

## Physicochemical Features of Complex Utilization of Solid and Liquid Wastes of Alumina Production

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### Abstract

Complex technology of waste utilization of alumina plant, which provides a stepwise going from the stage of statistically controlled accumulation of technogeneous products and impurities to a system of ecologically undangerous insulation and preservation of wastes, accompanied by the release of products into the processing cycle, is advanced. Starting from the calculated data as the base, this system ensures the highly efficient localization and rendering harmless of the contaminated areas of the hydraulic works by silt deposition based on the highly dispersed SiO<sub>2</sub>. The complex technological slime processing in accord with flotation – carbonization scheme together with neutralization of drainage and slime waters within the regime of carbonization and clarification make it possible to increase the degree of extraction of the alumina and other valuable components, to reduce the consumption of resources, and to have additional valuable products and additives used industrially.

### INTRODUCTION

One of the fundamental problems on a global scale is to work out the justified scientific methods of control over the technogenic processes. To scale, these processes are comparable not only with geological phenomena, but they also alter irreversibly the natural chemical composition of the environment into specific (technogenic) one that is not compatible with normal life [1]. Global character of anthropogenic action is due mainly to work of mining industry that forms technogenic after-landscape when extracting mineral and energy resources and provokes the rise of new processes of transformation of technogenesis prod-

ucts, which is impossible, in the present state of the science, to predict on frequent occasions.

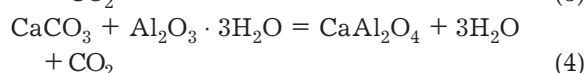
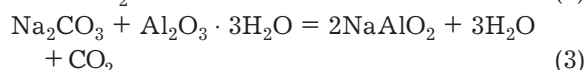
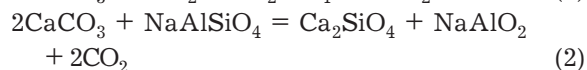
In the metallurgy, which is one of the most significant segments of the mineral use, the body of the exhausted industrial wastes depends on the target product content of the ore or concentrate, as well as on the used technology. Thus production of iron and aluminium, in spite of their high content in ores (up to 50–70 %), is connected with great quantity of wastes, which is caused by a large scale of extraction and processing of corresponding rocks. The great quantity of wastes is also generated by the extraction of rare metals: the content of these latter comprises several grams to each ton of the ore. These processes involve,

among mineral material, the reagents and different module components, maybe toxic, which leads to a rise in mass of the wastes as well as in technogenic load on the ambient medium.

As of now, the technogenic industrial wastes are essentially limited in use, for their utilization is economically unthinkable in modern practice. Because of this, it is essential to devise the new methods of localization and neutralization with full details, which will allow turning from the state of increasing technogenic stresses to the stage of insulation of technogenic systems and conservation of production wastes for the purpose of their further manifold utilization.

#### PRESENT STATE OF THE PROBLEM

The specific yield of solid wastes for domestic aluminium industry may run to 2.5–8.0 t/t  $\text{Al}_2\text{O}_3$ . This is because the Russia lacks its own resources of high-grade lateritic bauxites ( $\text{Al}_2\text{O}_3 \sim 45\text{--}60\%$ ;  $\text{SiO}_2 \leq 3\text{--}5\%$ ), which may be processed by Bayer method with specific yield of wastes of order 0.5–1.5 t/t  $\text{Al}_2\text{O}_3$ , and the alumina plants utilize nephelines ( $\text{Al}_2\text{O}_3$  25–30 %,  $\text{SiO}_2$  35–45 %) and low-grade bauxites [2]. In these conditions, the key step in the production is the high-expenditure process of caking aluminium ores with limestone and soda that is characterized by great material flows. Molar relation  $\text{CaO}/\text{SiO}_2$  in mixture is to be matched to 2 : 1 as closely as possible, whereas  $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$  – to 1 : 1, which assures the occurrence of following basic thermochemical reactions ( $t = 1250\text{--}1350\text{ }^\circ\text{C}$ ) [3]:



The alkali-aluminate solutions, which are formed in consequence of subsequent leaching of aluminates ( $\text{NaAlO}_2$ ,  $\text{CaAl}_2\text{O}_4$ ) under the action of caustic-carbonate soda, are applied to hydrochemical conversion of alumina production. Solid wastes of alumina production,

belite slimes, are transported as pulp with process waters to slime areas.

