Influence of Temperature and Load Duration on Glass/Ionomer Laminates Torsion and Bending Stiffness

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Summary

Because the characteristic visco-elastic properties of glass/ionomer laminates are not established and validated for a well-defined application scope, the laboratory for Research on Structural Models is performing non-destructive torsion tests and three-point bending tests on 1.1 m and 3 m long glass/ SGP laminates at controlled temperature and humidity. The main aim of this experimental research is the investigation of the long-term stiffness of relatively large-scale SGP-laminated components under extreme loading conditions.

The presently available results of long-term tests between 50°C and 65°C confirm the expected advantage of this kind of structural interlayer: after a load duration of multiple weeks, these specimens still behave much stiffer than glass/PVB laminates. However, the existence of a so-called plateau-value, which refers to a constant residual value of the shear modulus after an infinitely long loading period, could not clearly be observed.

Compared to torsion experiments, bending problems seem to be less sensitive to relaxation and creep effects during the performed load durations. On the other hand, the decrease of the torsion stiffness is also still noticeable after a loading duration of more than one week at 65°C.

Keywords: Ionomer interlayer, SGP, SentryGlas® Plus, Laminated glass, Temperature, Experiments, Bending, Torsion, Visco-elasticity

1. Laminated glass

Safety of the brittle material glass is often increased by laminating it with a soft interlayer. Hereby, multiple glass sheets are adhesively connected across their entire surface with a polymer interlayer. This interlayer can absorb impact energy, preventing all glass sheets to break simultaneously, and it keeps the broken glass fragments together.

Contrary to monolithic glass, which behaves fully elastic until it breaks, a glass/polymer laminate usually behaves visco-elastic before and after breakage. This means that the stiffness of the laminate depends on the temperature and the load duration of the interlayer: a glass laminate will creep under a constant load and relaxation will occur under enforced constant deformation. These phenomena will also speed up at increased temperature.

Nowadays Polyvinyl Butyral (PVB) is the most used interlayer material, but to improve specific mechanical properties - which become more and more important since laminated glass is often given a structural function - the stiffer ionomer interlayer material SentryGlas® Plus (SGP) was developed by DuPont de Nemours. In spite of its increased mechanical behaviour, it is still a complex visco-elastic material.

Because the knowledge of the exact mechanical properties of this improved interlayer is currently limited, a test programme has been executed concentrating on the pre-breakage long-term stiffness of relatively large-scale glass/ionomer laminates at elevated temperatures.

2. Test Programme

To incorporate the influence of the lamination process (a process with high pressure and an elevated temperature-cycle) on the properties of the interlayer, only tests were performed with laminated glass. This is in contrast to e.g. the standard dynamic mechanical analysis carried out by the manufacturer on just the interlayer material [1].

Furthermore, as a consequence of the varied realistic loading conditions of structural glass, the test programme is subdivided into two simplified loading conditions: three-point bending about the weak axis and torsion (see *Fig. 1*). Afterwards, the combination of these two conditions can describe the most realistic situations. For example the first-order bending stiffness of a laminated beam about the strong axis depends on the elastic bending stiffness of the individual glass sheets, but its second-order critical buckling load is determined by the visco-elastic bending around the weak axis and the torsion stiffness of the laminate.

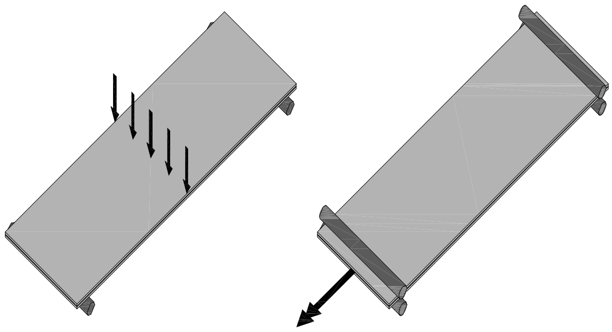

Fig. 1 Basic principle of the test programme

In addition, these are two common conditions for which there already exists profound theories. The bending of laminated materials around their weak axis is thoroughly described by Wölfel [2], while the torsion of laminated glass is well investigated by Scarpino et al. [3]. By further simplifying the test programme according to the stipulations of these theories, the incorporation of the test results should be convenient.

2.1 Test specimens

For this test programme, four different series of test specimens were available. *Table 1* shows an overview of their main properties:

Table 1 Nominal dimensions of the four series of test specimens

Appellation	Number	Type of glass	Length [mm]	Width [mm]	Glass thickness [mm]	SGP thickness [mm]
M	3	annealed	1100	360	6	/
A	8	toughened	1100	360	2 x 6	1.52
B	4	annealed	1100	180	2 x 8	1.52
C	4	toughened	3000	360	2 x 8	1.52

2.1.1 Second-generation SGP

The series A, B and C were laminated with a second-generation SentryGlas® Plus, named SGP5000. At present, this is the most recent version of the structural ionomer interlayer. It differs from SGP2000 because the adhesion to the air-side of the glass (the side of the glass sheet which was not in contact with the molten thin during the float-process) is improved.

