CIVIL ENGINEERING JOURNAL

Article no. 6

THE CIVIL ENGINEERING JOURNAL 1-2026

BONDING PROCEDURES, ARTIFICIAL AGEING AND THEIR EFFECT ON THE DURABILITY OF GLASS-TO-GLASS ADHESIVE JOINTS

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Received: *30.11.2025*

Received in revised form: *15.03.2026*

Accepted: *23.04.2026*

ABSTRACT

In the context of modern architecture, glass is widely regarded as a fundamental design element, representing a material of increasing interest to architects and engineers. The fundamental challenge in using glass is to design convenient connections. Adhesive joints are more convenient connections compared to mechanical fixings due to ensuring uniform stress distribution. This study focuses on small glass-to-glass specimens: (i) bonding of the specimens, (ii) artificial ageing, and (iii) shear tests. Two different transparent adhesives were tested, 2-component epoxy and UV-cured acrylate.

Proper specimen bonding is essential. Two-component epoxy required careful sealing during curing to prevent leakage. The UV-cured acrylate adhesive needed a careful curing process to avoid bubble formation due to shrinkage of the adhesive. To determine resistance to environmental effects, a combination of DVS 1618 procedure and UV radiation was used for artificial ageing of specimens. Shear tests on the reference set showed excellent results for the acrylate adhesive, which achieved an average shear strength of 10.17 MPa. Problems with adhesion appeared after artificial ageing. Epoxy adhesive achieved an average shear strength of 4.55 MPa in the reference set. Two specimens had problems with adhesion to glass. After ageing, the specimens achieved a higher average shear strength (4.86 MPa) than in the reference set. The aged specimens failed only by glass breakage. Both adhesives showed high potential for use in glass construction joints.

KEYWORDS

Transparent adhesives, Glass, Bonded joints, Artificial ageing, Double-lap shear joint, Epoxy adhesive, Acrylate adhesive

INTRODUCTION

Structural glass has gained significance in contemporary architecture due to the continuous demand for transparency and the aesthetic lightness of structures. Given the limited dimensions of glass panes and transportation of them, it is often necessary to join individual components into larger, load-bearing units. Traditional mechanical joints, such as bolted or clamped connections, have

DOI 10.14311/CEJ.2026.01.0006

a major disadvantage as drilling holes weakens the glass panes and indicate local stress concentrations [1, 2].

Adhesive bonds (or joints) represent a promising alternative to mechanical connections. They enable a more uniform transfer of forces distributed across the entire bonded area, thereby minimizing stress peaks. This feature is critical for brittle glass, which is unable to plastically redistribute stresses [1, 2]. Bonded joints are used in a wide range of applications, including facades made of solid glass blocks (e.g., the Crystal Houses façade, constructed from glass masonry bonded with UV-curing adhesive) [3, 4] or in creating structural glass components where they ensure composite behaviour as fully glazed enclosure in Dresden [5], glass-timber structure [6], tensegrity floor [7] etc.

A critical aspect for the reliable use of adhesives in construction is their long-term durability, as they are exposed to external environmental factors. Factors that can significantly affect the strength, stiffness, and optical properties of adhesives include humidity (or moisture), temperature, and UV radiation. For transparent adhesives, UV radiation, in particular, can lead to unfavourable changes in material properties and discoloration. Therefore, ageing evaluation is critical for lifespan prediction.

This work focuses on the experimental analysis of adhesively bonded small glass-to-glass specimens, which is key to obtaining fundamental information on the mechanical characteristics of the adhesives and the adhesive joint. For bonded joints, shear behaviour is particularly important, as it is critical for transferring loads in composite and façade systems. The shear strength of the joint is highly dependent on the adhesion of the adhesive to the substrate, the cohesion of the adhesive, joint geometry, and the bond line thickness.

The aim of this article is to examine in detail:

1. The bonding process and the preparation of small glass-to-glass specimens with particular attention to the use of two distinct adhesives.
2. The determination of the shear strength of bonded joints.
3. The influence of artificial ageing on the mechanical properties of the adhesives.

