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Permanent Hydrothermal Exposure on Load-bearing Adhesives in Glass Constructions

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The German research team FABIG develops a bioenergy building skin including modules of glass which contain a liquid medium processing biomass. Inside the facade modules, load-bearing adhesives were applied that are subject to permanent water exposure. Water is known as a major hazard for adhesives because water molecules diffuse into the adhesive polymer matrix and into the interface between adhesive and substrate. As a result, material characteristics as well as the adhesion properties may change significantly. Additionally, the adhesive is exposed to conventional aging in building skin as the temperature ranges between -20°C and +80°C. This paper focuses on the effect of water on load-bearing adhesives in a bioenergy facade. It evaluates potential adhesives for permanent hydrothermal application. The paper introduces water as a key aging medium. Furthermore, it describes the construction of an innovative flat plate photobioreactor as an example for load-bearing adhesives under permanent hydrothermal treatment. The conditions inside the photobioreactor, which lead to particular mechanical, physical and chemical loads for constructive elements in comparison with conventional facade systems are presented. The main part describes the results of experimental tensile tests on the adhesive short-term behavior considering temperature conditioning and chemical treatment with substances emerging from bio-processing like storing in acid, base and hydrogen peroxide solution. The paper concludes with an outlook on future research work of the team including ARUP Deutschland GmbH (Berlin, Germany), ADCO Technik GmbH (Rostock, Germany), SSC GmbH (Hamburg, Germany) and Technische Universität Dresden (Dresden, Germany).

Keywords: Bioenergy facade, Glass, Load-bearing adhesives, Hydrothermal aging

1. Introduction

In facade constructions water is a major hazard for adhesive systems. Consequently, any water – being rain from the outside or moisture from the inside – is drained off directly. A waterproof layer stops rain from penetrating into the construction and a drainage system channels it off carefully. Avoiding any permanent water exposure is particularly important for adhesive systems. Water molecules diffuse into their polymer matrix and enter the interface between adhesive and substrate. As a result, material characteristics as well as the adhesion properties may change significantly. In spite of the well-known interference, some glass construction require load-bearing adhesives under permanent water

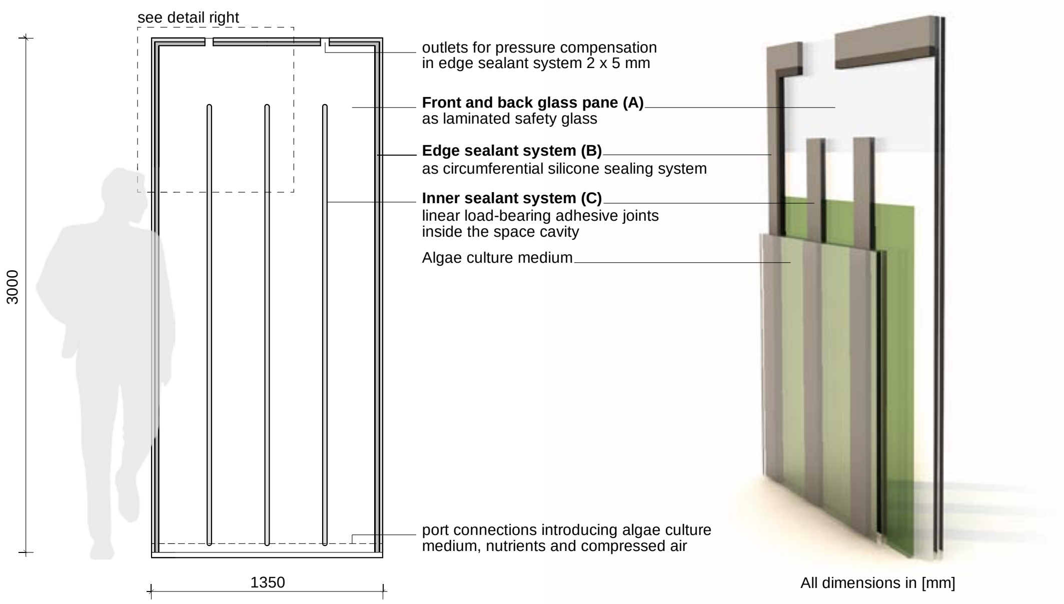

Figure 1: Components of a flat panel photobioreactor for facade integration.

exposure. It is the challenge to identify adhesives which meet the physical and mechanical requirements and guarantee them even after a long period of permanent hydrothermal treatment.

2. Construction of a Bioenergy Facade Module

An example for such special applications are bioenergy facades made of glass. The German research team FABIG (**F**assaden mit **A**lgen**bi**oreaktoren aus **G**las) develops flat panel photobioreactors as modules for the bioenergy facade. The Technische Universität Dresden evaluates load-bearing adhesives for permanent water exposure. Figure 1 illustrates the design of the photobioreactor with a size of 1.35 m x 3.00 m. The construction resembles common insulated glass units comprising front and back glazing (A) and an edge sealant system (B). Inside the unit, linear load-bearing adhesives are arranged (C). The construction is completed by port connections at the bottom part.

The laminated front and back (A) glazing confine an inner glazing cavity of 10 mm. Instead of a noble gas, the glazing cavity is filled with a liquid medium which is very similar to water in terms of mechanical characteristics. The liquid serves as culture medium for microalgae producing biomass whilst performing photosynthesis. The photoactive organisms are cultivated all over the world in open systems like lakes and raceway ponds or they are processed in closed systems. Flat plate photobioreactors are a special type of closed systems and provide the microalgae with sufficient carbon dioxide and specific nutrients to ensure optimal growth. Solar energy enters through the transparent corpus of the reactor. [Bley 2009, Kaltschmitt 2016] To ensure the serviceability of the module, two types of load-bearing adhesive joints are arranged inside the module connecting both glass panes: First, a circumferential structural adhesive joint (B) is applied along the edge. Secondly, an inner sealant system composed of three linear adhesives joints (C) is applied within the glazing cavity.

