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# Leaching of phase-separated glasses in the $Na_2O–B_2O_3–SiO_2–Fe_2O_3$ system

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The leaching behavior of heat-treated phase-separated iron-containing sodium borosilicate glasses within the range of compositions of $8Na_2O\cdot(22-x)B_2O_3\cdot70SiO_2\cdot xFe_2O_3$, where $x$ varies from 0.3 to 10 mol.%, and $(8-x)Na_2O\cdot22B_2O_3\cdot70SiO_2\cdot xFe_2O_3$, where $x$ varies from 2 to 6 mol.%, in the 3M aqueous HCl solution at boiling, was studied. It has been shown that the introduction of $Fe_2O_3$ in these phase-separated glasses increases their chemical durability, the values of porosity and the average pore diameter, but reduces the specific surface area in the porous glasses based on them, compared with glass without $Fe_2O_3$. The compositions suitable for producing porous glasses were determined.

**Key words:** $Na_2O–B_2O_3–SiO_2–Fe_2O_3$ system, phase-separated glasses, chemical durability, magnetite.

## Introduction

It is well known that porous glasses (PGs) derived from glass forming sodium borosilicate (SBS) system are widely used as materials for various purposes [1–3]. Filling the pore space of the PG with different dopants allows one to create composites with new useful properties. Imparting new unique properties to the composites is possible not only by impregnating the PG but also by modifying the matrix itself.

For example, to produce new composite materials with multiferroic properties (combining both the electric and the magnetic components [4, 5]) it is required that the matrix itself would already possess magnetic properties before the introduction of a ferroelectric dopant into it. Such materials can be used as a nonvolatile memory elements and/or durable recording media with a high stability and reliability of the operation (FeRAM, FLESH-memory). To create these matrices, phase-separated glasses of the $Na_2O–B_2O_3–SiO_2–Fe_2O_3$ system can be used, in which ferric oxide was introduced into the charge at the initial stage of glass melting [6]. The following leaching allows to extract components of the chemically unstable phase [7]. At the same time, the presence of iron in the form of magnetite ($Fe_3O_4$) gives magnetic properties to the resulting porous matrix [8, 9].

The successful obtaining of a surviving porous matrix directly depends on the structure and chemical stability of the initial phase-separated glass. In this connection, it is necessary to systematically study the effect of $Fe_2O_3$ on phase separation and leaching behavior in the four-component $Na_2O–B_2O_3–SiO_2–Fe_2O_3$ system depending on the content of $Fe_2O_3$ and $Na_2O$, which is addressed in this work.

## Materials and methods

In this work, two series of iron-containing SBS glasses were studied: 1) $8Na_2O\cdot(22-x)B_2O_3\cdot70SiO_2\cdot xFe_2O_3$, where $x$ varies from 0.3 to 10 mol.% and 2) $(8-x)Na_2O\cdot\cdot22B_2O_3\cdot70SiO_2\cdot xFe_2O_3$, where $x$ varies from 2 to 6 mol.%, synthesized using the conventional glass-melting method [10]. The initial components of the charge were $Na_2CO_3$ of ultra high purity grade, $H_3BO_3$ and $Fe_2O_3$ of reagent grade, and $SiO_2$ in the form of ground quartz glass. The samples were synthesized in platinum crucible with a volume of 300 ml in a silit (silicon carbide) furnace with forced stirring of the melt at 1500–1540 °C in air for 2–4 h depending on the composition. After pouring the glass melt onto a metal plate, the obtained glass was annealed in a muffle furnace at 520–550 °C for several minutes and then cooled to room temperature (20 °C) in the furnace during 6–7 hours.

To obtain the phase-separated structure, the initial (after the synthesis) glasses were heat-treated at 550 °C for 144 hours.

The compositions of glasses, density, and volumetric concentration of the components are shown in Table 1. The density ($\rho$) of phase-separated glasses was determined by hydrostatic weighing in water, the measurement error $\pm 0.005$ g/cm$^3$.