Problem of artificial ageing

The long-term service life, or durability, of adhesive joints in constructions, is a critical aspect, as they are exposed to complex and interactive environmental factors such as moisture, temperature, and UV radiation [8, 9]. Any property of the joint can deteriorate, but changes of mechanical properties and failure behaviour are essential from the engineering point of view. Material constants and strength values obtained only from short-term tests are insufficient for the reliable design of bonded constructions [10, 11], which often require a service life of 20 to 25 years [12] (though civil engineering applications may require service lives above 50 years [13]).

To determine the effects of these influences in a relatively short time, methods of artificial (accelerated) ageing are therefore used. These procedures are typically based on guidelines or standards such as ETAG 002 (for structural sealant glazing systems (SSGS)) [14], which describes procedure involving immersion in water. Other relevant standards include EN ISO 9142 [15], which guides the selection of standard atmospheric laboratory conditions for cyclic ageing. Other general tests and standards that are applied include: EN ISO 9227 [16] (often used for salt spray/corrosion tests), EN ISO 4892 [17] (commonly used for radiation exposure), ASTM D904 [18] or ASTM D1828 [19] (Atmospheric exposure). Tests are also often developed based on individual assessment by engineers [11] or developed internally by manufacturers [12].

Test scenarios include exposure to high relative humidity (such as 90 % R.H. or 100 % R.H.), immersion in water, thermal cycling, or exposure to corrosive atmospheres, such as SO_2 (sulphur dioxide atmosphere) [8, 11, 20]. UV radiation is particularly critical for transparent adhesives, where the absorption of high-energy, short-wavelength photons can trigger photochemical ageing processes. This subsequently leads to changes in both mechanical and optical properties. [9, 21]

However, conversion to actual years of natural ageing is very difficult and is not typically declared as a simple coefficient. There is no universal artificial test plan nor a precise method for predicting the lifespan of adhesive joints, because every adhesive-substrate interface is unique [12]. The extrapolation of mechanical properties over a longer period than tested is not obvious [11]. Sometimes, it is even shown that the applied artificial ageing protocols can "completely overstate" the long-term behaviour. [8, 12]

Overall, it is often concluded that accelerated tests tend to overestimate the reduction in joint strength compared to natural ageing [9, 10].

Research objective

The objective of the research was to find an adhesive or adhesives suitable for bonding load-bearing glass structures, especially for the purpose of bonding the glass frame corner, as illustrated in Figure 1. As mentioned above, in order to ensure the successful bonded joint, it is necessary to meet a number of requirements which are described in detail below.

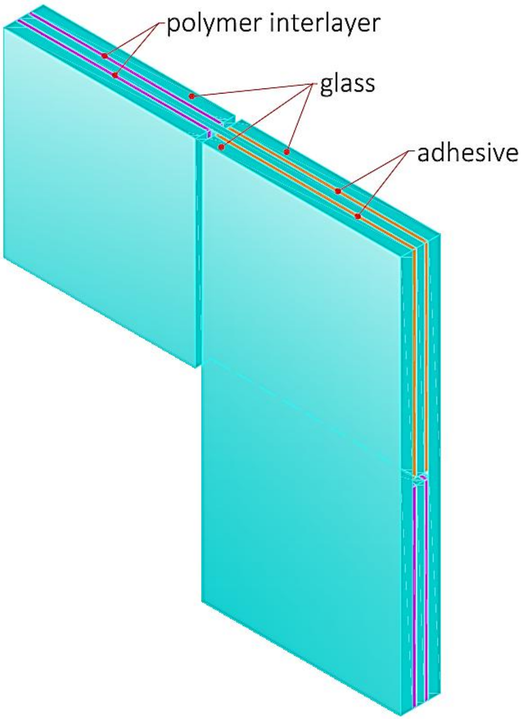

Fig. 1 - Glass frame corner (purple colour - polymer interlayer, orange colour - adhesive)

A fundamental requirement is that adhesives must be transparent. The adhesive is not visible in the glass, and the joint must appear as though it is non-existent, with the glass itself being the only visible component. Critical requirement is that adhesives must demonstrate resistance to the effects of environment. This includes exposure to elevated and low temperatures (ranging from -20 °C to 80 °C), humidity, and UV radiation.