As it is not known which impact these changes have on the mechanical properties of the material, it seems important that this modified material is tested.

2.1.2 Effective dimensions

It is generally known that the effective dimensions of products differ from their nominal values. For glass, the permissible deviations are fixed in European standards. For example, the thickness of a 6 mm float glass must be between 5.8 mm and 6.2 mm (for 8 mm glass, the interval is 7.7 mm and 8.3 mm) [4]. Also the acceptable variation on the length and the width is specified in function of the nominal size and glass thickness.

Because for the calculation of both the torsion and the bending stiffness the thickness is raised to the third power, it is important to determine the effective thickness as accurate as possible. Consequently, the individual glass thickness of these test specimens was measured prior to testing. Through this, no groundless assumptions must be made based on the overall thickness of the laminate, which is the only thickness measurable after lamination without breaking the test specimen. *Table 2 and 3* present the measured thicknesses. For this, the thickness was measured twice in the middle of each sheet as shown in *Fig 2*. The measurement was done both for the unlaminated glass sheets (t_{glass}) as for the finished laminate ($t_{laminate}$).

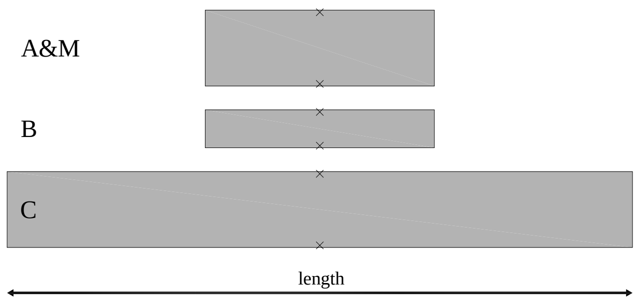

Fig 2 Indication of the measurement locations

Table 2: Effective thickness of series M

Test specimen	**t_{glass} [mm]**
M01	5,93
	5,96
M02	6,03
	6,00
M03	5,87
	5,89

Table 3 Effective thickness of the test specimens A. B and C

Test specimen	**t_{glass} [mm]**		**$t_{laminate}$ [mm]**	**t_{SGP}**	**Test specimen**	**t_{glass} [mm]**		**$t_{laminate}$ [mm]**	**t_{SGP}**
A01	5.87	5.91	13.44	1.66	B01	7.86	7.85	17.29	1.59
	5.88	5.91	13.45			7.85	7.85	17.29	
A02	5.88	5.95	13.37	1.56	B02	7.71	7.74	17.03	1.58
	5.88	5.95	13.40			7.71	7.75	17.03	
A03	5.89	5.87	13.34	1.57	B03	7.74	7.75	17.15	1.66
	5.92	5.87	13.35			7.76	7.74	17.15	
A04	5.88	5.88	13.31	1.54	B04	7.85	7.86	17.29	1.60
	5.89	5.90	13.31			7.85	7.85	17.31	
A05	5.87	5.94	13.38	1.61	C01	7.75	7.75	17.05	1.55
	5.88	5.90	13.43			7.75	7.75	17.04	
A06	5.88	5.90	13.43	1.59	C02	7.74	7.75	17.07	1.57
	5.96	5.93	13.42			7.74	7.75	17.05	
A07	5.90	5.92	13.44	1.57	C03	7.74	7.74	17.07	1.57
	5.90	5.96	13.38			7.75	7.74	17.03	
A08	5.88	5.91	13.43	1.64	C04	7.74	7.74	17.05	1.60
	5.90	5.90	13.43			7.73	7.74	17.09	

The actual thickness of the SGP5000 interlayer t_{SGP} is determined by subtracting the sum of the two average glass thicknesses from the mean total thickness. The first noticeable observation is that this generally results in a larger thickness than the nominal value of 1.52 mm. Nevertheless, the interlayer thickness was measured before the lamination and the nominal value was found to be accurate. This could mean that the lamination process has a non-negligible effect on this material.

Apart from that, it is remarkable that the individual glass thicknesses always (apart from specimen M02) vary between the nominal thickness and the minimum allowed thickness of 5.8 mm and 7.7 mm.

Besides the effective thickness, also the length and the width of the specimens was accurately measured. However, because of the much smaller impact of these deviations on the results, these measurements are not further discussed in this article.

2.2 Torsion test setup

The torsion test setup for this test programme is mainly based on the setup used by Kasper [5]. Hereby, the test specimen is clamped between a fixed support and a rotating support. To purify the enforced torsion and to minimize the stress concentrations, the supports each consist out of two round bars [6]. Small aluminium strip between these steel bars and the glass prevent direct steel to glass contact.

As can be seen in *Fig 3*, the torsion moment is introduced with a mechanical jackscrew. With this, a precise deformation can be enforced for a long term, excluding e.g. the possibility of a pressure loss in a hydraulic jack. The force of the jack is digitally measured and transferred through a ball bearing to the lever arm which is connected to the rotating support of the test specimen. The rotation axis of this support exactly runs through the centre of the tested laminate.

