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Corrosion effects on soda lime glass

Fred Veer
Faculty of Architecture, Delft University of Technology
f.a.veer@tudelft.nl, www.glass.bk.tudelft.nl
Yurii Rodichev
1G.S. Pisarenko Institute for Problems of Strength of NASU, Kiev, Ukraine,
rym@ipp.kiev.ua

Although soda lime glass is the most common used transparent material in architecture, little is known about the corrosion effects on long term strength and the interaction between corrosion and defects. Extensive testing on soda lime bars under different environmental conditions and different degrees of damage has resulted in a more clear picture of the stress-corrosion mechanisms involved. The effects of these on long term strength are discussed.

Keywords: Glass strength, stress corrosion

1. Introduction

Soda lime glass is commonly used as it is a durable material. It is however susceptible to stress corrosion. A review of this is given by Haldimann et al. in [1,2]. Although there is considerable previous research, such as [3,4], there are still many questions. One of them if only the pH of the water is critical.

A fundamental problem is the complex series of flaws that exist in cut and cut, ground and polished float glass. These significantly complicate the analysis of the results. Some of this is covered by Veer et al. in [5,6]. If it is difficult to determine the basic strength, determining the added corrosion product is an added difficulty.

To avoid some of these problems it was decided to use Schott AR glass rods. These have the same chemical composition as float glass, but as there are not cut, ground and polished; the results from these tests should be more easy to interpret. Initial results by Veer and Rodichev are given in [7]. These initial results gave some indications about the corrosion mechanism but as the scatter in test data was still significant additional tests were deemed necessary. This includes tests on glass bars with quantifiable damage created using a diamond indenter.

2. Methodology

Standard Schott Ar glass rods are cut down in to 250 mm long segments. These are tested in four point bending in a custom made rig on a Zwick Z100 universal testing machine equipped with climate chamber. Distance between the bottom supports was 200 mm, distance between the loading rollers was 100 mm. Test speeds of 50 mm/min and 0.5 mm/min were used. All specimens were conditioned for the environment where they were tested for several hours before the actual test. All specimens were handled with extra care and inspected for scratches and other damager before testing. The test rig is shown in figure 1.

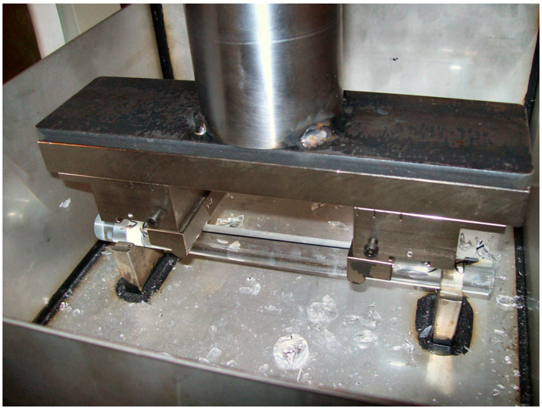
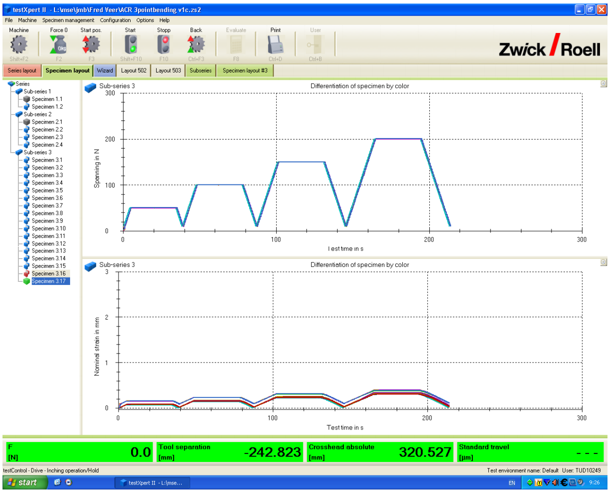


Figure 1: Test rig for glass bars.