Figure 2: A bioactive facade installed at the BIQ- Algenhaus in Hamburg, Germany.

A bioenergy facade with preceding photobioreactor modules is successfully tested since 2013 at the 'BIQ – Das Algenhaus' in Hamburg Wilhelmsburg, Germany. In contrast to the FABIG modules presented in this paper, the BIQ elements are clamped on four sides and no load-bearing joints are applied. The conceptual smart material house was built during the International Building Exhibition (IBA) as a residential building. Figure 2 shows the preceding pilot project with the external bioactive system that supports the building's heating and warm water supply. Additionally, the algae biomass that is high in omega-3 fatty acids, antioxidants, vitamin and enzymes is used in the pharmaceutical or food industry. [Wurm 2013, Wurm et al. 2013, SSC 2010]

3. Load Assumptions

The adhesive joints inside the reactor and along its edges are exposed to mechanical, physical and chemical loads.

First of all, the algae medium creates a hydrostatic pressure distribution that induces large deflection into the glazing. So, the leading mechanical loads arise from the culture medium filling. The reactor is filled with algae solution up to a height of 3.00 m, which causes a maximum hydrostatic pressure of 29.4 kN/m². Additionally, compressed air is introduced periodically by airlift at the bottom of the system. In consequence, compression waves load the system dynamically. The dynamic impact depends on the pressurized air amount, interval and injection mechanism. In transient two-phase computational fluid dynamic (CFD) the research partner Arup Deutschland GmbH evaluated the particle velocities, turbulences and pressure oscillations. The results were published in Aßmus et al. (2017).

Besides the mechanical impacts, physical loads affect the system. Physical loads include ambient temperatures in a facade system varying from -20 °C to +80 °C, UV-radiation and permanent water exposure. The simultaneous influence of water and temperatures elevated by solar irradiation affects the material properties as well as the interface quality between the adhesive and the glass. During water exposure, water molecules diffuse into the polymer and the interface between glass and epoxy. Possible consequences are a weakening of intermolecular interactions between polymer chains, an extraction of fillers and plasticizer and hydrolysis as cleavage of chemical bonds. These processes may reduce the tensile strength according to the duration of water exposure, shift the glass transition temperature towards lower temperature and support embrittlement. The addition of acid and base substances may also accelerate the described hydrothermal aging. Other chemical loads arise from cleaning and fouling processes in areas with insufficient turbulences. Effects are a pH-value varying between five to twelve as well as the influence of chlorids and hydrogen peroxide as cleaning agent according to Kerner (2015). The mechanical, physical and chemical loads set the base for test types and aging scenarios of an applied test program.

4. Test Concept

4.1. Test Program

The test concept introduces information on the preselection of adhesive products, specimen geometry, aging scenarios and test procedure. The tensile tests of the adhesive material offer valuable information on the mechanical behavior of the bonded glass module considering the impact of test temperature and aging medium. Furthermore, the results provide data for future numerical simulations.

The adhesive products were preselected in preliminary studies analyzing the mechanical behavior of the bulk adhesive material in uniaxial-tensile tests. Specimens according to EN ISO 527-2 provide the basis for the tests. Four groups with different chemical bases were evaluated. The selection included adhesive products with an epoxy, polyurethane, silicone and hybrid base. The results were discussed and published in Weller et al. (2016). Out of each group one adhesive product featuring best chemical resistance was preselected. Below, the adhesives will be referred as EP (2K), PU (1K), SI (1K) and HY (1K).

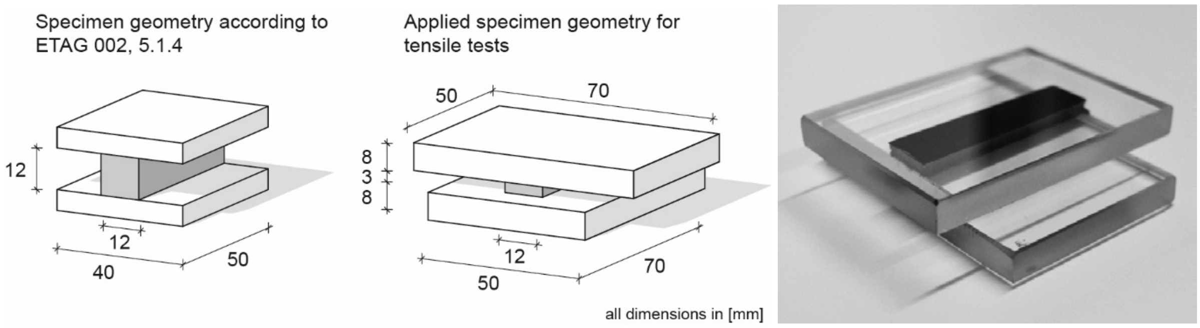

Figure 3: Specimens for tests according to ETAG 002 and EN ISO 13022.

Specimens according to ETAG 002 and EN ISO 13022 provided the basis for adhesion tensile tests. The adhesive thickness was adapted from 12 mm to 3 mm to realize a joint with epoxy adhesive. Figure 3 gives the specimen dimensions conforming to standards and the adapted specimen geometry including an image of a specimen during conditioning. The specimens were produced according to the manufacturer’s instruction and were cured at room temperature of 23 °C and relative humidity of 50 %.