The thickness of the adhesive layer and size of bonded area are other criteria of the selection. The thickness of the adhesive layer depends on the geometry of the glass joint. It has been determined that the double-lap shear joint will be realised. The thickness of the adhesive is thus given by the thickness of the polymer interlayer in laminated glass used in the joined construction, see Figure 1. It is expected that three PVB layers will be used (each 0.38 mm thick), which would result in a bonded layer thickness of approximately 1 mm. Because of the joint geometry, adhesives suitable for bonding medium to large bonded areas (for joints with an area of 10,000 - 90,000 mm²) were selected.

The final requirements relate to the technology for manufacturing the bonded joint. The following parameters are to be considered: the viscosity of the adhesive, and the open time (time from application of the adhesive to its solidifying). The bonded joint is created by the pouring of adhesive into the gap between the glass panes. The application method requires an adhesive with a low viscosity, thereby ensuring its flow into the comparatively narrow space between the glass panes. Furthermore, a sufficiently prolonged open time is required to prevent the adhesive from hardening during its flowing into the gap. An open time at least 20 minutes is suitable.

Adhesives that met the above-mentioned requirements for use in load-bearing glass structures in civil engineering were selected. In the initial phase of the research, the behaviour of the selected adhesives was verified through experimental testing of small specimens. The aim of this article is to present data of two selected rigid adhesives.

MATERIALS AND METHODS

Two rigid adhesives were subjected to experimental testing on two sets of specimens. Firstly, a reference set of specimens was prepared. Subsequently, a second set of specimens was subjected to artificial ageing. Technical parameters of each tested adhesive are stated in Table 1.

Tab. 1 - Technical parameters of adhesives in technical data sheets [22, 23]

Adhesive	Araldite 2020	Loctite AA 3491
Company	Huntsman	Henkel
Technology	Epoxy	Acrylic
Components	2 components	1 component
Curing	Chemical reaction	UV light
Viscosity	Ca 150 mPas	750-1500 mPas
Open time/curing time	40-50 min	seconds
Glass transition temperature	App. 39,5 °C	Not written

For the purpose of the experiment, float glass, characterised by a nominal thickness of 19 mm and dimensions 50 x 50 mm, was used for the bonding of the small specimens. Mechanical properties of the float glass are stated in Table 2. Thick glass panes were cut by water jet. The using of a water jet technique during the manufacturing process of the glass panes ensures that the glass panes does not crack.

Tab. 2: Mechanical properties of float glass [24, 25]

	Soda lime glass
Density	2500 kg/m3
Hardness (Knoop)	6 GPa
Bending strength	45 MPa
Modulus of elasticity	70 000 MPa
Thermal expansion	9·10-6 K-1
Poisson's ratio	0.23

Specimens were prepared as double-lap shear joints, see Figure 2. Each specimen was prepared using 3 glass panes. Middle glass pane was bonded 10 mm above outer glass panes. This geometry ensures possibility of punch test which leads in shear stress in adhesive layers.

DOI 10.14311/CEJ.2026.01.0006

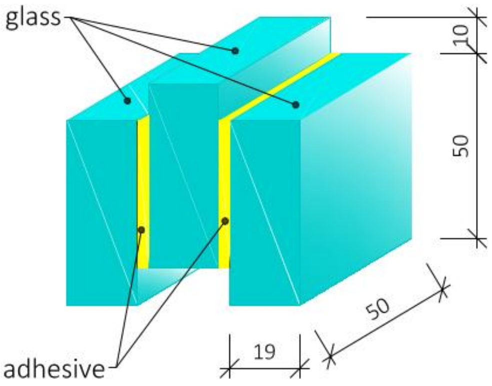

Fig. 2 - Geometry of small specimens

Number of bonded specimens for each adhesive is listed in Table 3.

Tab. 3: Number of bonded specimens

Adhesive	Epoxy adhesive	Acrylate adhesive
Reference set	5	4
Set exposed to artificial ageing	5	3

Bonding specimens

Nitrile gloves were used during both cleaning and bonding to prevent contamination of the bonded surface. Surface of glass panes was cleaned with lint-free wipes soaked in isopropyl alcohol; Figure 3 left. Following the cleaning of the surface, the bonding process was completed within approximately 30 minutes. This duration was sufficient for the isopropyl alcohol to evaporate from the bonded surface. Geometry of specimens was given by plastic device which was made on 3D printer. Gap between glasses was ensured with 1 mm plastic inserts. The assembled specimen was secured with clamps.