The chemical analysis of initial glasses (Table 1) was performed according to the standard techniques [11]. The crystalline phases in the glasses were identified by X-ray powder diffractometry (XRPD) on the DRON-2.0 unit, CuKα – radiation. Electron microscopic studies in the transmission mode (TEM) were carried out on the EM-125 (JSC SELMI) device at an accelerating voltage of 75 kV (resolution ~10 nm).

In this paper, the kinetics of leaching of phase-separated glasses in a 3 M HCl solution at boiling was studied. The growth rate of the leached layer thickness ($h$) was measured on polished plate-shaped glass samples with the dimensions of 10×10×3 mm, using an optical microscope MIN-8. The kinetics of extraction of the $Na_2O$, $B_2O_3$, $SiO_2$, $Fe_2O_3$ components from glasses was examined using polished plates with the size of 10×10×1 mm.

The concentration of glass components in the leaching solution was determined by standard procedures [7]. The leaching rate was estimated by the experimental value of components ($Q_{exp}$) passed from the glass surface unit ($S_0$) into the solution in a definite time. The ($Q_{exp}/S_0$) values were compared with the theoretically possible ones ($Q_{calc}/S_0$) which were calculated on the basis of the glass composition (in wt.%, not presented in the paper) and the value of $\rho$ [9].

As a result of a straight-through leaching of the investigated phase-separated glasses, PGs were obtained. The structure parameters of the PGs were examined by the BET method from nitrogen equilibrium adsorption and desorption isotherms at 77 K (specific surface area *SA*), and by the gravimetric method (porosity *W*). The average pore diameters *D* were calculated from the equation:

$$D = (4/SA) \cdot (1/\rho_{\text{app}} - 1/\rho_{\text{s}}),$$

here $\rho_s$ = 2.18 g/cm$^3$ is the density of the silica skeleton, $\rho_{app} = P/V$ is the apparent density of the porous glass (g/cm$^3$), *P* is the sample weight (g), and *V* is the sample volume (cm$^3$) [12].

The obtained results were compared with the leaching kinetics of iron-free glass with the composition (as synthesized, mol.%) 8 $Na_2O$, 22 $B_2O_3$, 70 $SiO_2$ according to [13] (hereinafter we are going to use the designation 8/70).

**Table 1.** Composition, density and volumetric concentration of glasses under study (double column)

| Designation of glass* | Glass composition as-analyzed, mol.% | | | | Volumetric concentration $C_0$, g/cm$^3$ | | | | Density $\rho$, g/cm$^3$ |
|---|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $B_2O_3$ | $Na_2O$ | $Fe_2O_3$ total | $SiO_2$ | $B_2O_3$ | $Na_2O$ | $Fe_2O_3$ total | |
| Series 1 | | | | | | | | | |
| 8/70–0.3 | 71.86 | 20.59 | 7.17 | 0.38 | 1.558 | 0.518 | 0.160 | 0.021 | 2.258 |
| 8/70–2 | 71.69 | 19.33 | 7.08 | 1.90 | 1.543 | 0.482 | 0.157 | 0.109 | 2.291 |
| 8/70–3 | 71.29 | 18.44 | 7.11 | 3.16 | 1.539 | 0.461 | 0.158 | 0.181 | 2.340 |
| 8/70–4 | 71.63 | 17.25 | 7.35 | 3.77 | 1.557 | 0.435 | 0.165 | 0.218 | 2.375 |
| 8/70–6 | 70.91 | 15.89 | 7.22 | 5.98 | 1.547 | 0.402 | 0.162 | 0.347 | 2.458 |
| 8/70–8 | 70.80 | 14.11 | 7.38 | 7.71 | 1.545 | 0.357 | 0.166 | 0.447 | 2.516 |
| 8/70–10 | 70.59 | 12.15 | 7.24 | 10.02 | 1.538 | 0.307 | 0.165 | 0.580 | 2.588 |
| Series 2 | | | | | | | | | |
| 22/70–2 | 72.22 | 20.59 | 5.26 | 1.93 | 1.527 | 0.505 | 0.115 | 0.108 | 2.246 |
| 22/70–4 | 71.83 | 20.51 | 3.72 | 3.94 | 1.531 | 0.329 | 0.080 | 0.219 | 2.288 |
| 22/70–6 | 70.51 | 21.72 | 1.86 | 5.91 | 1.444 | 0.515 | 0.039 | 0.321 | 2.320 |

*The numbers in the designation correspond first: in Series 1 – to the content of sodium oxide, in Series 2 – to boron oxide, the second through the fraction – to silicon oxide, and the last through the hyphen to the content of $Fe_2O_3$ according to the synthesis (mol.%).