Effects of test temperature	**Effects of aging medium**
Storing at -20ºC, Storing at +35ºC, Storing at +80ºC for 24 hours, 7 specimens per adhesive system	Storing in water, Storing in acid solution, Storing in base solution, Storing in hydrogen peroxide solution for 21 days, 7 specimens per adhesive system
Uniaxial tensile tests	

Figure 4: Test program.

The specimens passed a test program based on DIN EN 15434 and was adjusted to the special loads inside the reactor. Figure 4 shows the test program that covers the tensile behavior after different ambient temperatures and aging medium. The mechanical behavior was tested within the temperature application range for facades at -20 °C, +35 °C and +80 °C. For laboratory testing the liquid algae medium is represented by separate chemical aging agents. The testing concept comprised four aging scenarios to simulate the chemical loads inside the photobioreactor. The aging specimens were stored in water, acid, base and hydrogen peroxide solution for 21 days at 35 °C. After storing, the specimens were tested immediately without further conditioning at room temperature to avoid any reversible curing effects. The ideal temperature for algae growth ranges from 25 °C to 35 °C. Hence, 35 °C is assumed as service temperature and all specimens are stored and tested at 35 °C. Seven specimens of each group were stored and tested.

The tensile tests were executed at the Friedrich-Siemens-Laboratorium at the Technische Universität Dresden. An electromechanical testing system Instron 5880 (see Figure 5) recorded applied forces, longitudinal and transverse strain via a video extensometer. All tensile tests are displacement-controlled with a cross head speed of 1 mm/min. Additionally, dynamic mechanical analysis give information about the glass transition temperature T_g.

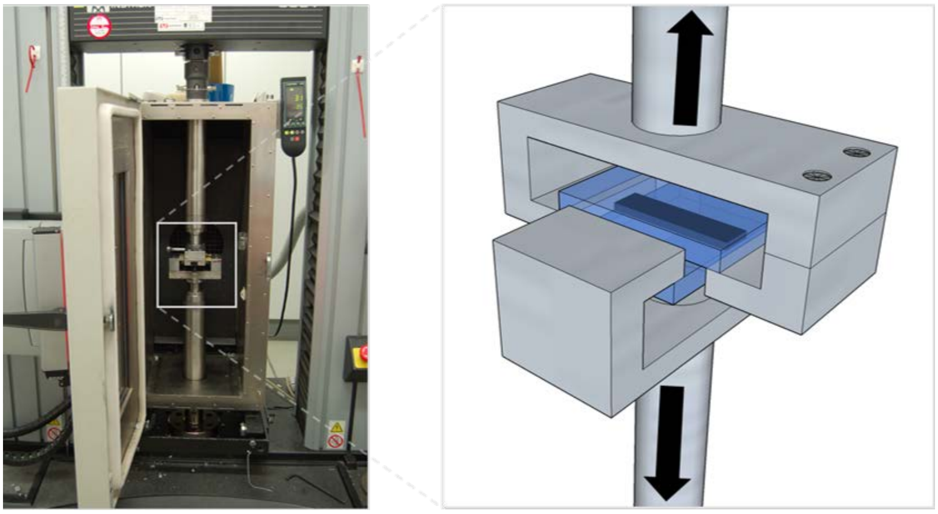

Figure 5: Specimens during tensile tests in the Instron 5880 (Popp 2017).

4.2. Evaluation Method

Based on the test data, the maximum tensile strength σ_{max} is determined for each specimen and statistical outliers are excludes. The analysis identifies the mean tensile strength σ_{mean} per test set, the characteristic tensile strength $R_{u,5}$, the effect of aging by ΔX_{mean} and the failure mode. Boxplots, bar charts and table summarize the test results.

The clearly arranged boxplot allows a quick visual understanding of different result distributions. It consists of the minimum and maximum test values, quartiles and the median. The first quartile (25 %), median and third quartile (75 %) limit the box. The span between the first and third quartile is equal to the interquartile range (IQR). Whisker at both end of the box indicate the minimum and maximum test value. According to J. W. Tukey, the whisker ranges to a maximum of 1.5 x IQR. Any data off the whisker range are exclude from further analysis as statistical outliers.

The maximum tensile strength is evaluated as arithmetic mean value and standard deviation excluding outliers. Additionally, the unaged series tested at 35 °C serves as reference series (σ_{ref}). On the one hand, the reference series serves to identify the characteristic tensile strength $R_{u,5}$ according to DIN EN 15434. On the other hand, the mean reference tensile strength is the base value to rate the aging effect. ΔX_{mean} indicates the ratio of the mean tensile strength after conditioning to the mean tensile strength of reference. The aging behavior is rated as excellent $\Delta X_{mean} \geq 0.75$, good $0.50 \leq \Delta X_{mean} < 0.75$, fair $0.25 \leq \Delta X_{mean} < 0.50$ and poor $0.25 > \Delta X_{mean}$ in relation to the reference series.

Additionally to the tensile strength, a visual inspection provides essential information on the joint quality and failure mechanism. DIN EN ISO 10365 distinguishes different failure modes, of which the following occur during the experimental test: substrate failure (SF) and cohesive substrate failure (CSF), cohesive failure (CF) and substrate-near cohesive failure (SCF) as well as adhesive failure (AF). Bar charts and pictures give an overview of the failure modes.

