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Viscosity-temperature relations in glasses composed of $SiO_2-Al_2O_3-Na_2O-K_2O-Li_2O-CaO-MgO-BaO-ZnO-PbO-B_2O_3$

Updated factors for calculation of viscosity (August 1976).

Viscosity-temperature relations in different glass systems have been investigated and published earlier (1), (2), (3), (4). The measurement techniques and methods of calculation have been described (1).

In this work the viscosity values of the different series have been pooled and completed with four unpublished measurements containing boron trioxide.

All glass compositions have been transformed in such a way, that the composing oxides were expressed as parts in weight per 100 parts of silica.

As the first step, the temperatures for viscosity levels log η: 2.0, 4.0 and 6.0 have been calculated by multiple regression analysis as functions of the oxide contents. It has been found, that all components have a linear effect on viscosity, – with the exception of boron trioxide, – which only can been expressed by a quadratic function.

The calculated temperatures for the viscosity levels log η: 2.0, 4.0 and 6.0 have been used to calculate the constants in the Vogel-Tammann-Fulcher equation:

$$T = \frac{B}{\log \eta + A} + T_0$$

where T = temperature in °C
B, A and T_0 are constants, log η is the log 10 poise of viscosity.

The values of these constants have than been calculated by multiple regression analysis as functions of the glass components.

Although the factors for calculating the temperatures for different viscosity levels are only an intermediate step, it is of interest to study the effects of different oxides on temperature at different viscosity levels:

	log η 2.0	log η 4.0	log η 6.0
Constant	1847.8	1249.7	962.9
Al_2O_3	+ 8.32	+ 5.23	+ 4.01
Na_2O	– 12.65	– 9.19	– 7.06
K_2O	– 5.93	– 4.17	– 3.53
Li_2O	– 35.54	– 30.04	– 26.45
CaO	– 11.27	– 3.99	– 0.74
MgO	– 5.87	– 0.12	+ 0.91
BaO	– 5.67	– 3.04	– 1.88
ZnO	– 5.37	– 1.88	– 0.71
PbO	– 4.85	– 3.17	– 2.24
B_2O_3	– 21.62	– 11.97	– 6.42
$(B_2O_3)^2$	+ 0.5122	+ 0.3182	+ 0.1900

All effects are decreasing with increasing viscosity. Some of the components (CaO, MgO) have practically no influence on viscosity at the "softening point" level of log η :7.6. Therefore the "softening point" is a very unsensitive value for any controle measurement!

At melting temperature, – about log η 2.0, – Li_2O has the largest viscosity decreasing effect. According to our investigations (to be published in Glast. Tidskr.) is about 1% Li_2O the highest quantity, which can be used without detrimental effect on the crystallisation behaviour of soda-lime-silica glasses, but the high price of Li_2O containing raw materials gives a practical limit of a few tenths of a percent. In soda-lime glasses of about 70% SiO_2 content 0.1% Li_2O decreases the melting temperature by about 5 °C.

The viscosity decreasing effect of Na_2O is about twice of that of K_2O. CaO and MgO decrease only the melting temperature, at higher viscosity levels their effect is unimportant, although CaO increases the annealing temperature.

K_2O, MgO, BaO, ZnO and PbO have nearly the

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same viscosity decreasing effect at melting temperature.

Alkali oxides and PbO decrease the viscosity even at higher viscosity levels and therefore an increase of these oxides leads to "long" glasses. The viscosity decreasing effects of CaO and B_2O_3 are highest at low viscosity levels and decrease quickly at higher viscosities. These components make "short" glasses.

The determined factors for calculating the Vogel-Tammann-Fulcher constants are the following:

	B	A	T_0
Constant	6237.013	1.713	149.4
Al_2O_3	+ 15.21	−0.0087	+ 1.40
Na_2O	− 66.01	−0.0162	+ 0.50
K_2O	− 5.41	+0.0066	− 2.36
Li_2O	−115.18	−0.0318	−13.29
CaO	− 60.63	+0.0064	+ 7.71
MgO	+ 56.21	+0.0589	− 2.12
BaO	− 21.03	+0.0026	+ 1.09
ZnO	− 3.76	+0.0160	+ 0.96
PbO	− 25.44	−0.0050	+ 0.82
B_2O_3	−155.11	−0.0465	+12.03
$(B_2O_3)^2$	+ 4.0999	+0.001627	− 0.2765

where all components are expressed as weight parts per 100 parts of SiO_2!