## Results and discussion

The results of dilatometric measurements along with the XRD and TEM data for the 1st series of glasses are described in [10]. It was shown that over the entire range of selected compositions the interconnected phase-separated structure with crystalline inclusions of $Fe_3O_4$ is formed during heat treatment at 550 °C for 144 h. Magnetite starts to form in the glass containing 3 mol.% of $Fe_2O_3$. The content of magnetite increases with the further increasing of the amount of iron (III) oxide added to the initial charge. Because of the interconnected structure, all glasses of this series have been subjected to leaching. The previously unpublished electron-microscopic photographs of the 1st series of glasses and the glass 22/70–2 from the 2nd series are shown in Fig. 1.

In the 2nd series of glasses, according to TEM, glass 22/70–2 with 6 mol.% of $Na_2O$ (Fig. 1, *b*) has an interconnected phase-separated structure with the diameter of liquation channels 45–65 nm. However, with decreasing the $Na_2O$ content and with increasing the $Fe_2O_3$ content, respectively, the structure tends to change from interconnected to a droplet-matrix one (glass 22/70–6). Glass 22/70–4 is intermediate as the droplets of the boron-rich phase in it are somewhat connected. According to XRD, even at a low content of $Fe_2O_3$ (2 mol.%) a small amount of magnetite starts to form during the heat treatment at 550 °C for 144 hours. With an equal content of $Na_2O$ and $Fe_2O_3$ of 4 mol.% in addition to magnetite, the crystalline compounds of $\beta$-$Fe_2O_3$ and $FeSiO_3$ (iron metasilicate) are formed. In the glass 22/70–6, magnetite and $FeSiO_3$ are the only iron-containing crystalline phases [14]. Due to the structural features of these glasses, we chose two compositions with 2 and 4 mol.% of $Fe_2O_3$ for the subsequent leaching.