DIN EN 15434 states three essential requirements for load-bearing adhesives concerning the reference tensile strength, the aging effect and the failure mode. First, the characteristic strength of the unaged reference is limited to $R_{u,5} \geq 0.5$ N/mm². Second, the effect of aging is restricted by the ratio of the conditioned strength to the reference tensile strength with $\Delta X_{mean} \geq 0.75$. Third, the code allows a maximum of 10 % adhesive failure. All test results are critically discussed regarding these three requirements.

5. Tensile Test Results

5.1. Influence of testing temperature on tensile strength

The charts in Figure 6 provide an overview of the tensile test results focusing on the effect of the testing temperature at -20 °C (blue), the reference set at +35 °C (yellow) and +80 °C (orange). The boxplot depicts the full data set including statistical outliers. Figure 7 visualizes the failure modes at different test temperatures. The chart distinguishes substrate failure (blue), cohesive failure (yellow) and adhesive failure (gray).

Table 1: Tensile strength during different test temperature.

		EP			PU			SI			HY		
Testing temperature		-20	+35	+80	-20	+35	+80	-20	+35	+80	-20	+35	+80
Mean tensile strength	[N/mm²]	6.6	8.3	8.2	3.0	1.7	1.7	1.0	0.9	0.7	2.4	1.2	1.1
Standard deviation	[N/mm²]	1.7	1.2	0.8	0.1	0.3	0.1	0.2	0.2	0.1	0.1	0.1	0.2
Coefficient of variation	[-]	0.3	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.0	0.1	0.2
Ru,5	[N/mm²]	-	5.9	-	-	1.1	-	-	0.5	-	-	0.9	-
ΔX_{mean}	[-]	0.8	-	1.0	1.7	-	1.0	1.2	-	0.8	2.0	-	1.0

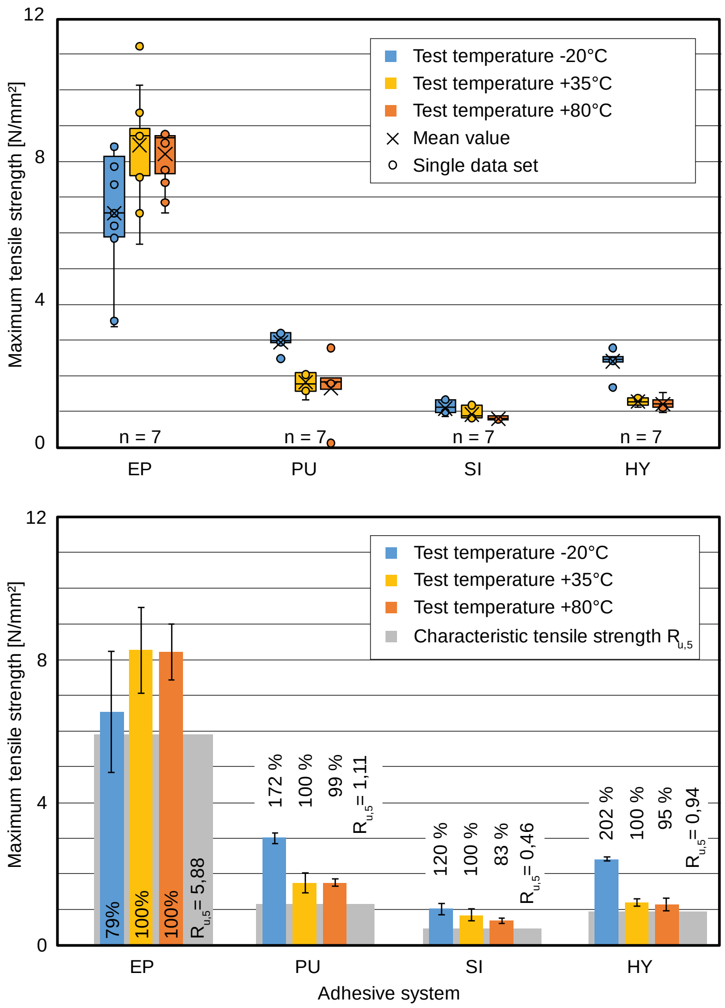

Figure 6: Maximum tensile strengths of adhesive specimens after temperature conditioning.

As a representative of thermosetting resins, the 2K-epoxy does not exibit its characteristic thermal states, like glassy and rubber state. Instead, the mechanical characteristics change continuously until decomposition temperature. The mean tensile strength at reference temperature $\sigma_{ref,EP} = (8.3 \pm 1.2)$ N/mm² decreases to $\Delta X_{mean} = 0.8$ at -20 °C and is stable at +80 °C. At high temperature, the epoxy maintains considerably larger strength than the polyurethane, silicone and hybrid adhesive because of its crosslinking between molecular chains. The failure mode changes above and below the glass transition temperature of $T_g = 49 \ldots 65$ °C. In the energy-elastic phase under the glass transition occurs 57 % (-20 °C) and 77 % (+35 °C) substrate failure. Whereas, adhesion failure dominates in the entropy-elastic state above glass transition.

The polyurethane features a mean tensile strength of $\sigma_{ref,PU} = (1.7 \pm 0.3)$ N/mm² at reference temperature. Although polymer segment mobility rises with higher temperatures, the polyurethane shows constant properties at +80 °C. In addition, the mean maximum strength rises to $\sigma_{-20,PU} = (3.0 \pm 0.1)$ N/mm² at -20 °C. The glass transition temperature of $T_g \leq -68$ °C is lower than all examined test temperatures. Hence, in the rubber state all adhesive specimens demonstrate an adhesive failure mode with a share of 74 % - 100 %.