The glass compositions in weight percentages, calculated temperatures for viscosity levels log η :2.0, 4.0 and 6.0 and differences between determined and calculated values (ΔT) are shown in *Tables 1A and 1 B.*

The standard deviations for the three viscosity levels are:

at logη 2.0 σ=4.63°C
at logη 4.0 σ=3.34°C
at logη 6.0 σ=3.14°C

The effects of the glass components on temperature in the viscosity region logη 2.0 −6.0 are shown on *Fig 1.* The effects are calculated as temperature changes as a result of increasing a component by 1 weight part per 100 parts of silica.

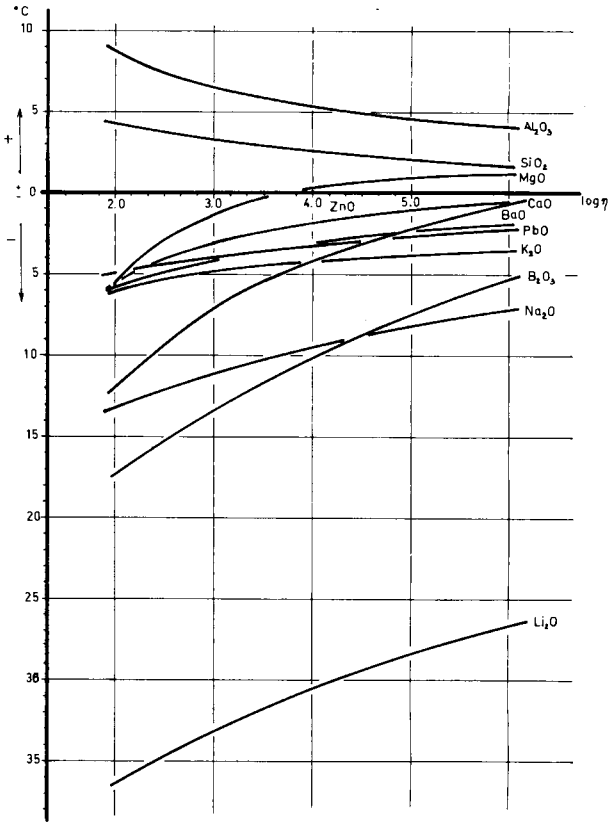

Table 1
Effect of increasing 1 part of oxide per 100 parts of SiO_2 on temperature at different viscosity levels.

References:

(1) Viscosity-temperature relations in the glass system $SiO_2-Al_2O_3-Na_2O-K_2O-CaO-MgO$ in the compositional range of technical glasses.
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Table 1A.