Mineralogical composition of belite slimes is single-type and presented mainly by dicalcium silicate  $\text{Ca}_2\text{SiO}_4$  (~80–90 %) with an admixture of minor amount of minerals of secondary origin. Distinctions in mineralogical composition are slight and depend on washing extent and storage life of obtained slime. As an example, the carbon dioxide content is commonly changed from 1.5 % for a freshly prepared slime to 5 % for a long stored one, suggesting that the degree of recrystallization of the slime under the action of the atmosphere is slight. More than 30 elements were identified in slimes by analytical methods. The chemical composition of slime of Achinsk Alumina Plant JSC (AAP), which is a consequence of the processing of nepheline ores of Kia-Shaltir deposit, is presented in Table 1.

The use of belite slimes in production of cement gives the chance to increase technical and economic characteristics of domestic alumina production. Limestone is added to the mixture along with slime, which provides going reactions of clinker formation ( $t = 1550\text{--}1650\text{ }^\circ\text{C}$ ) [4].

The use of high-base clinker minerals ( $\text{Ca}_3\text{SiO}_5$ ,  $5\text{CaO} \cdot 3\text{Al}_2\text{O}_3$ ) obtained on the basis of slimes of alumina production makes it possible to produce high-quality Portland cement of 400 and 500 types.

However the processing of the whole flow of produced slime is not necessarily successful. Glinozem Company (Pikalevo, Leningrad Region), for one, carries out processing belite slimes practically in full body (~2.3 Mt/year), whereas AAP, which made it possible to utilize hitherto more than one half the annual quantity (7.6 Mt) of slimes in the cement production, has stopped at the present time their processing for the lack of demand from the local building industry. In this connection the problem of storing wastes of AAP has been significantly dramatized. There is a need to find more and more increasing number of areas for slime fields and to provide the optimum protection against ground and surface waters.

A number of know-how aimed at reducing slime body, which is generated from processing nepheline starting material, was hitherto advanced [5, 6].

TABLE 1  
Averaged chemical composition of dry belite slime from AAP JSC

Basic component	Content, mass %	Admixture	Content, g/t
CaO	52.18	Zr	147.75
SiO <sub>2</sub>	29.66	Zn	100.00
Fe <sub>2</sub> O <sub>3</sub>	3.40	Cr	72.50
Al <sub>2</sub> O <sub>3</sub>	2.80	Cu	43.75
Na <sub>2</sub> O	1.94	Ni	26.25
CO <sub>2</sub>	1.87	V	21.25
MgO	1.40	Co	20.63
K <sub>2</sub> O	0.91	B	20.10
TiO <sub>2</sub>	0.40	U	10.75
FeO	0.38	Y	8.75
P <sub>2</sub> O <sub>5</sub>	0.38	Pb	65
BaO	0.3	Th	5.78
SrO	0.21	Ga	3.50
S <sub>total</sub>	0.12	Be	1.88
MnO	0.08	Mo	1.75
F	0.02	Sn	0.12

Notes. 1. Granulometric analysis of slime, mass %:  $d > 2 \text{ mm} - 2.0$ ;  $d = 2-1 \text{ mm} - 12.0$ ;  $d = 1-0.5 \text{ mm} - 21.0$ ;  $d = 0.5-0.25 \text{ mm} - 36.5$ ;  $d = 0.25-0.10 \text{ mm} - 24.4$ ;  $d < 0.10 \text{ mm} - 4.1$ . 2. A number of admixtures (Ti, Ba, Mn, Cr, Ni and others) are easily washed out of the slime and pass into wash and drainage waters. 3. Averaged chemical composition of drainage or subslime waters, mg/m<sup>3</sup>: dry residue 32 190, Na<sup>+</sup> 7583, K<sup>+</sup> 4041.58, CO<sub>3</sub><sup>2-</sup> 16 285.78, HCO<sub>3</sub><sup>-</sup> 334.38, Ca<sup>2+</sup> 12.42, Mg<sup>2+</sup> 3.16, Al<sup>3+</sup> 1600, Fe 0.1, SiO<sub>2</sub> 120.48, SO<sub>4</sub><sup>2-</sup> 1611.02, Cl<sup>-</sup> 593.48, PO<sub>4</sub><sup>3-</sup> 1.84, NH<sub>4</sub><sup>+</sup> 0.09, F<sup>-</sup> 1.0, NO<sub>3</sub><sup>-</sup> 3.1. pH 12.35.

