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# The effect of some glass components on the viscosity of glass

The aim of this investigation was to evaluate the effects of the most common glass components on glass viscosity and to be able to calculate the viscosity-temperature curve of a planned glass composition.

These calculations are based on three different independently performed experimental series. The first investigation was composed of the most common soda-lime glass components: $SiO_2$—$Al_2O_3$ $Na_2O$—$K_2O$—CaO—MgO and the results will be published elswhere (1).

The second investigation was aimed to establish the effect of the molecular relationship between $Na_2O$, $K_2O$ and $Li_2O$ in a basic houshold-type glass on viscosity and other different properties.

The third series was aimed to investigate the effects of $Li_2O$, BaO, ZnO, PbO and $B_2O_3$.

All the compositional changes were calculated on a molecular basis and in relation to the silica content.

The glass batches giving 2000 g of glass were mixed in a porcelain ball mill, melted in platinum lined ceramic crucible in an electric furnace at 1400—1425° C overnight, poured out, mixed and remelted for good homogeneity.

Viscosity values were determined in the range of $10^2$—$10^7$ poise in a rotating cylinder viscometer described elswhere (1).

The viscosity-temperature curves were calculated by the Fulcher-Tamman equation:

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

Where: T = temperature in °C
log$\eta$ = log poise viscosity
B, A and $T_o$ = constants

The experimentally determined viscosity values were smoothed by an iterative least-squares method to the Fulcher equation and the standard deviations for each viscosity-temperature curve where less than 1,0° C.

## Experimental Results

As the calculations are based on different experimental series, there is no randomization or any balance in the material of the investigation. This is a serious bias, but to construct a single balanced experimental plan for 10 different components on several levels should practically be impossible. E. g. 10 components on three levels each, gives 59049 experiments. The only practical way was to make 2—3 experiments for every component and balance the experiments with the results of the first series, which was a statistically correct, balanced investigation. This method puts very high demand on good reproducibility and high accuracy on the viscosity measurements, but as the results prooved, no severe loss of accuracy has resulted.

The glass compositions where calculated on a molecular basis as moles per mole of silica.

The effect of $B_2O_3$ was measured on two levels and the results did not fit into the pattern. It was obvious that more points are necessary for the evavaluation of the $B_2O_3$-effect and therefore it was decided to make a separate investigation for this, which will be published separately.

The molecular compositions and the experimentally determined Fulcher-constants are shown on *Table 1.* The compositions no. 1—10 comes from the series for the investigation of $Li_2O$, BaO, ZnO and

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Table 1. Glass compositions expressed in moles, and corresponding Fulcher-constants.