In the case of the two-component adhesive, the individual components had to be weighed out and subsequently mixed. The mixture was stirred with a wooden spatula for approximately 1 minute. The process of mixing resulted in the generation of air bubbles within the mixture. In order to remove the bubbles, the mixture was filtered through a nano-mesh sieve, which effectively captured the bubbles.

Whole specimen had to be sealed around bond line. This ensured no adhesive flown out of the specimen. Proper sealing of the specimens was very important due to low viscosity of adhesives. It was especially important for Araldite adhesive, which has longer open time. The adhesive has therefore more time to find any small aperture in sealing. Firstly, it was attempted to seal the specimen with tape only, but this proved insufficient. The adhesive was able to flow out of the specimen through the folds. Due to the thin gap, even a small amount of adhesive leaking out resulted in the gap being filled only halfway, for example. The use of silicone for sealing was not possible due to the possibility of adhesive contamination and thus the invalidation of the results. At last, using plastic material similar to modelling clay proved to be the most suitable method of sealing. Specimen prepared for bonding is shown in Figure 3 right.

Fig. 3 - Cleaning of the glass panes (left), specimen prepared for bonding (right)

Using UV adhesive showed different problems and that was curing. Specimens with UV adhesive were cured using handheld UV-light source. In this case LOCTITE CL32 LED Spot with wavelength 405 nm was used, see Figure 4. During bonding, two problems occurred. Ensuring geometry by clamps showed problem, how to lighten and thereby cure the adhesive. The problem was solved by using tape instead of clamps. Tape was used from sides with small overlap on front and back side of the specimen, see Figure 4. The second problem was shrinkage of adhesive during curing. Curing had to be carried out carefully from bottom part of the specimen. After curing small area on the bottom of the specimen can be cured area above. This specific procedure eliminated bubbles caused by shrinkage in the adhesive layer (Figure 5) and make addition adhesive into the bonding gap possible.

Specimens with two-component adhesive were cured at room temperature for 24 hours. For specimens with UV adhesive, the complete curing of the entire bonded surface was achieved within approximately 10 minutes.

Fig. 4 - Set-up for bonding specimen with UV adhesive - from left: specimen secured by tape, UV protecting glasses, UV adhesive with dispenser gun and application needle, LED spot

DOI 10.14311/CEJ.2026.01.0006

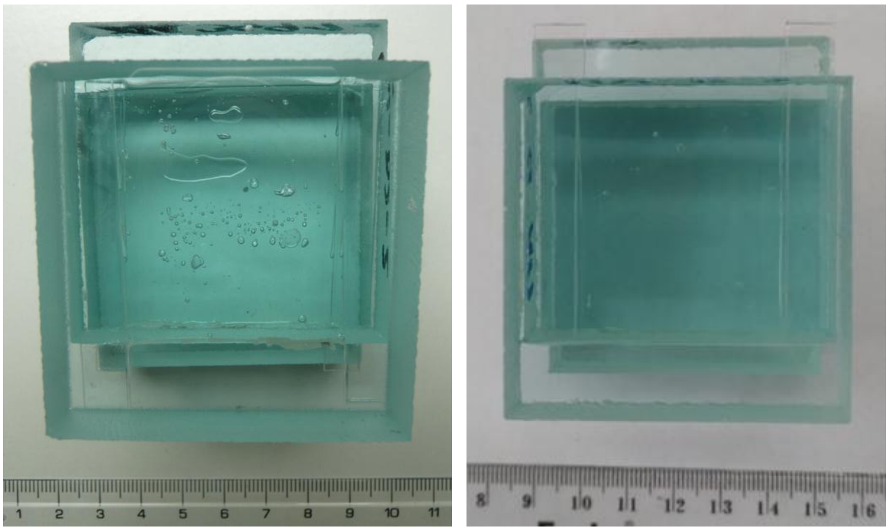

Fig. 5 - Bonded specimen with bubbles caused by shrinkage (left), better bonded specimen with less bubbles (right)

Artificial ageing

It was necessary to select or develop artificial ageing method capable of simulating natural ageing. In this research, technical guideline DVS 1618 [25] and UV radiation was combined. Technical guideline DVS 1618 was designed for elastic thick layer adhesives used in rail vehicle applications. It contains procedure of artificial ageing which is described in Table 4.