Nr	SiO_2	Al_2O_3	Na_2O	K_2O	Li_2O	CaO	MgO	BaO	ZnO	PbO	B_2O_3	°C for: logη 2 calc.	ΔT	°C for: logη 4 calc.	ΔT	°C for: logη 6 calc.	ΔT
S1	77.02	0.19	12.03	0.13	–	10.12	–	–	–	–	–	1503.7	– 5.3	1054.3	– 4.8	843.3	– 5.4
2	66.65	8.26	10.78	2.25	–	10.50	1.68	–	–	–	–	1535.0	2.4	1089.0	2.0	877.2	1.1
3	66.50	5.98	10.55	4.00	–	11.92	0.74	–	–	–	–	1478.2	1.2	1054.2	0.9	853.4	0.0
4	66.88	4.00	10.85	6.25	–	9.58	2.15	–	–	–	–	1455.3	1.9	1034.4	1.0	831.1	0.4
5	65.96	2.23	10.41	8.20	–	11.08	1.24	–	–	–	–	1402.5	0.6	1002.9	0.4	810.1	– 0.1
6	68.73	4.08	11.87	0.02	–	13.32	1.85	–	–	–	–	1446.0	– 3.6	1044.9	– 1.4	853.1	– 2.1
7	71.41	2.21	12.44	2.60	–	10.10	0.77	–	–	–	–	1465.9	– 2.9	1034.0	– 2.1	829.9	– 2.5
8	68.47	0.36	12.00	4.40	–	11.78	2.15	–	–	–	–	1382.5	5.7	996.2	– 2.5	809.0	– 2.5
9	65.62	7.11	11.28	6.05	–	8.50	1.19	–	–	–	–	1509.9	4.3	1058.2	2.0	844.6	1.3
10	64.95	5.36	11.29	8.40	–	10.04	–	–	–	–	–	1445.5	3.9	1017.2	1.9	815.9	1.2
11	67.34	7.30	12.71	0.03	–	11.74	0.64	–	–	–	–	1499.0	– 1.6	1063.7	– 0.2	861.2	– 0.8
12	68.18	5.37	12.62	2.30	–	8.78	2.30	–	–	–	–	1494.3	– 0.7	1055.0	– 0.3	845.5	– 0.6
13	67.38	3.36	12.72	4.30	–	10.65	1.20	–	–	–	–	1424.3	– 1.1	1012.5	– 0.3	817.0	– 0.6
14	66.64	2.26	12.49	6.50	–	12.10	–	–	–	–	–	1375.1	– 0.8	981.3	– 0.3	795.9	– 0.5
15	66.93	–	12.66	8.70	–	9.60	1.68	–	–	–	–	1355.9	– 0.5	964.2	– 0.3	775.1	– 0.3
16	69.70	2.23	14.06	0.04	–	11.05	2.23	–	–	–	–	1422.7	– 4.7	1017.8	– 2.1	824.6	– 2.3
17	69.06	0.16	13.80	2.35	–	12.89	1.09	–	–	–	–	1357.8	– 4.5	978.7	– 2.1	798.5	– 2.3
18	65.60	7.18	13.47	4.40	–	9.45	–	–	–	–	–	1479.5	1.1	1033.4	0.9	827.7	0.6
19	63.32	5.08	12.71	6.20	–	10.51	1.71	–	–	–	–	1400.8	1.4	1000.3	1.7	809.2	1.5
20	65.46	3.59	13.44	8.20	–	8.57	0.72	–	–	–	–	1405.0	1.5	984.9	0.7	786.9	0.7
21	67.91	5.43	15.27	0.02	–	9.74	1.25	–	–	–	–	1458.9	– 3.8	1028.0	– 1.3	827.5	– 1.3
22	67.20	4.14	14.58	2.40	–	11.26	–	–	–	–	–	1412.9	– 3.1	999.8	– 1.1	808.8	– 1.2
23	67.69	1.95	14.87	4.40	–	8.83	1.74	–	–	–	–	1393.5	– 2.8	983.7	– 1.2	789.3	– 0.9
24	67.03	0.37	14.62	6.40	–	10.54	0.54	–	–	–	–	1336.4	– 3.2	948.9	– 1.5	766.2	– 1.1
25	59.52	6.73	13.16	7.60	–	10.98	1.98	–	–	–	–	1361.6	3.6	979.5	3.8	797.0	3.6
26	71.70	2.17	11.16	2.48	–	10.03	1.98	–	–	–	–	1480.1	– 2.3	1051.0	– 1.8	844.5	– 2.3
27	69.27	2.35	11.96	6.80	–	8.20	1.27	–	–	–	–	1453.8	0.8	1019.7	– 0.3	812.5	– 0.6
28	72.37	2.02	12.87	0.08	–	11.12	0.65	–	–	–	–	1467.3	– 4.9	1039.1	– 2.9	837.6	– 3.1
29	70.27	2.15	13.80	4.60	–	8.83	–	–	–	–	–	1444.7	– 2.2	1007.7	– 1.9	804.1	– 1.8
30	63.50	2.30	13.64	7.90	–	10.30	2.18	–	–	–	–	1332.7	0.3	955.4	1.1	773.6	1.3
D1	72.41	1.23	14.19	–	–	12.17	–	–	–	–	–	1423.4	7.3	1010.8	3.4	818.5	0.3
2	72.55	1.23	13.85	–	0.18	12.19	–	–	–	–	–	1421.1	8.7	1008.0	4.5	815.6	2.5
3	72.84	1.24	13.15	–	0.54	12.24	–	–	–	–	–	1416.9	5.4	1002.9	4.8	809.9	5.0
4	73.26	1.24	12.09	–	1.09	12.31	–	–	–	–	–	1410.2	4.9	994.8	5.9	801.2	6.9
5	68.40	1.16	13.41	–	–	8.30	–	8.73	–	–	–	1404.4	6.0	990.9	2.4	798.1	2.6
6	64.82	1.10	12.70	–	–	4.48	–	16.54	–	–	–	1385.7	– 2.7	971.2	– 1.1	777.9	– 1.3
7	70.39	1.19	13.80	–	–	9.85	–	–	4.77	–	–	1420.0	2.2	1009.8	3.1	816.1	3.2
8	69.36	1.18	13.59	–	–	6.47	–	–	9.39	–	–	1436.7	– 0.6	1015.8	– 1.4	814.8	– 1.5
9	70.92	1.20	13.90	–	–	11.92	–	–	–	–	2.05	1373.5	9.4	982.2	6.8	803.4	6.1
10	69.50	1.18	13.62	–	–	11.68	–	–	–	–	4.03	1325.6	13.1	956.1	6.3	789.9	3.6
13	68.94	1.17	13.51	–	–	9.97	–	–	–	6.40	–	1405.9	2.1	991.2	4.2	799.8	3.1
14	65.79	1.12	12.89	–	–	7.58	–	–	–	12.22	–	1395.5	– 3.2	974.0	– 7.9	781.6	– 5.8
15	68.13	1.16	13.35	–	–	11.45	–	–	–	–	5.92	1282.7	3.5	933.9	– 0.3	778.7	– 1.9
17	62.01	1.05	12.15	–	–	10.42	–	–	–	–	14.37	1200.0	1.4	905.3	0.7	772.4	0.6