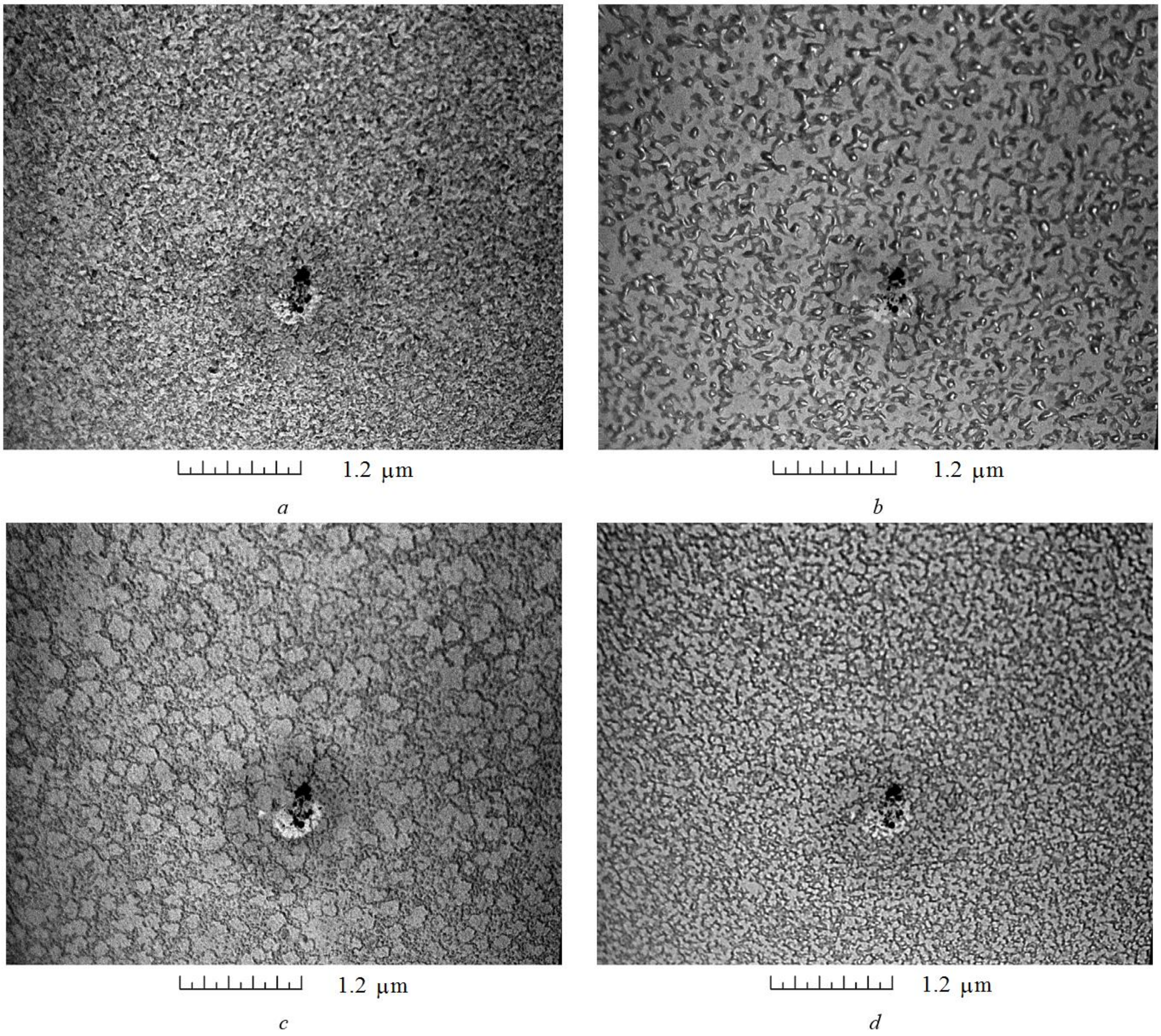

**Fig. 1.** TEM photographs for phase-separated glasses after heat treatment: a) 8/70–2, b) 22/70–2, c) 8/70–6, d) 8/70–10.

As one can see from Fig. 2, the addition of $Fe_2O_3$ to SBS glasses does not change the general nature of the diffusion-leaching process as evidenced by the linear character of the dependences. In some cases, the curves do not pass through the origin but cross the abscissa axis. This kind of dependences is characteristic of the interdiffusion process enhanced by the glass network hydrolysis [11]. The visual determination of *h* in the glasses 8/70–8 and 8/70–10 has been hampered by an intense coloration caused by the high iron content. For the glass 22/70–4, the visual determination of *h* (not shown in Fig. 2) was difficult due to chips and fractions appearing in the sample during leaching. After 4 hours of subjecting the sample to the acid solution, the inner tensions caused the glass sample destruction.

Within the glasses with the same $Fe_2O_3$ content of 2 mol.%, the glass 22/70–2 with a lower content of $Na_2O$ is characterized by a higher leaching rate (Fig. 2). It can be calculated from Fig. 2 that for a straight-through leaching of the glass layer of 0.5 mm it takes 1.8 h for the glass 22/70–2, while for the composition 8/70–2 the time of 2 h is required. It is known that the rate of the interaction process of glass with acid is determined not by the size of the phase formations but by the composition of the unstable phase.