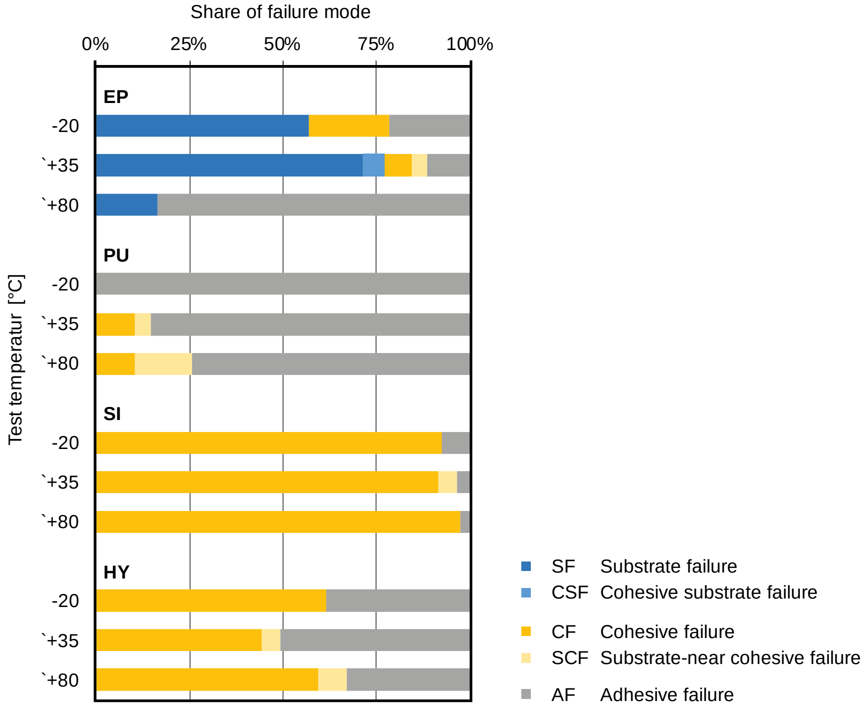

Figure 7: Failure modes of adhesive specimens after temperature conditioning.

In the case of the silicone, the tensile tests approved the polymer's well-known heat resistance. It has a mean maximum tensile strength of $\sigma_{ref,SI} = (0.9 \pm 0.2)$ N/mm². Test temperatures of -20 °C and +80 °C influence the tensile strength by ± 20 % only due to their inorganic backbone and high SI-O-bond energy. Similar to the examined polyurethane, the glass transition temperature ranges below the test temperatures. Hence, all tests result in almost identical adhesive failure of at least 92 %.

The hybrid adhesive displays temperature dependent properties. As the testing temperature increases, the tensile strength decreases continuously. At -20 °C the adhesive has a tensile strength of $\sigma_{-20,HY} = (2.4 \pm 0.1)$ N/mm², at +35 °C the strength decreases to $\sigma_{ref,HY} = (1.2 \pm 0.1)$ N/mm² and eventually drops to $\sigma_{+80,HY} = (1.1 \pm 0.2)$ N/mm² at +80 °C. The low glass transition temperature ($T_g \leq$ -66 °C) ranges below the temperature application limits. All specimens fail partly cohesively and partly adhesively. It can be assumed, that the inner strength of adhesive is approximately equal to the adhesion force to glass.

The complete test set features only single or no statistical outliers. The coefficient of variation, which is defined as ratio of the standard deviation to the mean value, is below 0,3 for EP and below 0,2 for PU, SI and HY. All adhesives meet the requirements of $\Delta X_{mean} \geq 0{,}75$ and can therefore be regarded as excellent temperature resistant between the upper and lower temperature application limits. Furthermore, all adhesives achieve $R_{u,5} \geq 0{,}5$ N/mm².

5.2. Effect of aging medium on the tensile strength

Figure 8 and Table 2 provide an overview of the tensile strength depending on the effect of aging medium. The bar chart compares the data set of the reference series (yellow) to the data set after the storage in water (blue), acid solution pH = 5 (orange), base solution pH = 12 (green) and hydrogen peroxide solution (gray). Similar to the previous evaluation, Table 2 summarizes the absolute mean tensile strength values and Figure 9 visualizes the failure modes as substrate failure (blue), cohesive failure (yellow) and adhesive failure (gray).

Table 2: Tensile strength after storing in different chemical aging mediums.

		EP				**PU**				**SI**				**HY**			
Aging medium		H_2O	pH5	pH12	H_2O_2	H_2O	pH5	pH12	H_2O_2	H_2O	pH5	pH12	H_2O_2	H_2O	pH5	pH12	H_2O_2
Mean tensile strength	[N/mm²]	5.3	6.1	5.4	3.2	1.9	1.8	1.7	0.7	0.7	0.7	0.8	0.7	0.6	0.6	0.6	0.8
Standard deviation	[N/mm²]	1.9	2.0	1.4	0.6	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1
Coefficient of variation	[-]	0.4	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.0	0.2	0.1	0.1	0.1
$R_{u,5}$	[N/mm²]																
ΔX_{mean}	[-]	0.6	0.7	0.6	0.4	1.1	1.0	1.0	0.4	0.8	0.8	0.9	0.9	0.5	0.5	0.5	0.6