In spite of evident merits, the considered versions of modernization of caking mode are unsuitable for full-scale introduction as the ones call for a marked rise in price of the existing production. These processes, as a long-standing practice of AAP shows, can be realized solely under conditions of the pilot area, which does not solve the problems in utilization and conservation of slimes.

In this connection the alumina plants would be forced to store belite slimes (wastes of hazard rate III-IV) on polygons which take up an area of hundreds of hectares. Then special-purpose hydraulic structures (slime pits), which provide clarification, cooling, accumulation and recovery of subslime water into the alumina production for recycling use in the process operations (repelling and hydraulic transportation

of slime, leaching, preparation of mixture, and so on), serve as the places of permanent or temporary disposition of these slimes.

The present technology of slime washing up to multimetric fill (the height of AAP fill runs into 100 m) and ensuing gathering of drainage waters by drains and drainage channels falls to prevent infiltration of technogenic solutions into the subsurface water-bearing horizons and transport of ecologically dangerous components by underground streams into the surface reservoirs (Fig. 1). What's more the majority of slime pits, now in operation or preservation, were designed and constructed for alumina plants without using safety antidrainage screens, which does not provide an appropriate protection of natural waters in the end.

SETTING UP A PROBLEM

As noted above, the belite slime is partially hydrated and carbonised in consequence of the interaction with atmospheric carbon dioxide, subslime and meteoritic waters. Contrary to the

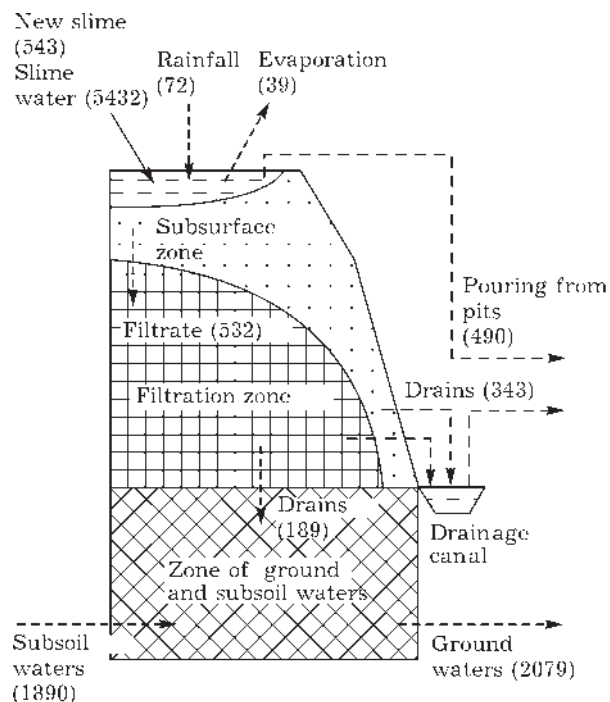


Fig. 1. Diagram of flows in AAP JSC slime pit (thousand tons/month). Amount of accumulated aged slime in filtration zone is about 100 Mt.