DOI 10.14311/CEJ.2026.01.0006

Tab. 4 - Accelerated ageing according to DVS 1618

Part	Processing	Duration
1	Conditioning at temperature 23 °C and 50 % RH	7 days
2	Immersion in distilled water at temperature 20 °C	7 days
	Conditioning at temperature 23 °C and 50 % RH	2 hours
3	Exposure to temperature 80 °C	1 day
4	Conditioning at temperature 23 °C and 50 % RH	2 hours
5	Cataplasm test (exposure to the temperature 70 °C and 100 % RH)	7 days
	Conditioning at temperature 23 °C and 50 % RH	2 hours
Extension	Shock cooling at -30 °C	1 day

This procedure was further extended by 500 h of UV radiation exposure, following Method E3 of the ČSN EN ISO 9142 standard. The whole artificial ageing method lasted app. 6 weeks, see Figure 6.

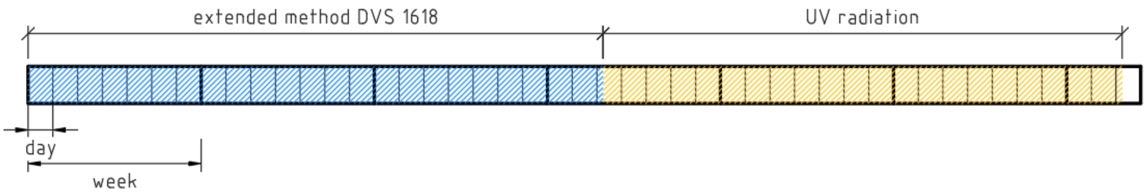

Fig. 6 - Ageing method based on DVS 1618

Combination of these two approaches ensures that the specimens were exposed to all related external effects including elevated and sub-zero temperatures, high humidity, and UV radiation.

Experimental set-up

The specimens were subjected to the punch test. In this experiment, a compressive load was applied on the central glass pane, thereby inducing shear stress in the adhesive. Glass is a brittle material and has never been in direct contact with hard materials such as steel due to stress concentrations. The specimen was equipped with elastic pads on both the inferior and superior surfaces. The elastic pads ensure uniform stress distribution and thereby eliminate stress peaks in the glass; see Figure 7.

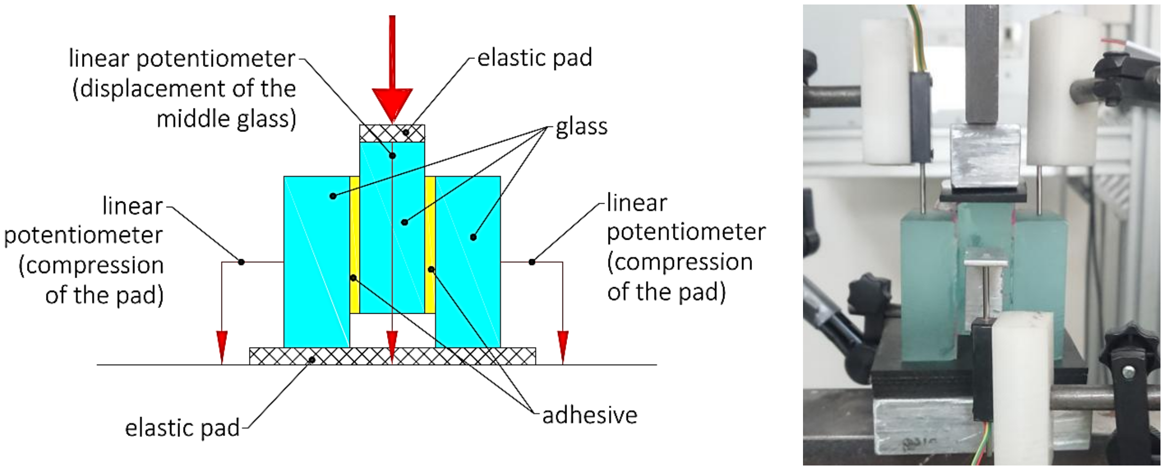

Fig. 7 - Schema of the experiment (left), photo of the experiment (right)

The experiment was conducted under displacement control, with displacement applied continuously until specimen failure. Crosshead speed was 0.05 mm/min. The slow crosshead speed of the test is intended to represent static or quasi-static load. Adhesives are viscoelastic materials, and the duration of the applied load is a critical factor in determining their load-bearing capacity.