| No | $SiO_2$ | $Al_2O_3$ | $Na_2O$ | CaO | $Li_2O$ | BaO | ZnO | PbO | $K_2O$ | MgO | B | A | $T_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.0 | 0.010 | 0.1900 | 0.1800 | | | | | | | 3838.7 | 1.448 | 302.8 |
| 2 | 1.0 | 0.010 | 0.1850 | 0.1800 | 0.0050 | | | | | | 3908.5 | 1.485 | 290.9 |
| 3 | 1.0 | 0.010 | 0.1750 | 0.1800 | 0.0150 | | | | | | 3997.5 | 1.510 | 272.5 |
| 4 | 1.0 | 0.010 | 0.1600 | 0.1800 | 0.0300 | | | | | | 4025.0 | 1.509 | 258.3 |
| 5 | 1.0 | 0.010 | 0.1900 | 0.1300 | | 0.0500 | | | | | 4058.4 | 1.561 | 258.7 |
| 6 | 1.0 | 0.010 | 0.1900 | 0.0800 | | 0.1000 | | | | | 3937.3 | 1.464 | 251.7 |
| 7 | 1.0 | 0.010 | 0.1900 | 0.1500 | | | 0.0500 | | | | 4083.6 | 1.568 | 273.3 |
| 8 | 1.0 | 0.010 | 0.1900 | 0.1000 | | | 0.1000 | | | | 4366.4 | 1.668 | 246.9 |
| 9 | 1.0 | 0.010 | 0.1900 | 0.1550 | | | | 0.0250 | | | 3758.4 | 1.363 | 286.2 |
| 10 | 1.0 | 0.010 | 0.1900 | 0.1300 | | | | 0.0500 | | | 4013.6 | 1.501 | 252.3 |
| 11 | 1.0 | 0.005 | 0.0415 | 0.1107 | 0.0191 | 0.0170 | 0.0423 | 0.0200 | 0.0995 | | 4965.0 | 1.877 | 203.4 |
| 12 | 1.0 | 0.005 | 0.0364 | 0.1107 | 0.0000 | 0.0170 | 0.0423 | 0.0200 | 0.1236 | | 4895.2 | 1.874 | 239.2 |
| 13 | 1.0 | 0.005 | 0.0253 | 0.1107 | 0.0233 | 0.0170 | 0.0423 | 0.0200 | 0.1114 | | 5005.2 | 1.890 | 204.4 |
| 14 | 1.0 | 0.005 | 0.0602 | 0.1107 | 0.0277 | 0.0170 | 0.0423 | 0.0200 | 0.0722 | | 4946.7 | 1.844 | 180.9 |
| 15 | 1.0 | 0.005 | 0.0546 | 0.1107 | 0.0126 | 0.0170 | 0.0423 | 0.0200 | 0.0928 | | 4901.6 | 1.848 | 209.4 |
| 15 | 1.0 | 0.005 | 0.0500 | 0.1107 | 0.0000 | 0.0170 | 0.0423 | 0.0200 | 0.1100 | | 4864.8 | 1.854 | 233.1 |
| 17 | 1.0 | 0.005 | 0.0889 | 0.1107 | 0.0000 | 0.0170 | 0.0423 | 0.0200 | 0.0711 | | 4778.9 | 1.796 | 215.5 |
| 18 | 1.0 | 0.005 | 0.0661 | 0.1107 | 0.0190 | 0.0170 | 0.0423 | 0.0200 | 0.0749 | | 4899.9 | 1.831 | 193.3 |
| 19 | 1.0 | 0.005 | 0.0611 | 0.1107 | 0.0094 | 0.0170 | 0.0423 | 0.0200 | 0.0896 | | 4871.2 | 1.839 | 212.4 |
| 20 | 1.0 | 0.010 | 0.1900 | 0.1800 | | | | | 0.0400 | | 3861.8 | 1.489 | 280.4 |
| 21 | 1.0 | 0.010 | 0.1900 | 0.1800 | | | | | 0.0800 | | 3791.8 | 1.513 | 268.2 |
| 22 | 1.0 | 0.030 | 0.1900 | 0.1800 | | | | | | | 3974.7 | 1.433 | 298.6 |
| 23 | 1.0 | 0.045 | 0.1900 | 0.1800 | | | | | | | 4005.3 | 1.410 | 303.1 |
| 24 | 1.0 | 0.010 | 0.1850 | 0.1800 | | | | | | | 3964.5 | 1.473 | 292.4 |
| 25 | 1.0 | 0.010 | 0.1750 | 0.1800 | | | | | | | 4028.3 | 1.490 | 292.4 |
| 26 | 1.0 | 0.010 | 0.1600 | 0.1800 | | | | | | | 4123.6 | 1.515 | 292.4 |
| 27 | 1.0 | 0.010 | 0.1900 | 0.1300 | | | | | | | 4154.0 | 1.401 | 262.8 |
| 28 | 1.0 | 0.010 | 0.1900 | 0.0800 | | | | | | | 4368.9 | 1.328 | 235.6 |
| 29 | 1.0 | 0.010 | 0.1900 | 0.1500 | | | | | | | 4065.7 | 1.427 | 274.6 |
| 30 | 1.0 | 0.010 | 0.1900 | 0.1000 | | | | | | | 4288.3 | 1.364 | 245.0 |
| 31 | 1.0 | 0.010 | 0.1900 | 0.1800 | | | | | | | 3933.3 | 1.465 | 292.4 |
| 32 | 1.0 | 0.010 | 0.1900 | 0.1550 | | | | | | | 4044.0 | 1.433 | 277.6 |
| 33 | 1.0 | 0.010 | 0.1900 | 0.1300 | | | | | | | 4155.2 | 1.402 | 262.8 |
| 34 | 1.0 | 0.010 | 0.1900 | 0.1800 | | | | | | 0.0300 | 4114.5 | 1.624 | 281.6 |
| 35 | 1.0 | 0.010 | 0.1900 | 0.1800 | | | | | | 0.0450 | 4204.5 | 1.707 | 276.3 |