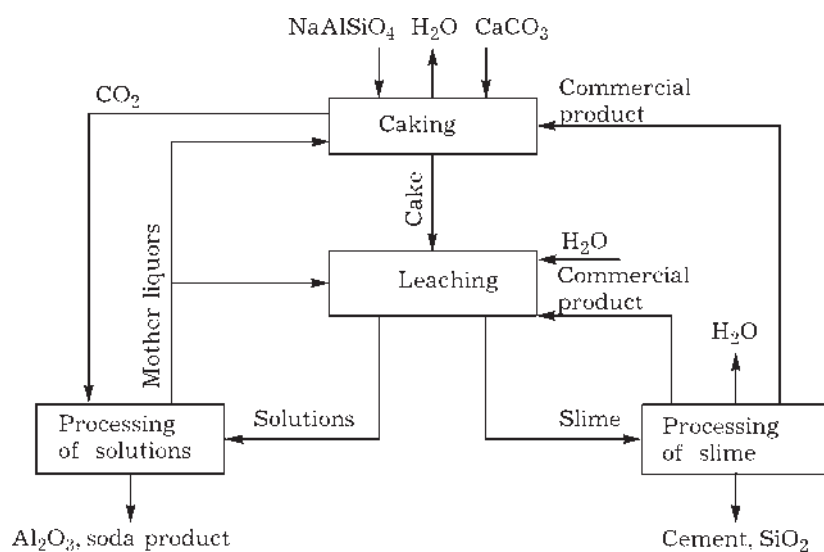


Fig. 2. General scheme of waste-free and ecologically safe production of alumina by caking.

expectations that has unfavourable effect upon the binding and antidrainage properties. Inasmuch as the bonded water content of the washed slime is of order 4 %, no more than 10 % slime react with solution and water-tight structures are not formed. Clearly it takes a reactivity to promote through increasing the degree of dispersion (grinding) or through introduction of agents favouring polymerisation of cement-forming phases.

With the aim of elaborating ways of reduction in the negative action of high-alkali return waters on the surrounding medium, the possible methods of belite slime conversion into technologically effective and ecologically safe, under slime storage conditions, product have been examined. The proposed procedure of reducing drainage volumes is that silica given off in a stage of desilication of products of alumina production is used as a silt deposit in the course of the slime storage and conservation

(Fig. 2). The set problem was solved by the methods of thermodynamic simulation in accord with the material balance of hydraulic-engineering structure (Table 2, see Fig. 1) [7]. The computer model has been developed, that represents the basic regularities of physicochemical transformations of belite slime and technogenic solutions under operating slime storage conditions. The sum of potential components at equilibrium includes 155 dependent ones in aqueous solution, among them a solvent ( $H_2O$ ), 14 gases and 35 mineral phases. The required thermodynamic data are taken from handbooks and scientific publications [8–11].

## RESULTS AND DISCUSSION

### First stage of investigations

An investigation of the processes of belite slime transformation by the methods of com-

TABLE 2

Material balance of AAP JSC slime storage, t/h

Coming	Body	Expense	Body
Slime pulp (L : S = 10 : 1)	7000	Settling of solid wastes	720
Ash pulp (L : S = 60 : 1)	1200	Moisture of recent wastes (40 %)	480
Weather waters	100	Water return to production	6200
		Water evaporation	50
		Drains into aged slime	850
<i>Total</i>	8300	<i>Total</i>	8300

Note. Volume of drainage waters, which enter the area of subsoil ones, totals 263 m<sup>3</sup>/h.

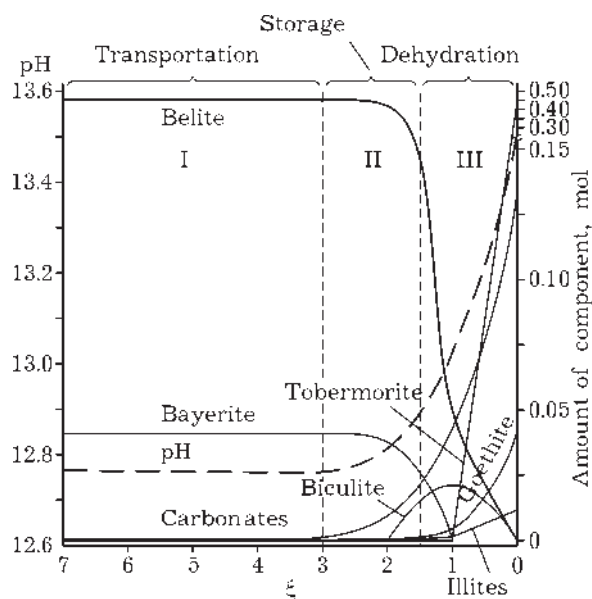


Fig. 3. Variations in mineral structure of belite slime under the action of sublimed waters during pulp transportation (I), slime storage (II) and during conditions of dehydrated deep horizons of slime pit (III).  $\xi$  is degree of reaction advancement  $-\log v$  corresponding to fraction of slime (100 g) reacted with 1 kg solution.