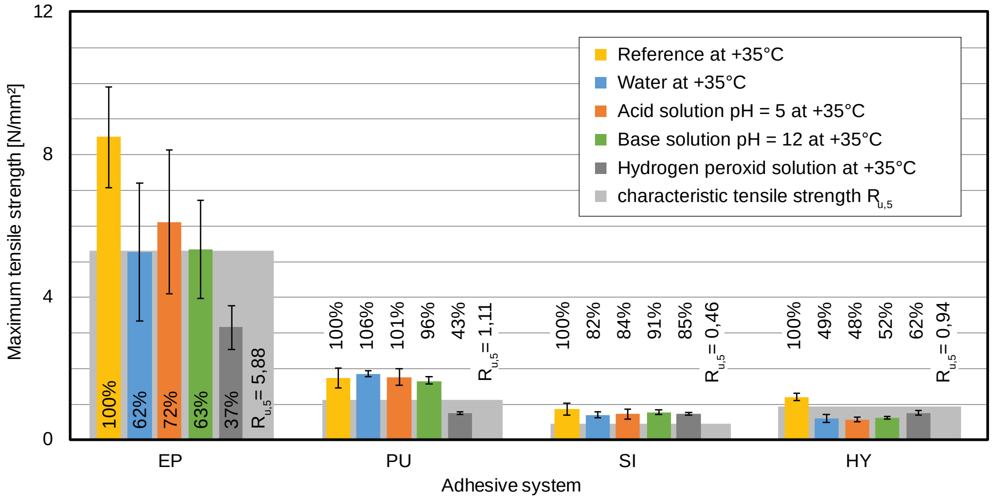

Figure 8: Mean and characteristic maximum tensile strength of adhesive specimens after chemical aging.

First of all, the epoxy performs good after storing in water, acid and base solution with $0.62 \leq \Delta X_{mean} \leq 0.72$. As the epoxy's resistance decreases due to aqueous solutions, the adhesive failure increases and reduces the tensile strength. Whereas substrate failure dominates the reference set, the epoxy fails adhesively with a share of 62 % to 76 % after aging. Furthermore, the epoxy is particularly sensitive to hydrogen peroxide solution. The mean tensile strength drops down to $\sigma_{H2O2,EP} = (3.2 \pm 0.2)$ N/mm² and the adhesive failure share is 85 %. The reported change of the mechanical properties is caused by hydrothermal aging.

Similar to the epoxy, the mean tensile strength of the polyurethane decreases clearly due to hydrogen peroxide exposure. The hydrolysis in the presence of hydrogen peroxide weakens the interface strength to a merely fair resistance of $\Delta X_{mean} = 0.43$. In contrast, polyurethane performed excellent after the treatment with water, acid and alkaline aging mediums $0.96 \leq \Delta X_{mean} \leq 1.06$. In general, the strength of the joint mainly depends on the adhesion between glass and polymer. During the reference test series the polyurethane already fails adhesively with a share of 85 %. The aging changes this rate for all specimens to 100 % adhesive failure.

The silicone performs excellent during all aging scenarios with $0.82 \leq \Delta X_{mean} \leq 0.91$ and a cohesive failure ratio ≥97 %. Even the hydrogen peroxide aging does not affect the mechanical properties significantly during testing duration. The silicone test results meet the requirements of DIN EN 15434 concerning the 10 % adhesive failure criterion and the durability criterion of $\Delta X_{mean} \geq 0.75$.

In contrast to the excellently performing silicone, the hybrid adhesive achieves only a fair to good resistance rate. After aging with acid solution (pH = 12) the tensile strength drops down to 48 % compared to the reference. During the reference set the specimens fail partly cohesively and partly adhesively. After aging, the visual inspection indicates adhesive failure only and points out the hybrid sensitivity towards all aging mediums. The epoxy and the polyurethane display potential effects of water molecules diffusing into the polymer matrix and the interface. The effect of storing in water differs barely from acid and base treatment. The difference in strength between the respective scenarios reaches 10 % at most. It is assumed, that the addition of high (pH = 12) and low (pH = 5) pH-solutions influences the mechanical properties of the examined adhesives and their interface quality between adhesive and glass only marginally. On the other hand, hydrogen peroxide proved to be a major hazard for the joint durability. The epoxy and the polyurethane are very prone to this specific cleaning agent featuring a loss of strength with a ratio of $\Delta X_{mean} = 0.37$ and $\Delta X_{mean} = 0.43$ according to the reference, although the polymers show good or even excellent resistances to the other aging mediums.