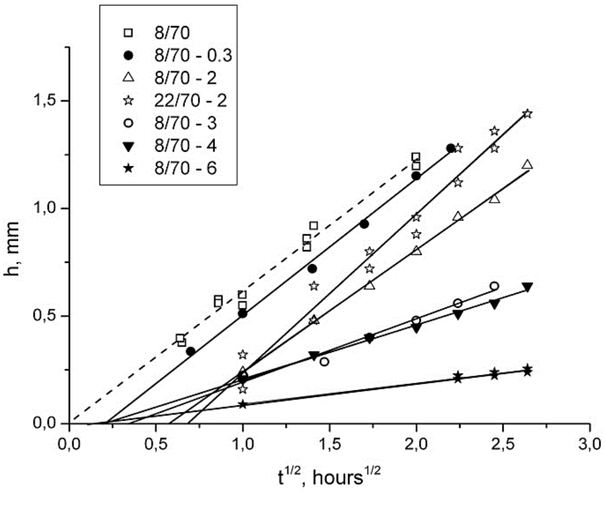

**Fig. 2.** Kinetic dependences of porous layer thickness in the phase-separated glasses leached in 3M HCl solution at boiling. The values for the glass 8/70 are given according to [15].

Thus, even though the size of liquation channels for the glass 22/70–2 is twice as great as for the glass 8/70–2 (20–

33 nm) (Fig. 1), the amount of $Na_2O$ introduced in the initial charge of the glass 22/70–2 was less than in the glass 8/70–2, which means that the compositions of the unstable boron-rich phases in these glasses would be different even with the same amount of $Fe_2O_3$. Also, one should take into account that the pore diameter in the glass 22/70–2 (Table 2) is 3 times larger than in the PGs obtained from the glass 8/70–2, which possibly could simplify the leaching process [15].

Considering the fact that the sodium ion exchange process occurs to be the fastest during leaching, the leaching rate of the porous glass can be characterized through the sodium extraction kinetics [15]. The dependencies of boron and iron (III) oxides extraction of these glasses are similar to the sodium extraction kinetic curves (Fig. 3).

All components of the unstable boron-rich phase ($Na_2O$ and $B_2O_3$) in the glasses of the 1st series containing up to 4 mol.% of $Fe_2O_3$ are fully extracted into the leaching solution along with $Fe_2O_3$, which means that in these compositions all iron, including the crystalline formations, exists in an unstable phase. $Fe_2O_3$ is present in the obtained PGs only in the form of impurities (hundredths of a percent, Table 2). Figure 3 shows that for the glass 8/70–6 the curves of $Na_2O$ extraction have not reached the plateau for the selected time of leaching. The samples retain their geometric shape without destruction. Perhaps the taken time of leaching is not enough to obtain a porous glass with through porosity. The value of *SA* (60.1 $m^2/g$) (Table 2) apparently corresponds to the *SA* of the pores in the surface layer of a glass sample since the through porosity has not been reached. The further increase of the iron (III) oxide content in the glasses leads to a decrease of components extraction which completely stops at the $Fe_2O_3$ content of 10 mol.% (Fig. 3); thus, glasses 8/70–8 and 8/70–10 are not suitable for producing PGs, at least at the selected acid concentration.

The silica, which is the basis of chemically resistant glass framework, hardly transfers from the glass sample to the leaching solution: the amount of $SiO_2$ in it is less than 10 %.

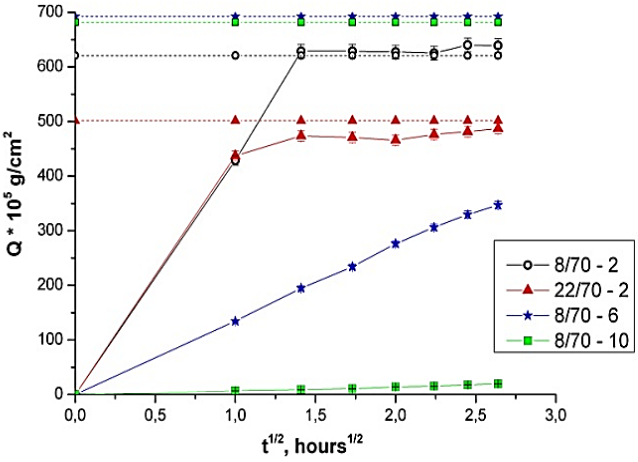

**Fig. 3.** The kinetics of $Na_2O$ extraction from glass samples. $Q_{exp}$ / $S_0$ values – solid lines, $Q_{calc}$ / $S_0$ values – dashed lines.