PbO, — the compositions no. 11—19 from the series for the investigation of the relationship between $Li_2O$, $Na_2O$ and $K_2O$ and no. 20—35 are "dummies" calculated from the soda-lime glass series.

The dependence of the Fulcher constants (B, A and $T_0$) on the glass components was calculated by multiple regression analysis and resulted in three equations:

"B" = 2830.0 A — 6802.0 N — 4566.7 C — 611.6 L — 3622.9 Ba + 1121.1 Z — 3650.3 Pb — 1519.0 K + 6590.0 M + 5991.5.

"A" = 1.29799 A — 1.37112 N + 1.22366 C + 0.90151 L + 1.73879 Ba + 3.13803 Z + 1.32178 Pb + 0.90479 K + 5.63513 M + 1.50848.

"$T_0$" = 308.48 A — 53.25 N + 584.23 C — 1515.11 L + 95.40 Ba — 49.03 Z — 207.86 Pb — 253.60 K — 410.44 M + 195.29.

where:

$$A = \frac{Al_2O_3}{SiO_2},\ N = \frac{Na_2O}{SiO_2},\ C = \frac{CaO}{SiO_2}$$

$$L = \frac{Li_2O}{SiO_2},\ Ba = \frac{BaO}{SiO_2}\ Z = \frac{ZnO}{SiO_2}$$

$$Pb = \frac{PbO}{SiO_2},\ K = \frac{K_2O}{SiO_2} \text{ and } M = \frac{MgO}{SiO_2}$$

calculated in moles.

For practical calculations the equations has been recalculated into weight relationships, where the factors are calculated for the weight of the components per weight of $SiO_2$, or percentage of component per percentage of $Si0_2$. The equations are the following:

Table 2. Compositions in weight percentages, determined and calculated temperatures and deviations at log$\eta$ 2.0, 4.0 and 6.0 viscosity levels.