puter simulation has shown that the processes of slime hydration are accompanied by a recrystallization of dicalcium silicate  $\text{Ca}_2\text{SiO}_4$  into the structure of a cement mineral having composition  $\text{Ca}_6\text{Si}_6\text{O}_{18} \cdot n\text{H}_2\text{O}$ . The ions  $\text{Ca}^{2+}$  released in the process form a calcite and calcium carbaluminate in the presence of  $\text{CO}_3^{2-}$  and  $\text{AlO}_2^-$  (Figs. 3, 4). Bayerite is formed in the initial stages of the slime hydrolysis (see Fig. 3). The slime amount reacted with the solution is augmented with time. The concentration of the dissolved substances is also augmented. Tobermorite, the most effective cement-forming structure, is generated where the reacted slime amount exceeds 10 g/kg  $\text{H}_2\text{O}$ . But the total mass of tobermorite is minor. What's more the dominant phases are carbonates, biculite, goethite for as long as the degree of interaction does not exceed 10 g/1 kg  $\text{H}_2\text{O}$  (see Fig. 3).

During conditions of the absence of any contact with the atmosphere, that is, when the amount of free carbon dioxide is restricted, tobermorite is generated at lower stages of the process ( $\sim v \cdot 10^{-1.5}$ ). In such a manner the "old" slime particles under 0.1 mm in size, which are

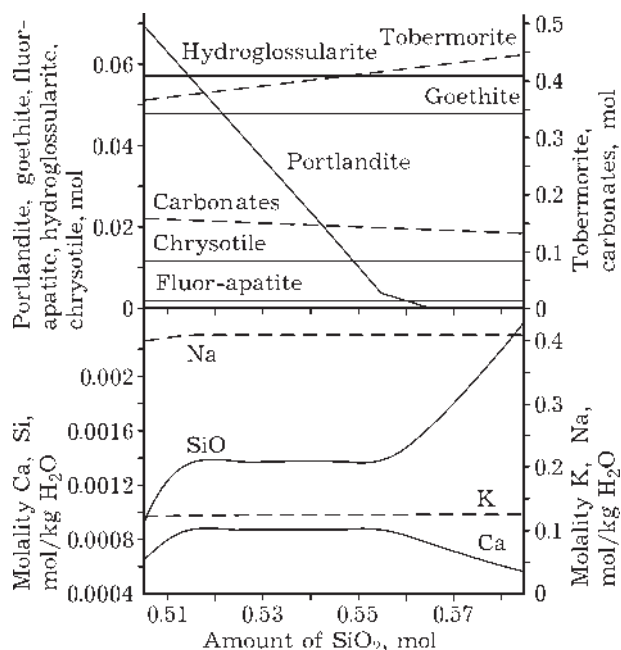


Fig. 4. Constitution of solid phases and molality of solution as functions of silica amount introduced into system (10 g slime to 1 kg solution).

placed at the deep levels of slime storage ( $W < 20\%$ ), are rearranged. A comparison between simulation results (see Fig. 3) and chemical and mineralogical studies shows that the extent to which the stored slime is rearranged forms 2–8 %, which corresponds around  $v \cdot 10^{-2}$ . This moderate extent of the source material conversion reduces the particle capacity for polymerization. In the field of hydration ( $v \cdot 10^{-1.5}$ ), that corresponds to the lower levels of slime storage, tobermorite is generated to a small extent (under 5 %), which is inadequate to form watertight structures (see Fig. 3). The higher degree of advancement of the reaction ( $v \cdot 10^{-1.5} - v \cdot 10^0$ ) is called for cementing. However the performance of this process is impossible without additional grinding of the slime.

