 days of drying under natural conditions. As a result, the required sizes of brex storage can be decreased. The threshold level of compressive strength can be easily achieved by a simple increase in the fraction of this combined binder. Note that the total fraction of a binder in the brex produced at Suraj Products Ltd. accounts for at most 5.6% of the brex mass, which is significantly lower than the required content of Portland cement used for vibrating pressing (10–12%). The use of bentonite in the binder composition changes the character of fracture of briquettes and makes it viscoplastic, which simplifies the transportation of brex to the site of their application. A quantitative description of the detected effect is the subject of a further investigation.

The moisture release during the strength tests of briquettes at the third day can be related to restructuring in the agglomerates formed in cement during its hydration, which is accompanied by the release of part of chemically fixed water. It is known that, at a sufficiently high content of volume capillary moisture in cement, intense nucleation and growth of acicular aggregates take place at the third day of hardening [12]. It is these aggregates that are responsible for the connection of cement grains and prevent crack development in primary aggregates, and these aggregates were experimentally detected in the cleavages of commercial brex. The experimental investigation was carried out using a high-resolution scanning electron

microscopy (SEM) on an Auriga CrossBeam (Carl Zeiss) analytical working station equipped with an INCA X-Max energy dispersive spectrometer. The accelerating voltage was 20 kV. Figure 6 shows micrographs of acicular cement aggregates (ettringite). Ettringite forms during the hydration of cement as a result of the reaction between calcium aluminate and sulfate:  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 + 3\text{CaSO}_4 \rightarrow \text{Ettringite}$ .

Using SEM, we were able to reveal the elements of the decomposed coagulation structure. Ettringite particles surrounded by bentonite plates are visible in Fig. 7.

## CONCLUSIONS

(1) The use of bentonite in a charge for briquetting by stiff vacuum extrusion can substantially improve the service properties of agglomerated products, increasing the compressive strength and the impact strength.

(2) The homogenization of a charge using bentonite for 1 day increases its extrusion ability and the strength brex, which ensures the achievement of the required strength of briquettes at a lower binder content in the charge. The effect revealed in this work can be important for practice: brex based on a cement–bentonite binder can be used as a charge component for a metallurgical furnace within 3 days of drying under natural conditions. As a result, the required sizes of brex storage can be decreased.

(3) The threshold level of compressive strength can be easily achieved by a simple increase in the fraction of the combined binder. Note that the total fraction of a binder in the brex produced at Suraj Products Ltd. accounts for at most 5.6% of the brex mass, which is significantly lower than the required content of Portland cement used for vibrating pressing (10–12%).

(4) The presence of bentonite in the charge composition as a binder changes the character of fracture

of briquettes and makes it viscoplastic, which simplifies the transportation of brex to the site of their application.

(5) A quantitative description of the detected effect is the subject of a further investigation. In particular, we are going to study the possibility of using slag Portland cement in combination with bentonite as a binder.

#### REFERENCES

1. I. F. Kurunov and A. M. Bizhanov, "Stiff vacuum extrusion Steele—promising method for the sintering of metallurgical raw materials and wastes," *Byul. NTiEI: Cher. Metallurgiya*, No. 4, 46–49 (2012).
2. A. M. Bizhanov, I. F. Kurunov, N. M. Durov, et al., "Mechanical strength of brex: Part I," *Metallurg*, No. 7, 32–35 (2012).
3. A. M. Bizhanov, I. F. Kurunov, N. M. Durov, et al., "Mechanical strength of brex: Part II," *Metallurg*, No. 10, 36–40 (2012).
4. Koizumi Hideo, Yamaguchi Arata, Doi Teranobu, and Noma Fumio, "Fundamental development of iron ore briquetting technology," *ISIJ* **74** (6), 22–29 (1988).
5. Jpn. Patent S63 196689 (A), 1988.
6. E. A. Bogdan and R. L. Cole, US Patent 5395441, 1995.
7. Komine Hideo and Ogata Nobuhide, *Can. Geotech. J.* **40**, 460–475 (2003).
8. L. I. Dvorkin and O. L. Dvorkin, *Building Mineral Binding Materials* (Infra-Inzheneriya, Moscow, 2011).
9. V. V. Ozhogin, *Fundamentals of the Theory and Technology of Briquetting of Fragmented Metallurgical Raw Materials* (PGTU, Marioupol', 2010).
10. A. I. Bulatov and V. S. Danishevskii, *Grouting Mortars* (Nedra, Moscow, 1987).
11. G. K. Jones, "Chemistry and flow properties of bentonite grouts," in *Proceedings of Symposium on Grouts and Drilling Muds in Engineering Practice* (Butterworths, London, 1963), pp. 22–28.
12. E. I. Shmit'ko, A. V. Krylov, and V. V. Shatalova, *Chemistry of Cement and Binding Substances* (Prospekt Nauki, St. Petersburg, 2006).

*Translated by K. Shakhlevich*