In general, the presented data show the following regularity: with increasing the $Fe_2O_3$ content in glasses, the extraction of alkali borate components and $Fe_2O_3$ decreases.

Table 2 shows that, compared with the glass 8/70, the introduction of even a small addition of $Fe_2O_3$ (0.3 mol.%) results in the increase of porosity nearly 1.5 times and of the pore diameter approximately 2–3 times, but leads to a reduction of the specific surface area around 2 times. Among PGs derived from iron-containing glasses, the composition 8/70–3 has the highest proportion of $Fe_2O_3$ remaining in the pores, the most developed *SA* and the maximum porosity. For the glasses containing 6–10 mol.% of $Fe_2O_3$, the values of *SA* and *W* can be attributed to the surface porous layer as no PGs with through porosity could be obtained.

In the glasses containing the same amount of $Fe_2O_3$ (2 mol.%) (8/70–2 and 22/70–2) in the initial phase-separated glass, the composition with a lower $Na_2O$ content forms the PG with a 3 times smaller *SA* and a 3 times greater pore diameter, maintaining the same value of porosity.

**Table 2.** The parameters of the obtained porous glasses

| Designation of initial phase-separated glass | Porous glass composition as-analyzed, mol.% | | | | $\rho_{app}$, g/cm$^3$ | Parameters of porous structure | | |
|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $B_2O_3$ | $Na_2O$ | $Fe_2O_3$ total | | *SA*, $m^2/g$ | *W*, $cm^3/cm^3$ | *D*, nm |
| 8/70* | 95.53 | 4.22 | 0.25 | - | - | 260.0 | 0.26 | 1.7 |
| 8/70–0.3 | 96.61 | 3.18 | 0.21 | - | 1.5469 | 124.5 | 0.35 | 6.1 |
| 8/70–2 | 96.57 | 3.18 | 0.24 | 0.01 | 1.4865 | 174.5 | 0.36 | 4.5 |
| 8/70–3 | 91.96 | 7.68 | 0.30 | 0.05 | 1.5398 | 201.8 | 0.39 | 4.3 |
| 8/70–4 | 96.91 | 2.84 | 0.24 | 0.01 | 1.4735 | 183.7 | 0.35 | 4.6 |
| 8/70–6 | 77.49 | 10.09 | 8.49 | 3.93 | 1.9849 | 60.1 | 0.29 | 3.0 |
| 8/70–8 | 73.00 | 12.99 | 6.40 | 7.60 | 2.4214 | 4.9 | 0.19 | - |
| 8/70–10 | 70.32 | 12.28 | 7.54 | 9.86 | 2.5067 | - | 0.18 | - |
| 22/70–2 | 93.15 | 6.52 | 0.32 | 0.01 | 1.5517 | 51.9 | 0.39 | 14 |

*Data according to [12].

Despite the fact that the results of leaching kinetics indicate that iron in the glass 22/70–2 fully transfers into the HCl solution and according to chemical analysis $Fe_2O_3$ exists in PGs in the form of impurities, the appearance of the PG sample shows that $Fe_2O_3$ remains in the glass, giving it an even color (Fig. 4). The rest of the leached glasses were either transparent or opaque without brown coloring. It could be presumed that the iron ions are present either in the glass matrix or in secondary silica formations [16].