Character of processes associated with slime storage shows that particle polymerisation can be stimulated through incorporation of special mineralises (colmatants) into the slime pulp. Since the formation of carbonates and carbaluminates presents competitive tendency for the slime conversion, whereas the release of clinker mineral tobermorite is controlled by the silica content, the greatest effect with colmatage can be achieved by the use of highly dispersed and reactive  $\text{SiO}_2$ . Figure 4 shows the basic reg-

ularities of variations in the equilibrium composition of solid phases derived from the silica introduction into the return waters–belite slime system. It was found that tobermorite becomes the dominant equilibrium phase with an increase in concentration of dissolved silica. Tobermorite becomes the dominant phase in the presence of a colmatant at that stage of the belite slime conversion ( $v \cdot 10^{-2}$ ) when it is found as traces during the most favourable conditions, while insulated against the atmosphere, but without a colmatant.

Physicochemical model of the return waters–belite slime–colmatant system makes it possible to select the most favourable conditions for the generation of cementoid structures, which significantly improve the antifiltration capacity of the storage slime (Table 3).

### Second stage of investigations

Following a common practice, waste water is diluted with pure one [4], but in this case a dilution in the proportion 1 : 100 gives no way of the attainment of MPS (maximum permissible concentration) for waste water. The most efficient method for a drop in pH and slime water purification is carbonisation. Figure 5 shows the course of variations in the composition of subslime water on treatment with carbon dioxide (0–0.7 mol CO<sub>2</sub> per 1 kg H<sub>2</sub>O). The results of a simulation show that the carbon-

ised solution is practically neutral (pH ~ 7.3) at a consumption of 0.3 mol CO<sub>2</sub> per 1 kg H<sub>2</sub>O; concentration of aluminium ions is reduced from 1200 to 1–3 mg/L, and from 25 to 0.2 mg/L for silicon; concentration of calcium ions is stabilized at a level of 10 mg/L, whereas that of sodium ions is kept constant (~8 g/L). The fall in solubility leads to the formation of authigenic phases, which are presented for the most part by bayerite admixed with illite-smectis, carbonates, goethite, hydroxylapatite, dolomite, hydrogrossularite (less than 2 % as a whole). The generated sediment can be extracted by the thickening procedure and following coagulation and directed to the alumina production.

It has been determined that carbonisation of subslime water with the aim to purify it of Al<sub>2</sub>O<sub>3</sub> (and partially Na<sub>2</sub>O) makes it possible to direct a purified water into the system of a return water supply of the alumina works or to drain it into water bodies upon the corresponding dilution. The degree of utilization of furnace gases in alumina production, which is commonly no more than 20–30 %, can be elevated in this case through carbonisation of waters mentioned above and Al(OH)<sub>3</sub> deposition. As an example, this technology was developed for carbonisation of alkali-aluminate solutions. The extent to which subslime water is purified of alumina runs to 98.5 % and to 46.6 % in the case of alkalies. Efficiency in purification may be improved (up to 90 % Na<sub>2</sub>O)

TABLE 3

Changes of physicochemical properties of belite slimes in storage

Parameters	As of now	After 10 years		After 30 years	
		without colmatants	with colmatants	without colmatants	with colmatants
Content of					
Ca <sub>6</sub> Si <sub>6</sub> O <sub>18</sub> · nH <sub>2</sub> O, %	4.03	5.22	8.12	6.41	12.88
W, %:					
point 100 m	40	25	18	15	12
point 0 m	17	15	9	10	6
pH (drain)	12.35	11.70	9.60	10.00	8.50
V (drain), m <sup>3</sup> /h	263	180	50	100	20

Notes. 1. Area of slime field map put in prolonged storage accounts for 190 ha. 2. Annual average quantity of precipitation is equal to 427 mm. 3. Averaged chemical composition of precipitation, mg/L (pH 5.63; E<sub>n</sub> = 0.896 V): Ca<sup>2+</sup> 1.97, Mg<sup>2+</sup> 0.1, (Na<sup>+</sup> + K<sup>+</sup>) 0.37, HCO<sub>3</sub><sup>-</sup> 5.68, SO<sub>4</sub><sup>2-</sup> 0.97, Cl<sup>-</sup> 0.3, NH<sub>4</sub><sup>+</sup> 0.12, NO<sub>3</sub><sup>-</sup> 0.014, P 0.014, Si 0.204.