Table 1B

Nr	SiO_2	Al_2O_3	Na_2O	K_2O	Li_2O	CaO	MgO	BaO	ZnO	PbO	B_2O_3	°C for: logη 2 calc.	ΔT	°C for: logη 4 calc.	ΔT	°C for: logη 6 calc.	ΔT
F2	73.50	1.63	13.8	0.50	–	10.1	–	–	–	–	0.28	1464.5	– 2.2	1027.5	– 1.4	824.7	– 4.6
3	73.2	1.68	13.9	0.50	–	10.1	–	–	–	–	0.50	1456.7	3.5	1022.8	4.5	821.9	0.4
4	73.7	1.68	12.9	0.50	1.0	10.3	–	–	–	–	–	1436.4	4.1	1001.6	7.2	799.9	9.1
5	72.9	1.65	13.1	0.48	1.0	10.4	–	–	–	–	0.27	1419.9	7.1	991.8	5.5	793.9	7.1
6	72.8	1.65	13.1	0.48	1.05	10.4	–	–	–	–	0.56	1410.0	2.8	985.4	– 2.3	789.7	3.3
7	73.4	1.69	12.1	0.48	2.05	10.3	–	–	–	–	–	1397.5	– 4.8	967.7	1.8	769.2	3.2
8	73.4	1.60	12.0	0.48	2.05	10.2	–	–	–	–	0.29	1393.0	– 3.9	964.9	– 0.9	767.7	0.7
9	73.2	1.60	12.0	0.49	2.00	10.2	–	–	–	–	0.46	1390.1	3.1	963.7	2.4	767.6	2.4
10	73.3	1.65	11.2	0.48	3.00	10.3	–	–	–	–	–	1365.4	5.1	939.2	0.7	743.0	2.0
11	73.0	1.63	11.3	0.50	3.00	10.3	–	–	–	–	0.31	1353.5	0.4	931.9	– 5.3	738.5	– 5.2
12	72.7	1.68	11.3	0.47	3.00	10.3	–	–	–	–	0.48	1348.0	3.9	928.6	– 3.9	736,7	– 4.2
13	72.6	1.65	13.9	0.49	1.00	10.4	–	–	–	–	–	1409.8	–10.3	984.0	–1.0	787.3	1.8
14	72.0	1.60	13.7	0.45	2.00	10.3	–	–	–	–	–	1360.1	– 1.8	942.4	– 3.2	750.7	– 1.1
15	71.4	1.60	13.9	0.46	2.70	10.0	–	–	–	–	–	1320.5	– 6.0	908.6	– 6.7	720.8	– 6.4
FAL																	
1	72	2	15	–	–	11	–	–	–	–	–	1434.6	4.4	1011.3	– 1.1	815.3	– 2.6
2	68	6	13	–	–	13	–	–	–	–	–	1463.9	7.3	1043.5	2.2	848.8	1.3
3	68	6	13	–	–	11	2	–	–	–	–	1481.3	6.1	1056.0	0.2	854.4	0.0
4	68	6	11	2	–	13	–	–	–	–	–	1484.3	– 6.1	1058.6	– 6.7	859.4	– 4.3
5	68	6	11	2	–	11	2	–	–	–	–	1499.7	– 1.0	1069.9	– 2.0	864.3	– 0.2
6	66	6	17	–	–	11	–	–	–	–	–	1406.0	– 3.7	991.7	– 3.5	803.7	– 4.0
7	66	6	15	–	–	13	–	–	–	–	–	1410.4	– 2.3	1007.8	– 1.0	823.1	– 1.7
8	66	6	15	–	–	11	2	–	–	–	–	1431.7	7.6	1022.3	4.3	829.8	3.1
9	66	6	13	2	–	13	–	–	–	–	–	1433.1	–10.7	1024.2	–4.8	834.5	–1.4
10	66	6	13	2	–	11	2	–	–	–	–	1452.1	– 2.7	1037.4	2.2	840.4	2.2
11	71	2	15	–	–	9	3	–	–	–	–	1437.0	6.8	1019.7	0.2	819.8	1.1
12	70	2	15	–	–	7	6	–	–	–	–	1435.7	3.3	1025.2	6.5	822.4	6.3
13	71.33	2	15	–	–	9.67	2	–	–	–	–	1436.6	– 0.2	1017.2	0.1	818.5	0.6
14	70.33	2	15	–	–	7.67	5	–	–	–	–	1436.4	– 5.3	1023.7	– 6.3	821.7	– 6.2