| No | Weight % | | | | | | | | | | °C at log$\eta$ 2.0 | | | °C at log$\eta$ 4.0 | | | °C at log$\eta$ 6.0 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Na_2O$ | CaO | $Li_2O$ | BaO | ZnO | PbO | $K_2O$ | MgO | Determ. | Calc. | Δ T | Determ. | Calc. | Δ T | Determ. | Calc. | Δ T |
| 1 | 72.41 | 1.23 | 14.19 | 12.17 | | | | | | | 1416.1 | 1423.7 | 7.6 | 1007.4 | 1009.3 | 1.9 | 818.2 | 817.3 | -0.9 |
| 2 | 72.55 | 1.23 | 13.85 | 12.19 | 0.18 | | | | | | 1412.4 | 1421.5 | 9.1 | 1003.5 | 1006.1 | 2.6 | 813.1 | 813.3 | 0.2 |
| 3 | 72.84 | 1.24 | 13.15 | 12.24 | 0.54 | | | | | | 1411.5 | 1417.5 | 6.0 | 998.1 | 1000.0 | 1.9 | 804.9 | 805.5 | 0.6 |
| 4 | 73.26 | 1.24 | 12.09 | 12.31 | 1.09 | | | | | | 1405.3 | 1410.8 | 5.5 | 988.9 | 990.4 | 1.5 | 794.3 | 793.5 | -0.8 |
| 5 | 68.40 | 1.16 | 13.41 | 8.30 | | 8.73 | | | | | 1398.4 | 1404.3 | 5.9 | 988.5 | 990.0 | 1.5 | 795.5 | 797.3 | 1.8 |
| 6 | 64.82 | 1.10 | 12.70 | 4.84 | | 16.54 | | | | | 1388.4 | 1385.2 | -3.2 | 972.3 | 971.0 | -1.3 | 779.2 | 777.4 | -1.8 |
| 7 | 70.39 | 1.19 | 13.80 | 9.85 | | | 4.77 | | | | 1417.8 | 1419.6 | 1.8 | 1006.7 | 1008.5 | 1.8 | 812.9 | 814.4 | 1.5 |
| 8 | 69.36 | 1.18 | 13.59 | 6.47 | | | 9.39 | | | | 1437.3 | 1435.8 | -1.5 | 1017.2 | 1014.7 | -2.5 | 816.3 | 813.2 | -3.1 |
| 9 | 68.94 | 1.17 | 13.51 | 9.97 | | | | 6.40 | | | 1403.8 | 1409.8 | 6.0 | 987.0 | 993.5 | 6.5 | 796.7 | 800.4 | 3.7 |
| 10 | 65.79 | 1.12 | 12.89 | 7.58 | | | | 12.22 | | | 1398.7 | 1395.9 | -2.8 | 981.9 | 977.6 | -4.3 | 787.4 | 783.5 | -3.9 |
| 11 | 66.89 | 0.57 | 2.86 | 6.91 | 0.64 | 2.90 | 3.83 | 4.97 | 10.43 | | 1484.0 | 1490.8 | 6.8 | 1048.2 | 1049.2 | 1.0 | 833.7 | 832.8 | -0.9 |
| 12 | 65.87 | 0.56 | 2.47 | 6.81 | 0.00 | 2.86 | 3.77 | 4.89 | 12.77 | | 1502.8 | 1503.8 | 1.0 | 1072.6 | 1069.0 | -3.6 | 860.9 | 854.7 | -6.2 |
| 13 | 66.71 | 0.57 | 1.74 | 6.89 | 0.77 | 2.89 | 3.82 | 4.96 | 11.65 | | 1491.4 | 1484.7 | -7.2 | 1064.2 | 1047.5 | -6.7 | 838.8 | 831.3 | -7.5 |
| 14 | 67.76 | 0.57 | 4.21 | 7.00 | 0.93 | 2.94 | 3.88 | 5.03 | 7.67 | | 1467.8 | 1465.6 | -2.2 | 1027.4 | 1029.5 | 2.1 | 811.5 | 816.1 | 4.6 |
| 15 | 66.90 | 0.57 | 3.77 | 6.91 | 0.42 | 2.90 | 3.83 | 4.97 | 9.73 | | 1483.2 | 1483.4 | 0.2 | 1047.6 | 1048.2 | 0.6 | 834.0 | 834.9 | 0.9 |
| 16 | 66.19 | 0.56 | 3.41 | 6.84 | 0.00 | 2.87 | 3.79 | 4.92 | 11.42 | | 1495.4 | 1498.2 | 2.8 | 1064.1 | 1063.9 | -0.2 | 852.5 | 850.7 | -1.8 |