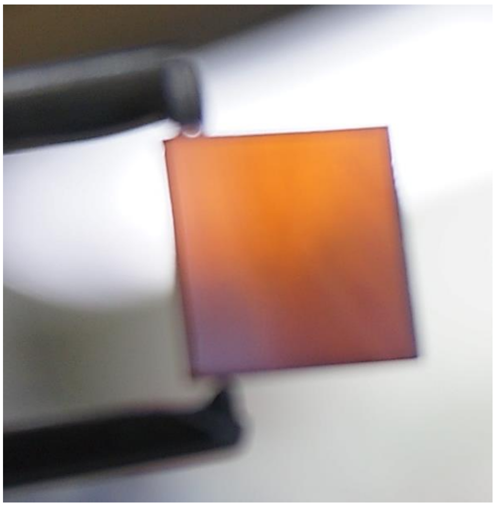

**Fig. 4.** Sample of a PG obtained from the glass 22/70–2 via leaching in 3M aqueous HCl solution for 7 hours.

## Conclusions

The results of this study have shown that the introduction of $Fe_2O_3$ in the initial phase-separated glasses in the $Na_2O$–$B_2O_3$–$SiO_2$–$Fe_2O_3$ system increases their chemical resistance, the values of porosity and the average pore diameter, but reduces the specific surface area in the porous glasses based on them, compared with the glass without $Fe_2O_3$ (8/70). The following compositions are amenable to the through-leaching, resulting in PGs formation: the glasses in the section of 8 mol.% of $Na_2O$ containing 0.3 to 4 mol.% of $Fe_2O_3$ according to synthesis and $Fe_2O_3$ stays in PGs as an impurity. Also, the glass containing 6 mol.% of $Na_2O$ and 2 mol.% of $Fe_2O_3$ is suitable for producing PG. The sample has an even brown color after leaching, indicating the existence of iron ions in the glass.

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## References

1. **Mazurin O. V., Porai-Koshits E. A.**, Phase Separation in Glass. Amsterdam, the Netherlands: North-Hollan Physics Publishers, 1984.
2. **Janowski F., Heyer W.**, Poröse Gläser herstellung, eigenschaften und anwendung. Leipzig, VEB Deutscher Verlag für Grundstoffindustrie, 1982.
3. **Enke D., Janowski F., Shwieger W.** Porous glasses in the 21st century – a short review // Microporous and Mesoporous Materials. 2003. Vol. 60. P. 19–30. http://dx.doi.org/10.1016/S1387-1811(03)00329-9
4. **Ciźman A., Rogacki K., Rysiakiewicz-Pasek E., Antropova T., Pshenko O., Poprawski R.** Magnetic properties of novel magnetic porous glass-based multiferroic nanocomposites // Journal of Alloys and Compounds. 2015. Vol. 649. P. 447–452. http://dx.doi.org/10.1016/j.jallcom.2015.07.106
5. **Ciźman A., Bednarski W., Antropova T. V., Pshenko O., Rysiakiewicz-Pasek E., Waplak S., Poprawski R.** Structural, dielectric, thermal and electron magnetic resonance studies of magnetic porous glasses filled with ferroelectrics // Composites Part B: Engineering. 2014. Vol. 64. P. 16–23. http://dx.doi.org/10.1016/j.compositesb.2014.03.024
6. **Stolyar S. V., Anfimova I. N., Drozdova I. A., Antropova T. V.** New two-phase iron-containing sodium borosilicate glasses for nanoporous materials with magnetic properties // Nanosyst., Nanomater., Nanotechnol. 2011. Vol. 9. P. 433–440 (in Russian).
7. **Pshenko O. A., Anfimova I. N., Kostyreva T. G., Dikaya L. F., Antropova T. V.** Chemical stability of two-phase iron-containing sodium borosilicate glasses in HCl solutions // Fiz. Khim. Stekla. 2012. Vol. 38. P. 858–860 (in Russian).
8. **Antropova T. V., Anfimova I. N., Golosovsky I. V., Kibalin Yu. A., Naberezhnov A. A., Porechnaya N. I., Pshenko O. A., Filimonov A. V.** Structure of magnetic nanoclusters in ferriferous alkali borosilicate glasses // Physics of the Solid State. 2012. Vol. 54. N 10. P. 2106–2111. http://dx.doi.org/10.1134/S1063783412100058
9. **Pshenko O. A., Drozdova I. A., Polyakova I. G. Rogacki K., Ciźman A., Poprawski R. Rysiakiewicz-Pasek E., Antropova T. V.** Ferromagnetic iron-containing porous glasses // Glass Physics and Chemistry. 2014. Vol. 40. N 2. P. 167–172. http://dx.doi.org/10.1134/S1087659614020175
10. **Konon M. Yu., Stolyar S. V., Dikaya L. F., Polyakova I. G., Drozdova I. A., Antropova T. V.** Physicochemical properties of glasses of the $Na_2O$-$B_2O_3$-$SiO_2$-$Fe_2O_3$ system in the $8Na_2O/70SiO_2$ section // Glass Physics and Chemistry. 2015. Vol. 41. N 1. P. 116–121. http://dx.doi.org/10.1134/S1087659615010150
11. **Antropova T. V.** Kinetics of corrosion of the alkali borosilicate glasses in acid solutions // Journal of Non-Crystalline Solids. 2004. Vol. 345–346. P. 270–275. http://dx.doi.org/10.1016/j.jnoncrysol.2004.08.095
12. **Antropova T. V., Anfimova I. N., Golovina G. F.** Influence of the composition and temperature of heat treatment of porous glasses on their structure and light transmission in the visible spectral range // Glass Physics and Chemistry. 2009. Vol. 35. N 6. P. 572–579. http://dx.doi.org/10.1134/S1087659609060042
13. **Antropova T. V., Kalinina S. V., Kostyreva T. G., Drozdova I. A., Anfimova I. N.** Peculiarities of the fabrication process and the structure of porous membranes based on two-phase fluorine- and phosphorus-containing sodium borosilicate glasses // Glass Physics and Chemistry. 2015. Vol. 41. N 1. P. 14–25. http://dx.doi.org/10.1134/S1087659615010022
14. **Konon M., Stolyar S., Drozdova I., Polyakova I., Antropova T.** Phase separation in the $Na_2O$-$B_2O_3$-$SiO_2$-$Fe_2O_3$ glass-forming system // Abstracts of the 24th International Congress on Glass. Shanghai, 2016. P. 286.
15. **Antropova T. V.** Physico-chemical processes of the formation of porous glasses and high-silica materials based on the phase-separated alkali borosilicate systems (Doctoral thesis). St. Petersburg, 2005. 588 p. (in Russian).
16. **Ehrt D., Reiss H., Vogel W.** Einbau und Verteilung von $Fe_2O_3$ auf die Mikrophasen in Gründglasern des Systems $Na_2O$–$B_2O_3$–$SiO_2$ // Silikattechnik. 1976. Bd. 27. H. 9. S. 304–309.