Some specimens were indented using a Knoop indenter with the length axis of the indenter perpendicular to the length axis of the specimen. The Knoop indenter was mounted in a Zwick z10. The loading pattern is given in figure 2, and consists of four steps of 50,100,150 and 200 N respectively. Each held for 30 seconds with slow loading and unloading. This was done to create beach marker trails on the fracture surface to better study the initiation and growth of the crack. After indenting the specimens were kept at room temperature for one week before the four point bending tests.



testXpert II - L:\mse\jmb\Fred Veer\ACR 3pointbending v1c.zs2

F [N]: 0.0
Tool separation [mm]: -242.823
Crosshead absolute [mm]: 320.527
Standard travel [µm]: - - -

testControl - Drive - Inching operation/Hold

Test environment name: Default User: TUD10249

Figure 2: Load sequence for glass indentation.

One series of specimens was pre-corroded (water strengthened) by corroding them in water at 80°C for 24 hours. The specimens were then dried, left to lie in air for 24 hours and 4 point bend tested in air at room temperature.

Fracture surfaces were examined using optical microscopy techniques. The results of this will be published later due to space constraints.

3. Results

There are four sets of results. The first deals with one set of experiments comparing tests in air with tests in demineralised water. The second set compares tests in air with tests in salt water and tests on pre-corroded (water soaked) specimens. The third set compares tests on undamaged bars in air with tests on bars with indenter damage in air. The fourth set compares tests on undamaged bars in water with tests on bars with indenter damage in water.

Table 1: Tests in air and demineralised water.

Specimen number	Air fast (MPa)	Air slow (MPa)	Demineralised water fast (MPa)	Demineralised water slow (MPa)
1	141.0	61.9	117.5	70.8
2	139.9	125.7	107.9	90.1
3	164.1	81.2	80.5	86.9
4	129.2	107.9	116.4	82.6
5	128.2	83.3	113.9	79.0
6	112.1	110.7	87.9	100.1
7	113.6	95.0	103.2	46.6
8	90.1	115.0	73.0	71.9
9	68.4	109.3	92.2	98.3
10	90.4	64.1	121.0	75.1
Average	117.7	95.4	101.4	80.1
Standard deviation / average	24.3%	23.0%	16.7%	19.5%

Table 2: Tests in air, salt water and pre-corroded specimens

Specimen number	Air fast (MPa)	Air slow (MPa)	Precorroded slow (MPa)	Precorroded fast (MPa)	Salt water slow (MPa)
1	118.9	91.1	117.1	81.2	77.3
2	84.7	107.2	88.6	113.6	89.7
3	115.0	62.7	94.7	89.0	62.3
4	91.5	76.2	100.4	104.3	57.7
5	94.7	75.1	66.2	115.3	94.0
6	157.4	118.5	90.8	150.6	68.7
7	122.5	82.2	101.5	119.3	66.2
8	108.6	82.6	74.8	80.8	63.0
9	98.6	110.4	91.5	91.1	69.4
10	131.7	66.2	104.0	60.9	53.4
Average	112.4	87.2	93.0	100.6	70.2
Standard deviation / average	19.4%	21.9%	15.7%	25.3%	18.8%

Table 3: Comparison of undamaged and indented bars in air

Specimen number	Air fast (MPa)	Air slow (MPa)	Indented fast (MPa)	Indented slow (MPa)
1	95.7	98.2	37.6	31.4
2	119.0	110.8	31.4	27.1
3	94.0	89.9	26.5	27.2
4	96.1	84.0	27.9	33.2
5	110.7	75.7	30.6	23.7
6	115.6	95.7	35.5	28.8
7	112.3	95.9	29.7	26.2
8	118.1	84.4	25.4	26.7
9	104.4	91.5	30.5	29.4
10	95.7	115.2	28.7	32.5
Average	106.2	94.1	30.4	28.6
Standard deviation / average	9.5%	12.8%	12.5%	10.6%

Table 4: Comparison of undamaged and indented bars in water at 20°C

Specimen number	Water fast (MPa)	Water slow (MPa)	Indented fast in water (MPa)	Indented slow in water (MPa)
1	77.4	67.8	30.2	30.2
2	85.3	76.5	25.2	20.1
3	78.2	65.7	26.8	18.6
4	77.8	71.1	27.4	21.3
5	84.9	98.2	31.4	20.9
Average	80.7	75.9	28.2	22.2
Standard deviation / average	5.0%	17.3%	9.0%	20.6%