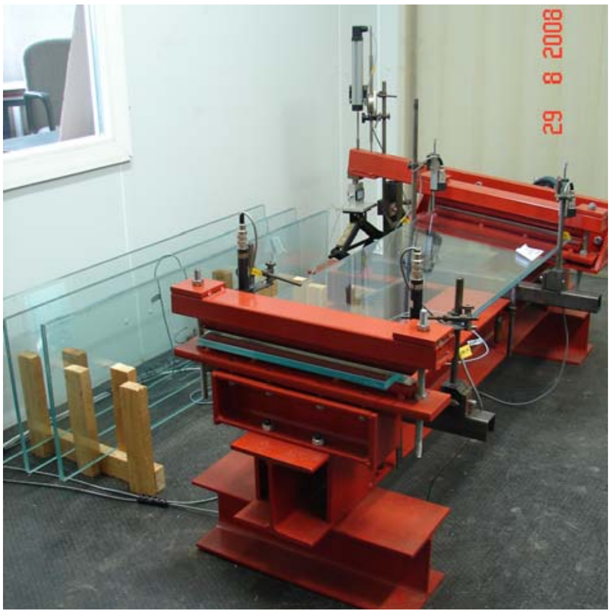

Fig 3 Torsion test setup

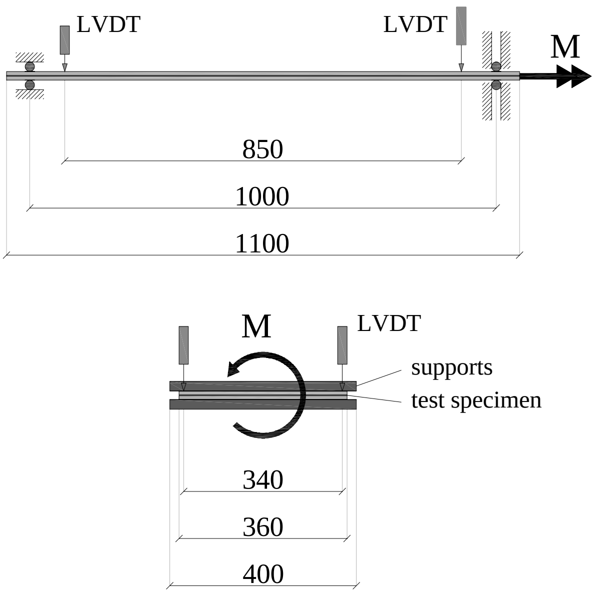

Fig 4 Schematic torsion test setup

Besides to the vertical displacements of the lever arm above the ball bearing, the vertical displacement of four points on the top surface of the glass/ionomer laminate is measured. *Fig 4* schematically shows the position of these digital displacement transducers and also the distance between the two supports.

Furthermore *Fig 3* depicts the storage of the test specimens of series A before testing. The glass/SGP laminates are stored vertically to minimize the possible creep under self-weight. Also there is a void of about 5 cm between the specimens to optimize the temperature regulating air flow.

2.3 Bending test setup

Because the relative bending stiffness of glass/SGP laminates with similar material stiffnesses is heavily influenced by the span of the two line supports [7], bending tests were performed with two different specimen sizes. A span of 1050 mm was applied for specimen series B, while the series C had a support span of 2950 mm. The combination of these tests should round up the knowledge of the bending behaviour of glass/ionomer laminates.

Halfway the experimental programme, a major adjustment was implemented on the bending test setup. Because of this, the tests and their results are discussed separately according to the applied setup.

2.3.1 Setup 1

The first bending experiments were performed on a rather common setup. As shown in *Fig 5*, the test specimens were simply laid down on two well positioned linear supports. In the middle of the laminate a fixed line load was introduced with a loading system with weights. On top of this loading system, the vertical deformations were measured with two LVDT's.

Fig 5 Small bending test setup 1

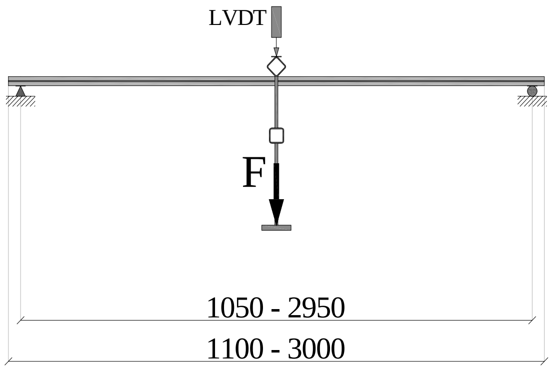

Fig 6 Schematic bending test setup 1

Contrary to the span of the standardised four-point bending test [8], the small test specimens span 1050 mm in stead of 1000 mm. This was changed this way in order to reduce the undesired effects of the cantilever sections. The large specimens span a distance of 2950 mm, which corresponds to the earlier research performed at the Laboratory for Research on Structural Models [9].