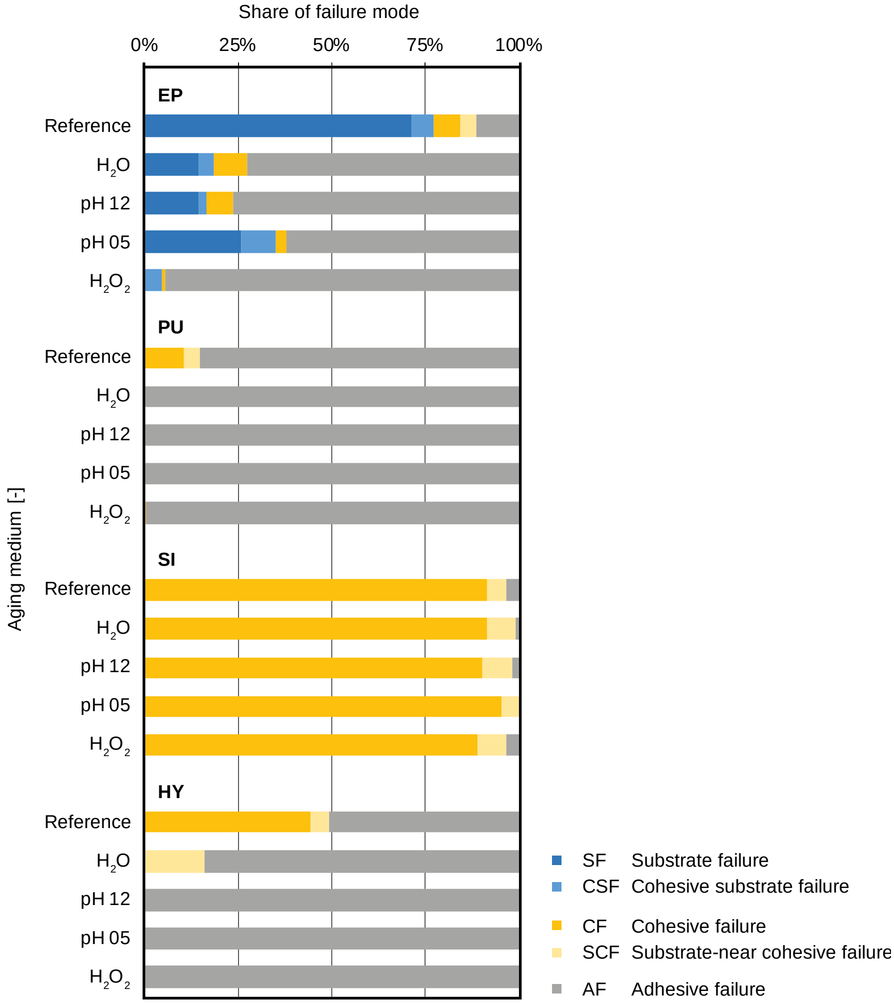

Figure 9: Failure modes after chemical aging.

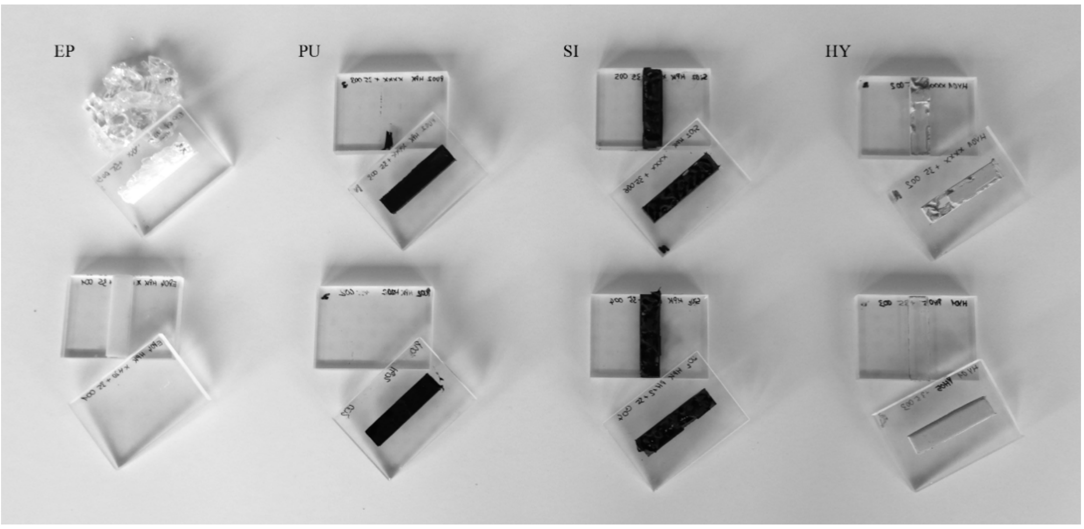

Figure 10: Exemplary failure modes of specimens of the reference series (above) and specimens after chemical aging (below).

6. Conclusion

Table 3 summarizes the tensile test results. It gives the mean and characteristic tensile strength and classifies the adhesive resistance to temperature and aging treatment. Furthermore, the criteria according to DIN EN 15434 are rated (rating see caption). The unaged epoxy has a maximum tensile strength of $\sigma_{ref,EP} = (8.3 \pm 1.2)$ N/mm². Whereas specimens with polyurethane $\sigma_{ref,PU} = (1.7 \pm 0,3)$ N/mm², silicone $\sigma_{ref,SI} = (0.9 \pm 0.2)$ N/mm² and hybride $\sigma_{ref,HY} = (1.2 \pm 0.1)$N/mm² achieve considerably lower values.

All adhesive products show excellent resistance to different test temperature $\Delta X_{mean,Temp} \geq 0.75$. In contrast, the aging scenarios affect the measured tensile strength significantly. EP performed good after aging, except for hydrogen peroxide exposure. The cleaning medium caused adhesive failure in 95 % of the specimens and reduced the maximum tensile strength to $0.63\,\sigma_{ref}$. Likewise, the polyurethane showed a decrease of the mean tensile strength due to hydrogen peroxide exposure. In contrast, PU performed excellent after an exposure to water, acid and alkaline aging scenarios with $0.96\,\sigma_{ref}$. Silicone proved to have an excellent aging behaviour. The silicone only shows slight deviation in maximum tensile strength due to water impact $\Delta X_{mean,SI} \geq 0.82$. The maximum tensile strength of the hybride adhesive decreases down to $0.5\,\sigma_{ref}$ due to aging.

Table 3: Rating of structural adhesives for an application as load-bearing adhesives considering hydrothermal aging.