Table 5: summary of results

Test series	Mean failure stress	Standard deviation/mean	Number of tests
Air fast 1	117.7	24.3%	10
Air fast 2	112.4	19.4%	10
Air fast 3	106.2	9.5%	10
Air slow 1	95.4	23.0%	10
Air slow 2	87.2	21.9%	10
Air slow 3	94.1	12.8%	10
Demi water fast	101.4	16.7%	10
Demi water slow	80.1	19.5%	10
Salt water slow	70.2	18.8%	10
Pre-corroded fast	100.6	25.3%	10
Pre-corroded slow	93.0	15.7%	10
Air indented fast	30.4	12.5%	10
Air indented slow	28.6	10.6%	10
Water fast	80.7	5.0%	5
Water slow	75.9	17.3%	5
Water indented fast	28.2	9.0%	5
Water indented slow	22.2	20.6%	5

4. Discussion

The results are summarized in table 5. If we look at the results it becomes obvious that the three fast and slow series in air, which were done with about a month between each successive series due to limited machine availability, do not coincide. Figure 3 shows a Weibull plots for the three fast series separately. In figure 4 the data is combined to give a single Weibull plot. There is no clear reason for the differences. It does make it clear that considerable care must be taken in comparing data from different time periods. As all glass specimens were prepared beforehand and all specimens were cut in a single session an aging phenomenon could be responsible but there is no logical basis for this and this is discounter for now.

The data does however give a lot of useful information. Figure 5 shows Weibull plots for the slow tests in salt and demineralised water. The salt water is clearly more corrosive. Normal water seems to be in the middle in terms of average bending strength as is seen in table 5. Thus not only the temperature and pH of the water are important, the electrical conductivity also plays a role.

Figure 6 shows Weibull plots of fast tests in air for indented and normal specimens. Figure 7 shows the same for the slow tests in air. The strength of the indented bars corresponds with the strength of 10 mm thick annealed float glass which has been cut, ground and polished, [5].

The indentations apparently do not improve the predictability of the strength. Although the standard deviations are lower, the Weibull plots show non-linearity comparable to the non-indented bars. The indentations however decrease the strength considerably. The specimens also break into only two pieces, while non indented specimens usually produce four to six fragments. This is to be expected as the fracture energy is much lower. The results might be taken to suggest that indentation damage reduces stress corrosion susceptibility in air. The difference in average bending strength between the fast and slow tests on normal specimens is some 20%, while for the indented specimens this is only some 6%. This neglects the fact that indented specimens fail at much lower stress levels and thus much faster in constant displacement tests and there is thus less time for corrosion to take place. The indented specimens in water show a more significant strength loss than the normal specimens. Presumably immersion in water allows for much more rapid corrosion of the already severely damaged specimens as the corrosive agent is readily available. Supply of the corrosive agent is thus a critical determining factor in the stress corrosion of glass.

Soaking glass in water is commonly assumed to increase the strength. The pre-corrosion that takes place is supposed to make the “cracks” less sharp and thus lower the stress concentrations. Figures 9 and 10 show Weibull graphs for the pre-corroded and normal specimens. No increase in strength due to pre-corrosion is visible, if anything a decrease is found. This implies that damage only occurs when the specimens are stressed while exposed to a corrosive environment.

A last point deals with reliability. Indenting the specimens should in theory give more predictable results as the specimens fail from a similar macro-flaw. Figure 11 shows the tests data for the fast and slow tests in indented specimens in air. Figure 12 gives a micrograph of an indentation. The indentation is clearly not regular or smooth. Some small geometrical differences might cause deviations. Some increase in Weibull linearity is observed compared to the normal specimens in figures 3 and 4, but there is still no clear single Weibull line. This implies that even after indentation there might be some differences in failure. Fractographic analysis might give some answers, [8]. One answer might be that the bars are less homogeneous than float glass and thus contain other sources of failure besides surface damage.

Long term strength of glass is clearly dependent on a number of variables. Even the strength of glass without macro damage is decreased due to corrosion in air. Direct exposure to water will accelerate the process. Although heavily damaged glass in air does not seem to show rapid strength loss due to corrosion, direct exposure to water will cause more rapid strength loss. As the structure and thus the strength of the regular glass bars is similar to the strength of the surface of float glass this implies that regular float glass that suffers surface damage in services will also degrade in strength especially when regularly exposed to (salt) water. Strength values for the surface of less than 20 MPa are possible.