2.3.2 Setup 2

The processing of the results of the tests with bending setup 1 showed that the combination of the self-weight of the test specimen with the central line-load resulted in a very complex situation. Therefore, an alternative test setup was designed to minimize the effects of the self-weight on the creep deformations of the laminate under a three-point bending condition. To resolve this issue, the test specimen was placed vertically and a more sophisticated loading system with a pulley was developed to introduce a line load horizontally.

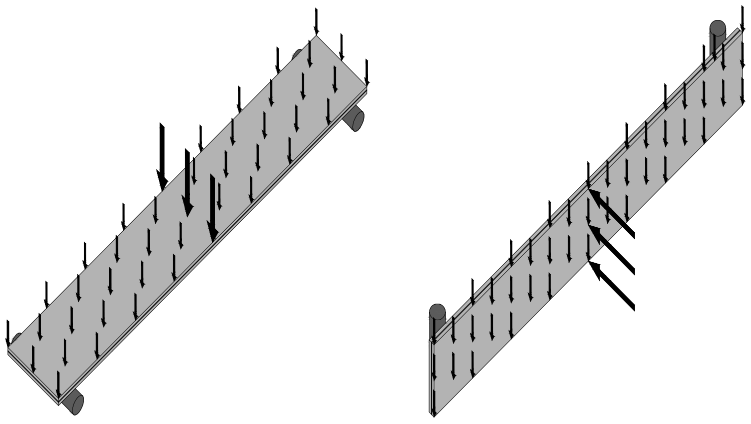

Fig 7 Schematic difference of the loading in bending setup 1 (left) and bending setup 2 (right)

In this new situation, the self-weight acts perpendicular to the introduced line load and has therefore hardly any impact on the deformations caused by the applied load (principle see *Fig 7*). The uniformly distributed force also loads the laminate about its strong axis, so the interlayer is theoretically quasi unloaded.

Fig 8 shows the realisation of the altered bending test setup for the test specimen series C (the small bending test setup 2 is similar for the test series B). In this, the two supports hold the test specimen both vertically and horizontally and span, as already stated in setup 1, 1050 mm and 2950 mm. Through a more complex loading system, the weights introduce a horizontal line load about the weak axis of the laminate.

Fig 8 Large bending test setup 2

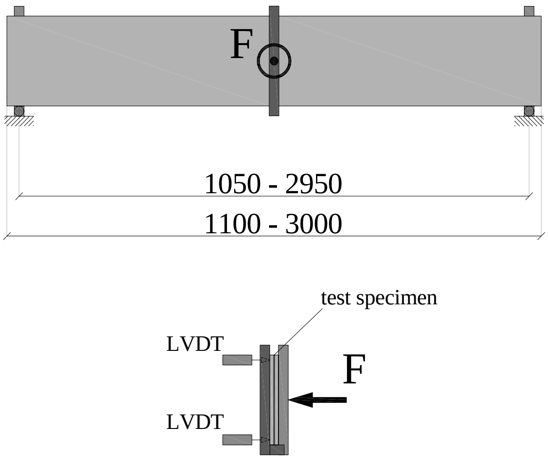

Fig 9 Schematic bending test setup 2

Right behind the line load, with a distance of 1 cm to the borders, two LVDT's continuously record the deformation. Contrary to the previous setup, these transducers are directly mounted on the surface of the glass. This way, the recording can start even before the loading system touches the test specimen.

As like for the test specimens of series A (*Fig 3*), the series B and C are stored vertically with a intermediate gap (see *Fig 5* and *Fig 8*). This way, the test specimens can slowly acclimatize to the desired temperature and air humidity of the experiments.

2.4 Experimental proceeding

All five test setups were built up in a closed chamber with controlled temperature and air-humidity. In this room, the air control always started at least 60 hours before the beginning of the first test. This ensured the right temperature of the interlayer for each test.

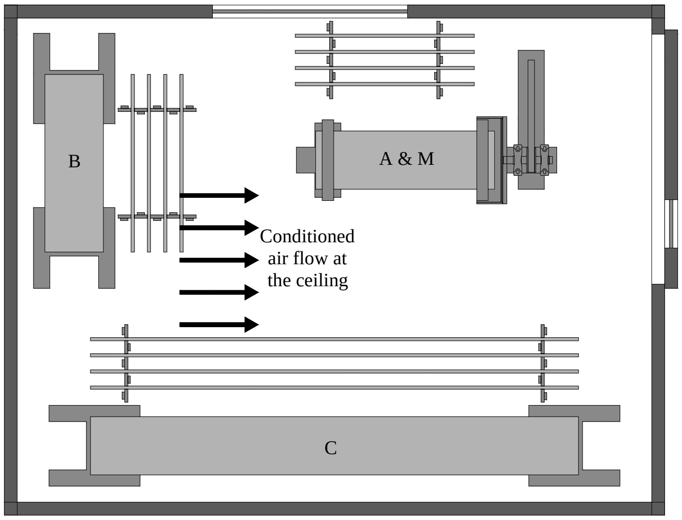

Fig 10 Arrangement of the test setups in the chamber with controlled environment

2.4.1 Torsion tests

In total, thirteen torsion tests are discussed in this contribution. Three of these were short-term tests on the monolithic specimens of series M, while the other ten were long term tests at elevated temperatures on the glass/SGP laminates of series A. *Table 4* summarizes the temperatures and the load durations of these last ten tests.