| 17 | 67.12 | 0.57 | 6.16 | 6.94 | 0.00 | 2.91 | 3.85 | 4.99 | 7.48 | | 1474.4 | 1481.1 | 6.7 | 1040.0 | 1048.8 | 8.8 | 828.8 | 839.1 | 10.3 |
| 18 | 67.48 | 0.57 | 4.60 | 6.97 | 0.64 | 2.93 | 3.87 | 5.01 | 7.93 | | 1472.3 | 1471.7 | 0.6 | 1033.6 | 1036.6 | 3.0 | 819.0 | 824.1 | 5.1 |
| 19 | 66.89 | 0.57 | 4.22 | 6.91 | 0.31 | 2.90 | 3.83 | 4.97 | 9.40 | | 1481.3 | 1483.9 | 2.6 | 1046.7 | 1049.3 | 2.6 | 833.8 | 836.7 | 2.9 |
| 20 | 69.27 | 1.18 | 13.58 | 11.64 | | | | | 4.34 | | 1387.3 | 1384.4 | -2.9 | 984.0 | 983.4 | -0.6 | 796.1 | 796.5 | 0.4 |
| 21 | 66.38 | 1.13 | 13.01 | 11.15 | | | | | 8.33 | | 1347.6 | 1345.8 | -1.8 | 956.0 | 957.7 | 1.7 | 772.9 | 775.8 | 2.9 |
| 22 | 72.69 | 1.23 | 13.87 | 12.21 | | | | | | | 1433.9 | 1431.6 | -2.3 | 1016.8 | 1014.9 | -1.9 | 822.9 | 821.6 | -1.3 |
| 23 | 73.23 | 1.24 | 13.22 | 12.30 | | | | | | | 1446.7 | 1447.2 | 0.5 | 1026.2 | 1026.0 | -0.2 | 830.2 | 830.3 | 0.1 |
| 24 | 74.07 | 1.26 | 12.23 | 12.44 | | | | | | | 1465.5 | 1470.4 | 4.9 | 1040.1 | 1042.7 | 2.6 | 841.1 | 843.2 | 2.1 |
| 25 | 74.95 | 1.27 | 14.69 | 9.09 | | | | | | | 1484.2 | 1482.2 | -2.0 | 1031.9 | 1030.6 | -1.3 | 824.1 | 823.3 | -0.8 |
| 26 | 77.66 | 1.32 | 15.22 | 5.80 | | | | | | | 1544.1 | 1543.8 | -0.3 | 1053.0 | 1053.0 | 0 | 829.5 | 829.9 | 0.4 |
| 27 | 73.91 | 1.25 | 14.49 | 10.35 | | | | | | | 1461.0 | 1458.2 | -2.8 | 1023.8 | 1021.8 | -2.0 | 822.0 | 820.7 | -1.3 |
| 28 | 76.55 | 1.30 | 15.00 | 7.15 | | | | | | | 1519.7 | 1518.7 | -1.0 | 1044.4 | 1043.9 | -0.5 | 827.3 | 827.2 | -0.1 |
| 29 | 72.41 | 1.23 | 14.19 | 12.17 | | | | | | | 1427.5 | 1423.5 | -4.0 | 1012.1 | 1009.1 | -3.0 | 819.3 | 817.1 | -2.2 |
| 30 | 73.66 | 1.25 | 14.44 | 10.66 | | | | | | | 1455.3 | 1452.4 | -2.9 | 1021.8 | 1019.7 | -2.1 | 821.6 | 820.2 | -1.4 |
| 31 | 74.95 | 1.27 | 14.69 | 9.09 | | | | | | | 1484.2 | 1482.2 | -2.0 | 1031.9 | 1030.6 | -1.3 | 824.1 | 823.3 | -0.8 |
| 32 | 70.68 | 3.60 | 13.85 | 11.87 | | | | | | | 1456.2 | 1455.1 | -1.1 | 1030.3 | 1029.4 | -0.7 | 833.3 | 832.9 | -0.4 |
| 33 | 69.43 | 5.30 | 13.61 | 11.66 | | | | | | | 1477.7 | 1478.6 | 0.9 | 1043.5 | 1044.4 | 0.9 | 843.7 | 844.6 | 0.9 |
| 34 | 71.37 | 1.21 | 13.99 | 11.99 | | | | | | 1.44 | 1417.0 | 1412.9 | -4.1 | 1013.2 | 1010.4 | -2.8 | 821.3 | 819.0 | -2.3 |
| 35 | 70.86 | 1.20 | 13.89 | 11.91 | | | | | | 2.14 | 1411.7 | 1407.6 | -4.1 | 1013.5 | 1010.7 | -2.9 | 822.1 | 819.8 | -2.3 |