The displacement of the glass panes was measured by four linear potentiometers. Two potentiometers measured displacement of the middle glass and two potentiometers measured compression of the glass panes to the pad. Used measurement equipment is written in Table 5.

Tab. 5: Details of the experiment equipment

Test machine	Shimadzu AGS-X
Linear potentiometers	Megatron MMR-1011 (measurement range 11 mm)
Test controlled by	displacement
Crosshead speed	0.05 mm/min
Measurement device	SPIDER 8, software CATMAN32
Sampling frequency	5 Hz

RESULTS

Reference set

The reference set of specimens demonstrated significant variations in shear strength among the adhesives. The epoxy adhesive achieved an average shear strength of 4.53 MPa (44.8 % of acrylic shear strength); see Table 6. A significant difference in shear strength is evident with epoxy adhesive, as illustrated in Figure 8. One specimen achieved a shear strength of less than 2 MPa. This specimen failed as a result of loss of adhesion; see Figure 9. In one specimen, failure occurred in a combined failure mode with dominant substrate failure; however, loss of adhesion was a contributing factor to the overall failure. This specimen also exhibited reduced shear strength. Other specimens failed due to glass breakage (Figure 10), and their shear strength was found to be similar at approximately 5.7 MPa.

Tab. 6 - Reference set

Adhesive	Average shear strength τ [MPa]	Standard deviation [MPa]	Dominant failure mode	τi/τi,max [%]
Epoxy	4.55	1.80	S*	44.8 %
Acrylate	10.17	0.52	S*	100.0 %

S* - substrate failure mode

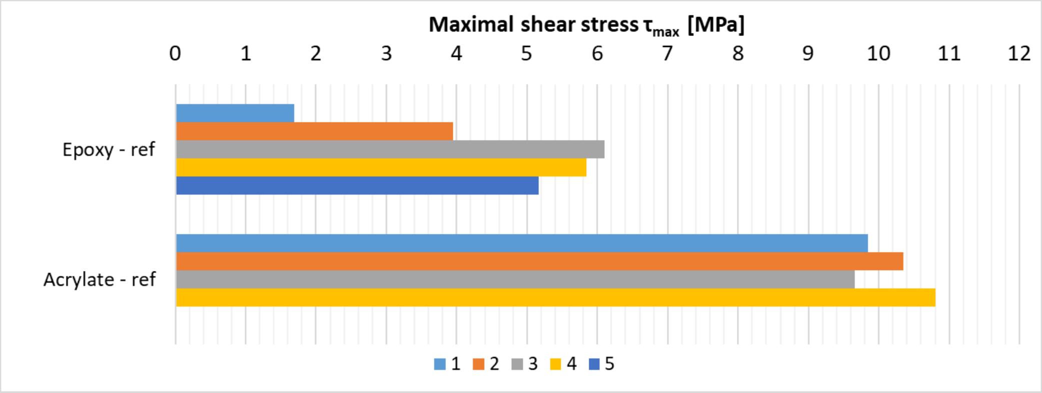

Fig. 8 - Shear strength of individual specimens in the reference set

The shear strength τ was calculated using Equation 1.

$$\tau = \frac{F}{A}, \tag{1}$$

where F is the force at breakage [N], and A is the bonded area [mm2] (the measured bonded area of both shear planes, excluding the area of the inserts).

In comparison, the acrylic adhesive achieved an average shear strength of 10.17 MPa. All specimens that were bonded with acrylate adhesive exhibited failure due to glass breakage (Figure 8, Figure 9, Figure 11). The standard deviation of these specimens is low, at only 0.52 MPa (Table 6).