Table 4 Overview of the torsion tests on series A

Test specimen	Load duration at 50°C [hours]	Load duration at 60°C [hours]	Load duration at 65°C [hours]
A01	-	0.5	96
A02	-	264	72
A03	-	-	217
A04	-	-	48
A05, A06 & A08	48	-	-
A07	120	-	-

Because the exact material properties of glass differ in function of the specific chemical composition [10], the tests on series M were performed to experimentally determine the shear modulus of the applied glass. As monolithic glass behaves fully linear elastic irrespective of the temperature until breakage, these three specimens were only briefly loaded at room temperature.

The load on the monolithic samples was a torsion deformation of about four degrees, while series A was loaded as fast as possible - because of the visco-elastic behaviour of the interlayer material - with a six degrees angle of the rotation support.

2.4.2 Three-point bending tests

As described in the previous section, four different bending test setups were used: a bending test setup 1 and a setup 2 for both the specimens of series B and C. On all four setups, experiments were carried out at high temperatures. *Table 5* and *table 6* show the load durations of all performed three-point bending tests.

Table 5 Overview of the three-point bending tests with bending test setup 1

Test specimen	Load duration at 50°C [hours]	Load duration at 65°C [hours]
B01 & C01	48	96
B02 & C02	48	72
B03 & C03	120	217
B04 & C04	48	48

Table 6 Overview of the three-point bending tests with bending test setup 2

Test specimen	Load duration at 60°C [hours]	Load duration at 65°C [hours]
B02 & C02	264	-
B03	-	57
C03	-	788

In the bending test setup 1, the loading system was positioned in the centre of the test specimen just after the glass/SGP laminate was horizontally laid on the supports. Hereafter, the two displacement transducers were placed on the top of the loading system. Finally, weights of 9 kg and 20 kg in total were put on the loading system of respectively the small and the large three-point bending test setup.

In setup 2, the laminate could be positioned vertically to its supports. After the loading system was fixed, the support of the weights was smoothly lowered. The specimens of series B en C were respectively loaded with 15 kg and 40 kg.

3. Torsion results

3.1 Torsion of monolithic glass

The three torsion tests on the monolithic specimens of series M were executed to refine the knowledge of the material properties of the applied glass. *Table 7* summarizes the main results.

Table 7 Results of torsion tests on series M

Test specimen	Torsion moment [Nm]	Torsion deformation [rad/mm]	Shear modulus of glass [N/mm²]
M01	56.692	7,38E-02	30375 ± 648
M02	58.890	7,37E-02	30508 ± 642
M03	53.792	7,42E-05	29595 ± 578

Out of these tests, the mean shear modulus of glass G_{glass} is found to be 30290 ± 643 N/mm². This value comes up to the theoretical expectations. Therefore, this shear modulus can be used in the processing of the torsion test results of the tests on the glass/SGP laminates. This should improve the accuracy of this research, as well as the calculation of the material properties of the ionomer interlayer.

3.2 Torsion of glass/SGP laminates

All ten torsion tests on the laminates of series A result in a relation between the loading duration, the force on the lever arm connected to the rotation support and the four displacements measured on top of the glass surface. *Fig 11* and *Fig 12* show an example of this basic data.

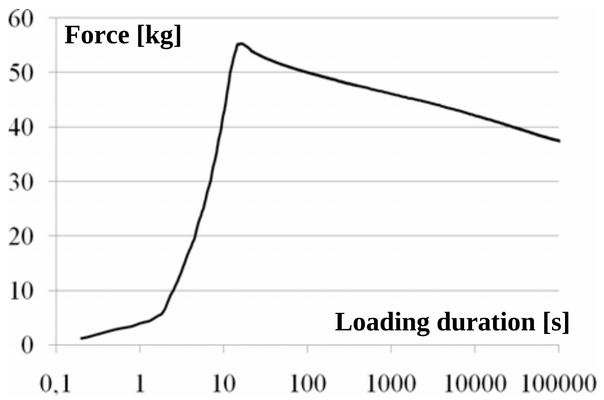

Fig 11 Registered load on the lever arm for test sample A02 at 65°C

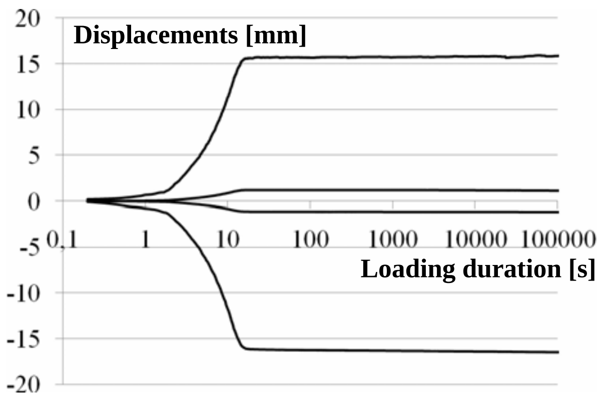

Fig 12 Registered displacements on the glass surface for test sample A02 at 65°C

With the theory developed by Scarpino et al. [3], it is possible to deduce the shear modulus of SGP G_{SGP} out of these results indirectly. The main basis for the theory is that the actual torsion stiffness of laminated glass can be expressed as the multiplication of the torsion stiffness of the individual glass sheets with a factor f:

$$(GI_t)_{laminate} = GI_{t,\ disconnected\ glass\ sheets} \cdot f \quad (1)$$

If the experimental outcomes are compared in terms of percentage to the stiffness of a monolithic glass plate with a thickness equal to the total thickness of the laminate, this results in a graph as shown in *Fig 13*. Out of this, the factor of increase f can be easily calculated.

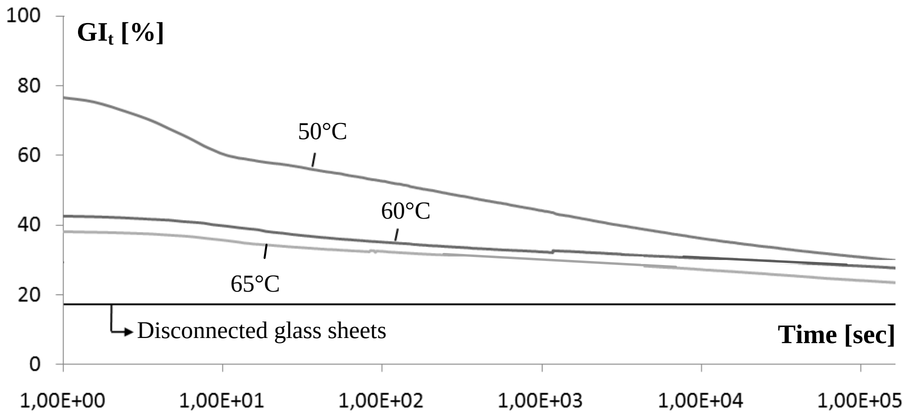

Fig 13 Mean experimental torsion stiffness in terms of percentage to the equivalent monolithic torsion stiffness.

For a symmetric laminate with two glass plies and one soft interlayer, meeting some additional requirements e.g. the length must largely exceed the width which must be much bigger than the total thickness, etc., formula (2) represents its dimensionless factor of increase. Since the test specimens of these experiments fulfil all the necessary requirements, this formula is applicable.

$$f = \frac{6t_{glass}^3 t_{SGP} + \frac{G_{SGP}}{G_{glass}} \cdot h^2 \left(4t_{glass}^2 + 6t_{glass}t_{SGP} + 3t_{SGP}^2\right)}{t_{glass}^2 \left(6t_{glass}t_{SGP} + \frac{G_{SGP}}{G_{glass}} \cdot h^2\right)} \tag{2}$$

In this formula, t_{glass} stands for the thickness of one individual glass sheet and t_{SGP} is the interlayer thickness (see *Table 3*). With the shear modulus of glass G_{glass} of 30290 N/mm² from the above mentioned torsion tests, the momentaneous shear modulus of the interlayer G_{SGP} can be determined for each recording. This finally results in a function between the main material property of the interlayer, namely G_{SGP}, and the temperature and the load duration, which is summarised in *Fig 14* to *Fig 17*.