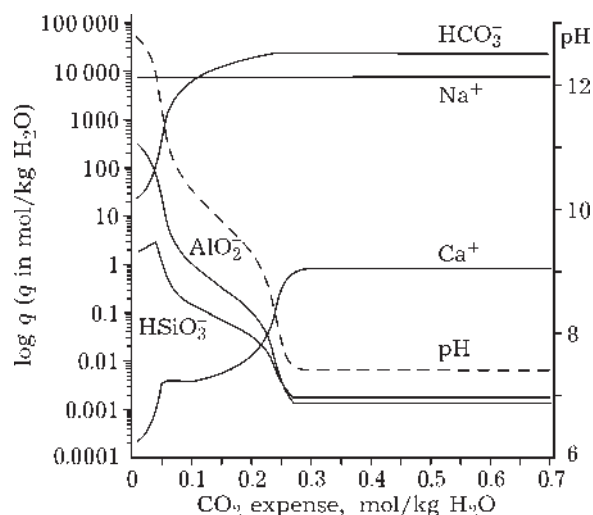


Fig. 5. Variation in solution composition in the process of sublime water carbonisation depending on carbon dioxide amount.  $q$  is amount of component.

through the use of zeolites in carbonisation. The clarification of carbonised solutions proceeds better with using white slimes, which reduce the content of suspended solids from 242.9 to 70.0 mg/L, and from 5.9 to 3.2 mg/L for  $Al_2O_3$  [12]. Recovery of sediments resulting from this technology (Table 4) provides an elevated level of extraction of components from stock. Hence the carbonisation processing makes it possible to solve the problem of utilization of return (sublime) waters on the whole: firstly, to raise the alumina extraction from stock (by 30 kt/year); secondly, to put the composition of slime waters into correspondence with the standards for the purpose of their recycling in production.

The results of engineer estimates obtained on the basis of monitoring studies and computer simulation data and giving the chance to

evaluate a possibility for the safe conservation of belite slimes are listed in Table 3.

*Third stage of investigations*

As noted above, the use of belite slime in cement production by the traditional technology is of serious limits. However the modified technology of slime processing makes it possible to elevate efficiency in its utilization. This is due in part to recovery of a major portion of  $CaO$ , which is wasted as a slime component, into the process. The designing and introducing of relatively inexpensive technology of belite slime desilication to the point, where a lime module  $M_{lime}$  is more than 2, will give the chance to reduce the consumption of fresh limestone in alumina production as well as to begin the processing of recoverable resources accumulated on the slime field, with a consequent decline in ecological load on native objects.

The most effective mode of slime processing is called upon to contain a recrystallization and separation of minerals by the flotation enriching scheme with making up to 30 % calcite concentrate ( $CaCO_3$  content is 60–70 %,  $M_{lime} > 3.5$ ) for alumina production needs and up to 70 % recoverable wastes containing no less than 95 % belite and tobermorite ( $M_{lime} \sim 1.5$ ) (Table 5).

According to analytical data, the calcite content of the slime is no more than 6–7 %, which is inadequate to conduct process. The  $CaCO_3$  content is to account for 15–20 %. To do this requires an added grinding of the slime pulp in a classifying mill to increase the content of the most reactive fraction (0.074 mm) from 5 to 60 %. Thereafter one can effectively carry

TABLE 4  
Results of investigations into carbonisation of alkali-aluminate solutions