		EP	PU	SI	HY
Mean tensile strength	[N/mm²]	8,3	1,7	0,9	1,2
$R_{u,5}$	[N/mm²]	5,9	1,1	0,5	0,9
Resistance of maximum tensile strength after conditioning at…					
-20	[°C]	++	++	++	++
+80	[°C]	++	++	++	++
Resistance of maximum tensile strength after aging with…					
Water		+	++	++	o
Acid solution pH = 5		+	++	++	o
Base solution pH = 12		+	++	++	+
Hydrogen peroxide solution		o	o	++	+
10% Adhesion criterion		-	-	+	-
$\Delta X_{mean} \geq 0.75$ criterion		-	-	+	-

Rating resistance			Rating criterion
++	excellent	$0.75 \leq \Delta X_{mean}$	+ Criterion fulfilled
+	good	$0.50 \leq \Delta X_{mean} < 0.75$	- Criterion not fulfilled
o	fair	$0.25 \leq \Delta X_{mean} < 0.50$	
-	poor	$\Delta X_{mean} < 0.25$	

Regarding the investigated thermal and aging properties, silicone performed excellent without exception. Finally, only the silicone meets the requirements of DIN EN 15434 regarding a maximum of 10 % adhesive failure in combination with a minimum decrease after aging of $\Delta X_{mean} \geq 0.75$. Polyurethane also performed excellent but is prone to hydrogen peroxide. The adhesives on epoxy and hybrid basis showed good or fair resistance. Despite the smaller resistance of the epoxy against chemical attack, the absolute tensile strength is still higher than those of the other adhesives. Hence, the epoxy as a high strength adhesive and SI as a high-resistance adhesive will be considered in FE-modelling and tests true to scale.

The outcome proves evident effects on adhesives properties after an aging period of 21 days. Hydrogen peroxide and water proved to be a serious aging agent for the joint strength. The effect of storing in water differs barely from acid and base treatment. Consequently, the aging scenarios for further tests like creep and cycling load could be reduced.

7. Summary

The authors presented load-bearing adhesives in permanent water exposure using the specific example of a bioenergy facade with photobioreactor modules. Critical loads on the adhesive joint were distinguished: Hydrostatic loads occur due to a water column of 3.00 m, periodically injected pressurized air produces dynamic loads and the bio-processing in the building skin causes physical and chemical loads. Mechanical, physical and chemical loads set the base for a test program that evaluates the effect of the test temperature of -20 °C, +35 °C and +80 °C as well as the impact of water, acid, base and hydrogen peroxide solution on the tensile strength. Two adhesives were selected for further evaluaton: First the silicone, because it meets the requirements of 90% cohesive failure and the requirement of limited loss of strength after aging $\Delta X_{mean} \geq 0.75$ according to the criteria of the DIN EN 15434 only. Second the epoxy, because it still exhibits high tensile strength although it is prone to chemical attack. Future creep and cycling load tests in combination with tests true to scale will complete the testing series.

Acknowledgements

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References

Aßmus, E., Weller, B., Haskell, J., Sengewald, T.: Intelligent Future Building Skins – Studies on a Flat Plate Photobioreactor Prototype. Congress Report Vancouver – Engineering the Future. pp. 1138-1144. IABSE Zürich (2017)

Bley, Th.: Biotechnologische Energieumwandlung: Gegenwärtige Situation, Chancen und künftiger Forschungsbedarf. Springer-Verlag, Berlin, Heidelberg (2009).

Kaltschmitt, M., Hartmann, H., Hofbauer, H.: Energie aus Biomasse: Grundlagen, Techniken und Verfahren. Springer-Verlag, Berlin, Heidelberg (2016).

Kerner M. Anforderungen an den Photobioreaktor. Unpublished (2015)

Popp, C.: Lastabtragende Klebeverbindungen in Photobioreaktoren – Beanspruchungsanalyse und Klebstoffuntersuchungen. Structural requirements and analysis of load-bearing adhesives in photobiogenerator module. DIplomarbeit. Technische Universität Dresden (2017)

SSC Strategic Science Consult GmbH, Bioreaktor und Verfahren zum Betrieb eines Bioreaktors. Inventor: Kerner M., filed Mar 08, 2009. European Patent Nr. EP 2 228 432 A1. Issued Sep. 15, 2010.

Wurm, J., Pauli, M., Kerner, M., Hindersin, S., Krümmel, S., Breckner, I., Frechen, M., Sengewald, T.: Hinterlüftete Fassadenkonstruktion aus Photobioreaktoren. Abschlussbericht Forschungsprojekt. Fraunhofer IRB: Stuttgart (2013)

Weller, B., Aßmus, E., and Kerner, M.: Adhesive Joints in Photobiogenerators - Preliminary Studies on Adhesive Materials. Engineered Transparency 2016 – Glass in Architecture and Structural Engineering. pp. 119-128. (2016)

Wurm, J.: Die bio-adaptive Fassade, The bio-responsive facade. In: Detail Green. Vol. 1, 2013, pp 62-65.

DIN EN 13022-1:2014-08: Glass in building – Structural sealant glazing – Part 1: Glass products for structural sealant glazing systems for supported and unsupported monolithic and multiple glazing. German version. Deutsche Norm. Beuth Verlag, Berlin (2014)

DIN EN 15434:2006+A1:2010: Glass in building – Product standard for structural and/or ultra-violet resistant sealant (for use with structural sealant glazing and/or insulation glass units with exposed seals). German version. Deutsche Norm. Beuth Verlag. Berlin (2010)

DIN EN ISO 527-2:2012-06: Plastics – Determination of tensile properties – Part 2: Test conditions for moulding and extrusion plastics. German version. Deutsche Norm. Beuth Verlag, Berlin (2012)

EN ISO 10365:1995: Adhesives – Designation of main failure patterns. German version. Deutsche Norm. Beuth Verlag (1995)

ETAG 002-1: Guideline for European technical approval for structural sealant glazing systems (SSGS), Part 1: Supported and unsupported systems. European Organisation for Technical Approvals, Brussels (1999)