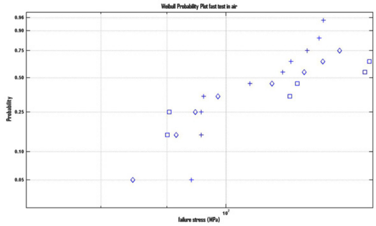


Figure 3: Weibull plots of the three series of fast air tests.

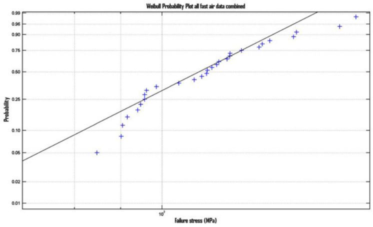


Figure 4: Weibull plot of all fast air tests in a single series.

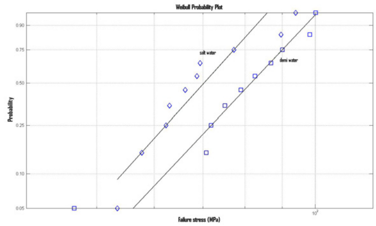


Figure 5: Weibull plot of slow tests in salt and demineralised water.

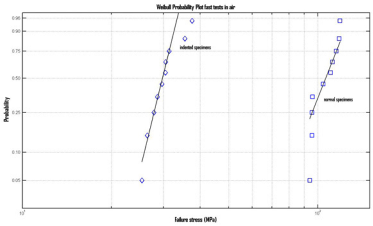


Figure 6: Weibull plot of fast tests in air on normal and indented specimens.

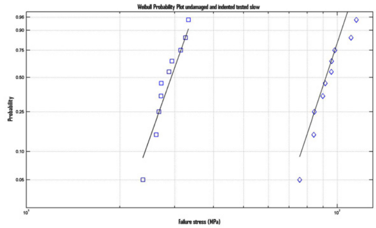


Figure 7: Weibull plot of slow tests in air on normal and indented specimens.

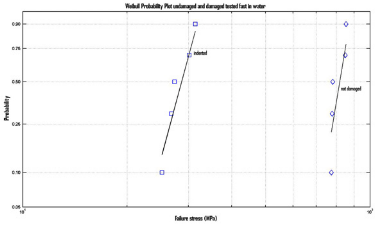


Figure 8: Weibull plot of fast test in water on normal and indented specimens.

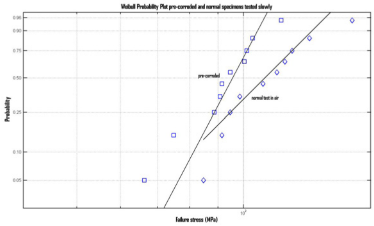


Figure 9: Weibull plot of results of slow tests in air on normal and pre-corroded specimens.

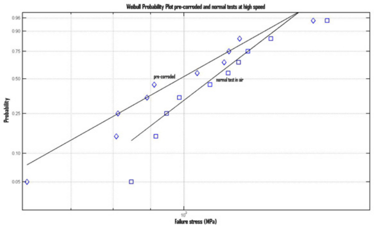


Figure 10: Weibull plot of results of fast tests in air on normal and pre-corroded specimens.

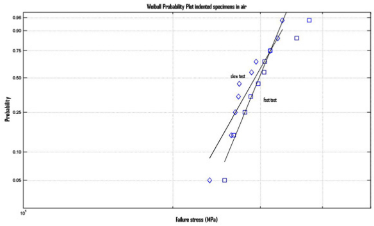


Figure 11: Weibull plot of slow and fast tests on indented specimens.

Figure 12: Micrograph of indentation.

5. Conclusions

From the results it is concluded that:

- corrosion of glass is faster in salt water and normal water than in demineralised water.
- the electrical conductivity of the water plays a role in the corrosion mechanism
- there is no evidence that water soaking increases the strength of glass
- indenting the glass severely reduces the strength, but does not increase the predictability of the strength
- indented specimens tested in air have less strength loss due to increased corrosion than non-indented specimens. Presumably the fast fracture does not allow for much corrosion in air.
- tested indented specimens under water suggests there is more corrosion damage in slow bending than for non-indented glass. This suggests that in indented glass the stress corrosion mechanism is reagent supply driven.

6. References

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