M. Konon, T. Antropova, T. Kostyreva, I. Drozdova, I. Polyakova

# NEVIENALYČIO STIKLO ĖSDINIMAS $Na_2O$-$B_2O_3$-$SiO_2$-$Fe_2O_3$ SISTEMOJE

## Santrauka

Tirta, kaip vyksta nevienalyčio ir termiškai apdoroto natrio boro silikatinio stiklo, į kurio sudėtį įeina geležis, ėsdinimas rūgštimi. Stiklo bandiniai, kurių sudėtis $8Na_2O\cdot(22-x)B_2O_3\cdot 70SiO_2\cdot xFe_2O_3$ ir $x$ svyruoja nuo 0,3 iki 10 mol %, $(8-x)Na_2O\cdot 22B_2O_3\cdot 70SiO_2\cdot xFe_2O_3$ ir $x$ svyruoja nuo 2 iki 6 mol %, buvo verdami 3M HCl koncentracijos vandeniniame tirpale. Nustatyta, kad $Fe_2O_3$ priedas padidina šio nevienalyčio stiklo cheminį stabilumą, poringumą ir vidutinį akučių skersmenį, tačiau sumažina savitąjį porėto stiklo paviršiaus plotą, palyginti su stiklu, kuriame nėra $Fe_2O_3$ priedo. Buvo ištirtos stiklo kompozicijos, kurios gali būti naudojamos norint pagaminti akytąjį stiklą.

**Reikšminiai žodžiai**: $Na_2O$-$B_2O_3$-$SiO_2$-$Fe_2O_3$ sistema, atskirų fazių stiklas, cheminis stabilumas, magnetitas.