Table. 3.

| Viscosity $\log \eta$ | Effect of 1 kg component per 100 kg silica in ± °C | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Na_2O$ | CaO | MgO | $Li_2O$ | $K_2O$ | BaO | ZnO | PbO |
| 2.0 | 4.8 | 9.1 | —15.3 | —12.0 | —5.1 | —39.9 | —6.3 | —5.9 | —5.5 | —4.6 |
| 3.0 | 3.5 | 7.0 | —12.7 | — 7.2 | —0.7 | —36.8 | —4.9 | —4.2 | —3.1 | —3.5 |
| 4.0 | 2.8 | 5.9 | —10.8 | — 4.3 | +0.8 | —35.0 | —4.1 | —3.1 | —1.8 | —2.8 |
| 5.0 | 2.2 | 5.1 | — 9.5 | — 2.5 | 1.2 | —34.0 | —3.6 | —2.4 | —1.2 | —2.4 |
| 6.0 | 1.7 | 4.6 | — 8.4 | — 1.3 | 1.1 | —33.4 | —3.3 | —2.0 | —0.9 | —2.1 |
| 7.0 | 1.4 | 4.2 | — 7.6 | — 0.2 | 0.8 | —32.9 | —3.1 | —1.7 | —0.7 | —1.9 |

"B" = 1667.7 A — 6594.1 N — 4892.8 C — 1230.0 L — 1419.6 Ba + 827.8 Z — 982.7 Pb — 968.8 K + 9822.6 M + 5991.5.

"A" = — 0.76490 A — 1.32922 N + 1.31105 C + 1.81302 L + 0.68133 Ba + 2.31718 Z + 0.35584 Pb + 0.57710 K + 8.39936 M + 1.50848.

"$T_0$" = 181.79 A — 5162 N + 625.95 C — 3047.00 L + 37.38 Ba — 36.21 Z — 55.96 Pb — 161.75 K — 611.78 M + 195.29.

To test the goodness of these equations, in *Table 2* are shown the compositions in weight percentages, determined and calculated temperatures for three viscosity levels and differences between determined and calculated values.

The standard deviations for $\log\eta$: 2.0, 4.0 and 6.0 levels are:

$$\sigma 2.0 = 4.10 \ ^\circ C$$
$$\sigma 4.0 = 2.97$$
$$\sigma 6.0 = 3.19$$

which are quite satisfactory for all practical purposes.

As it is difficult to see the effect on viscosity from the Fulcher constants, the effect of the increase by 1 kg of a component per 100 kg of silica on temperature at different viscosity levels in a basic soda-lime glass composition has been calculated and is shown on *Table 3*.

The basic glass composition, and its viscosity-temperature values are:

| | |
|---|---|
| $SiO_2$ | 73.0 % |
| $Al_2O_3$ | 0.5 „ |
| $Na_2O$ | 14.0 „ |
| CaO | 12.5 „ |

| $\log\eta$ | °C |
|---|---|
| 2.0 | 1417.0 |
| 3.0 | 1165.9 |
| 4.0 | 1006.5 |
| 5.0 | 896.4 |
| 6.0 | 815.8 |
| 7.0 | 754.2 |

Summarizing the effects of the different glass components on viscosity, the following general rules can be established:

1. The alkali-oxides decrease viscosity and tend to make the glass "longer". This is most characteristic for lithium oxide. Lithia is the most effective viscosity-decreasing component, its effect is more than twice as large as that of sodium oxide. Nevertheless, the use of lithium oxide is determined by its aptitude to increase the tendency to devitrification and its high price. The viscosity-decreasing effect of potassium oxide is about one half of that of sodium oxide.

2. The divalent oxides: lime has a strong viscosity decreasing effect only in the high temperature range, increasing lime content makes the glass "short". Magnesia has an effect similar to that of lime, but the viscosity decrease is much less compared with lime.
   The viscosity-decreasing effect of BaO, ZnO and PbO is almost identical and about the same degree as the effect of potassium oxide.

(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. To be published in Glass Technology. T. Lakatos, L.-G. Johansson, B. Simmingsköld.