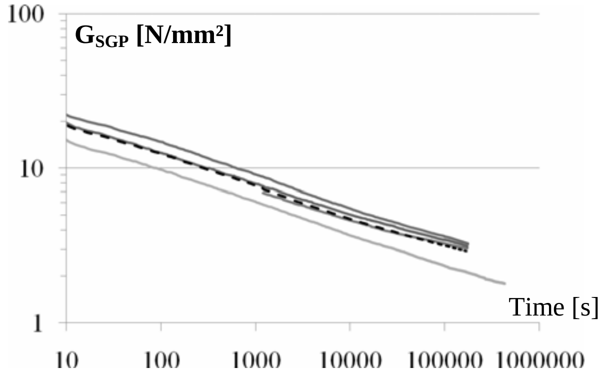

Fig 14 Experimental correlation between G_{SGP} and the load duration at 50°C

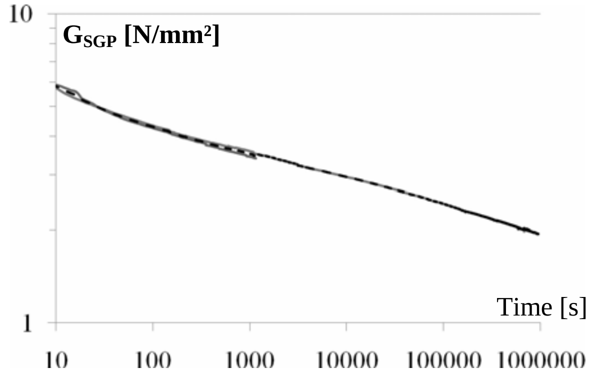

Fig 15 Experimental correlation between G_{SGP} and the load duration at 60°C

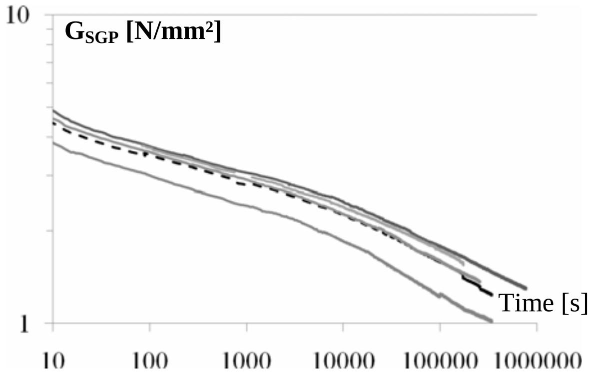

Fig 16 Experimental correlation between G_{SGP} and the load duration at 65°C

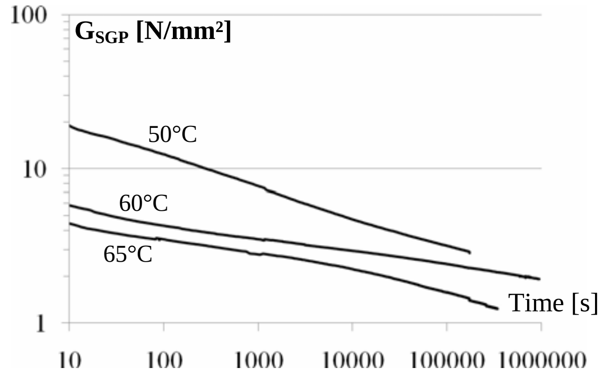

Fig 17 Correlation between the mean G_{SGP} and the load duration for all torsion experiments

4. Three-point bending test results

4.1 Results Setup 1

Because the registration of the bending deformations in bending test setup 1 was started only after the test specimen was placed on the supports, the deformation due to the self-weight had to be estimated. Otherwise, the material properties of the interlayer were impossible to deduce.

The best way to do this was found to be a calculation for the uniformly loaded plate with a reference bending stiffness, based on the increased deformation due to the line load in the centre of the laminate.

As a result, the total deformations due to the self-weight and the applied load could be calculated as the sum of the measured displacements and this calculated initial deformation. The results of this for the tests on both specimen series B and C are summarised in Fig 18 and Fig 19.

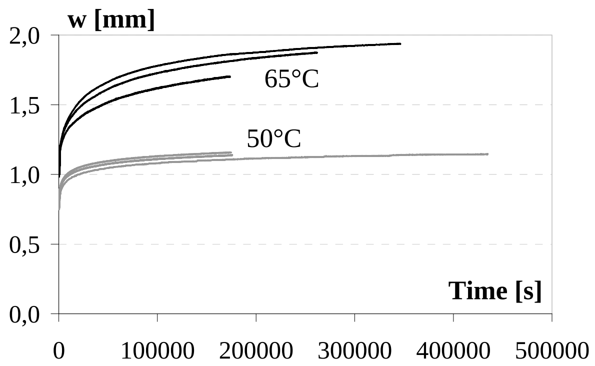

Fig 18 Total central deformation w for test series B with three-point bending test setup 1

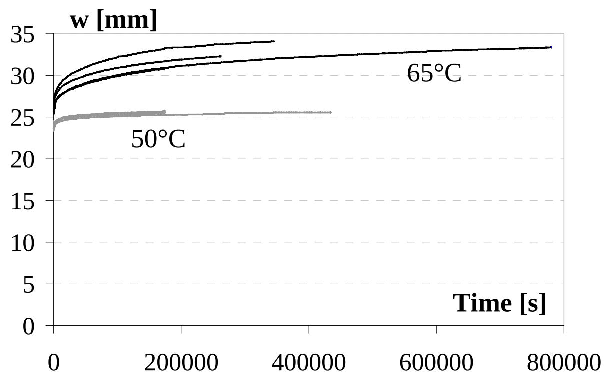

Fig 19 Total central deformation w for test series C with three-point bending test setup 1

Through a reciprocal calculation with the theory of Wölfel [2], developed to calculate the bending deformations of laminated beams loaded about their weak axis, it is possible to deduce the mechanical properties of the interlayer material from these results. Similar to the results of the torsion tests, this leads to a continuous relation between the shear modulus of SGP and the loading duration. *Fig 20* depicts this derivation.