Al <sub>2</sub> O <sub>3</sub> starting content, g/L	P <sub>CO<sub>2</sub></sub> , kPa	Chemical composition of precipitates, mass %			X-ray analysis of precipitates*
		Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	CO <sub>2</sub>	
1.0	300	57.24	0.64	7.28	Alumina gel
1.0	400	57.62	0.48	7.82	Alumina gel
5.0	300	51.78	6.54	12.65	Alumina gel, SHAC
10.0	300	43.32	10.80	18.59	SHAC, alumina gel
20.0	400	41.01	18.74	19.68	SHAC, NaHCO <sub>3</sub> , bayerite
80.0	300	50.68	10.89	9.02	Bayerite, NaHCO <sub>3</sub>

\*SHAC – sodium hydroaluminocarbonate.

out the processes of pulp carbonization (up to pH 6–7) and following flotation of the obtained calcite into a froth product with the use of water glass ( $\text{Na}_2\text{SiO}_3$ ) as a silicate depressor and sodium oleate ( $\text{C}_{17}\text{H}_{33}\text{COONa}$ ) as a oxyhydric collecting agent [13]. One can at once neutralize the liquid part of a pulp to the acceptable ecological standards and elevate the degree of utilization of acidic components ( $\text{CO}_2 + \text{SO}_2$ ) of furnace gases. The flotation chamber product – belite-tobermorite waste – can be separated and worked up to the condition required for the production of many structural materials and ceramic products (brick, concrete and others).

### Practical references

The results of the experiments have shown that the use of the microdispersed colmatant based on amorphous ultrafine (less than  $0.1 \mu\text{m}$ ) silicon dioxide makes it possible to reduce the filtration leakage from slime pits by 75–85 % and to remove the harmful impurities from the filtrate [14]. The colmatant expense is 50–150 t/mln  $\text{m}^3$ , and the cost is 4.2 thousand roubles/t; the waterproofing cost of 1  $\text{m}^2$  polygon of the burial of wastes is 240 roubles. The fine-grained dust of silicon production from dry dust extractors of the gas purification system, along with  $\text{SiO}_2$  resulting from slime desilicization, are used as a starting material for producing colmatants. The colmatant incorporation is suit-

able at the stage of slime deposition (at a point of disposal onto a map) with using a set-up for preparation and dosing.

Belite slime washing with carbonized alkali-aluminate solutions in the process of storage makes it possible to raise a lime module of slime from 2 to 2.5–3.5 through recrystallization of belite phase into tobermorite, hydrogarnet and others. The following treating of the newly formed phases allows removing a silica portion and its processing into the individual product ( $\text{SiO}_2$ ).

The proposed procedure of slime recovery in the caking process gives an added chance to reduce the  $\text{CaCO}_3$  consumption.

### CONCLUSION

The complex of technical measures for reducing filtration ability of the stored belite slime from alumina production, as well as for localization of ground water contamination, for pumping out contaminated waters by drainage systems, their conditioning (carbonisation) and repeat commercial utilization.

The proposed physicochemical methods of belite slime modification make it possible to cut the specific consumption of modulating agents (limestone and soda), to elevate the extent to which valuable components can be extracted from stock, to perfect a water circulation system, to reduce the load of stored slime on hydraulic and environmental protection objects.

TABLE 5

Results of flotation of carbonised slime pulp (L : S = 3 : 1)

Type of flotation machine	Concentrate yield, %	Content, %					
		in concentrate			in waste		
		$\text{CaCO}_3$	$\text{SiO}_2$	$\text{Ca}_2\text{SiO}_4$	$\text{CaCO}_3$	$\text{SiO}_2$	$\text{Ca}_2\text{SiO}_4$
FM-04	29.1	52.9	9.4	17.9	3.6	10.9	73.3
FAND-100	28.3	65.5	7.6	12.5	1.7	11.4	75.3

Notes. 1. Content in solid phase, mass % :  $\text{CaCO}_3$  19.7,  $\text{SiO}_2$  10.4,  $\text{Ca}_2\text{SiO}_4$  57.5. 2. FM-04M is the most widespread type of mechanical flotation machines used in flotation of cryolite from coal froth on aluminium plants. 3. FAND-100 is a new promising type of flotation column apparatus allowing high-efficiency selection of mineral particles on the model of falling pulp-air flow.



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