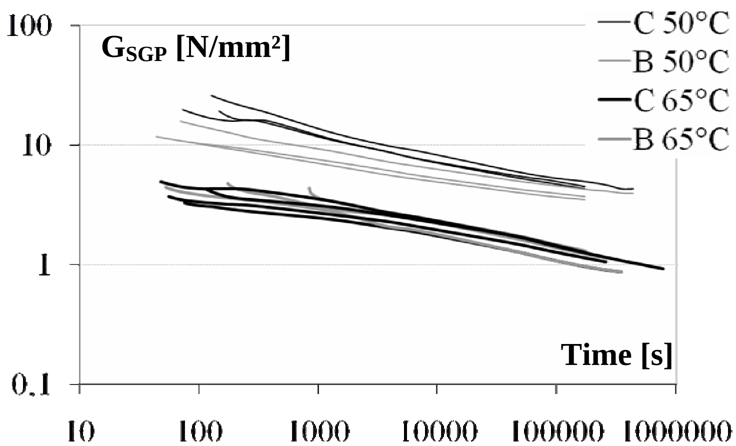

Fig 20 Correlation between the shear modulus of SGP and the load duration for all three-point bending experiments with test setup 1

4.2 Results series 2

Because the creep deformations with the first bending test setup is caused by both the uniformly distributed self-weight as the applied central line-load, the extrapolation of the material properties is based on some uncertain assumptions. Additionally, the creep starts for both loads at different moments. Therefore, the second bending test setup was developed. In this, the influence of the self-weight is eliminated as much as possible. By doing this, the load situation became much more clear, which simplified the handling of the results.

Fig 21 and *Fig 22* represent the mean direct measured deformations of the three-point bending tests with the test setup 2. The initial deformation must not be calculated and the creep is only caused by the load of the weights, which can be applied very fast.

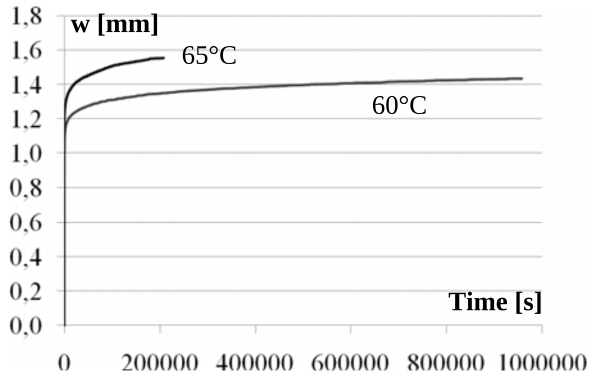

Fig 21 Central deformation w for test series B with three-point bending test setup 2

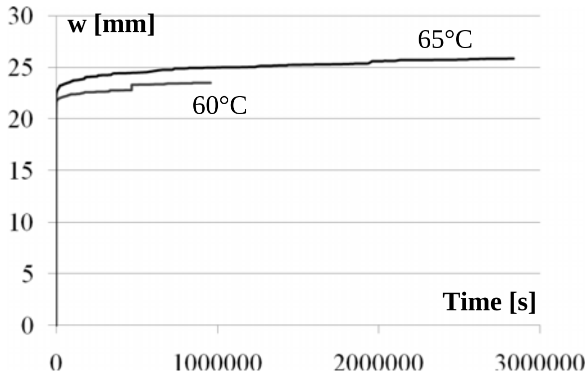

Fig 22 Central deformation w for test series C with three-point bending test setup 2

Just like with the previous bending tests, these results are transformed into a correlation between the G_{SGP} and the load duration by using the theory of Wölfel. The outcome is presented in *Fig 23*:

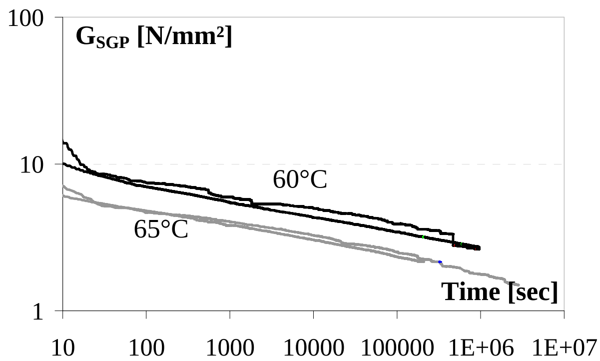

Fig 23 Correlation between the shear modulus of SGP and the load duration for all three-point bending experiments with test setup 2

5. Discussion and prospect

On the basis of torsion and bending experiments, the knowledge of the mechanical behaviour of glass/ionomer laminates is increased. Among other things, it became clear that this kind of structural interlayer - compared to the more traditional PVB - has a more important influence when the span between the supports in bending increases. On the other hand, torsion problems seem to be more sensitive to the relaxation effect anyhow, within the performed extreme circumstances.

Although these glass/ionomer laminates behaves significantly stiffer than glass/PVB laminates would, the decrease of the stiffness is still noticeable after a loading duration of more than 4.5 weeks. A so-called plateau-value, which refers to a constant residual value of the shear modulus after an infinitely long loading period, could therefore not be observed.

The next step in this research will be the extension of the test-temperatures to the lower range. Through this, a composed visco-elastic material model should be put together according to the model of Williams-Landell-Ferry [11]. A thorough comparison between the torsion and bending results, complemented with an extensive FEM analyse, should further check the applicability of the derived model. With this, also other loading conditions than pure torsion or three-point bending should be examined. This way, it can be verified if these two simplified loading conditions are appropriate for a full experimental analyses of new interlayer materials.

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Further details of these experiments are taken down in the master dissertations of De Vogel [12] and Depaepe [13].

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