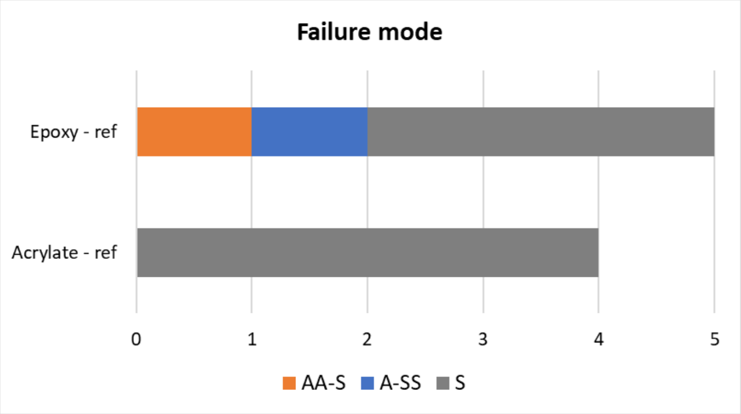

Fig. 9 - Failure mode of specimens in reference set (AA-S - combined failure mode with dominant adhesion failure, A-SS - combined failure mode with dominant substrate failure, S - substrate failure)

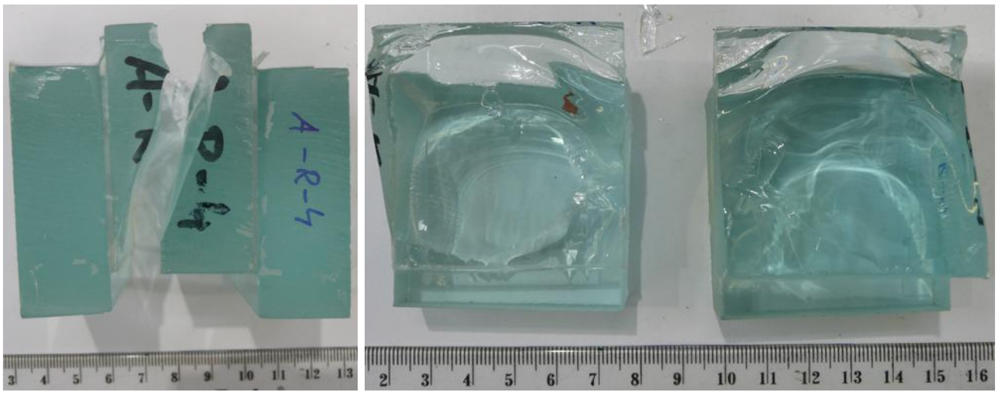

Fig. 10 - Specimen with epoxy adhesive in reference set after shear test - substrate failure

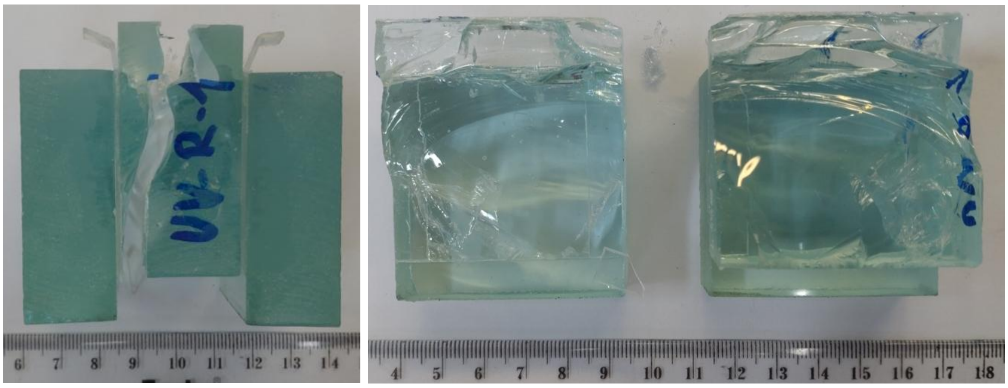

Fig. 11 - Specimen with acrylic adhesive in reference set after shear test - substrate failure

Artificial ageing

The importance of artificial ageing is not only in its role in determining mechanical properties, but also in its ability to influence visual properties. Visual properties cover especially colour changes and cracks or bubbles occurrence.

Specimens before and after artificial ageing are shown in Figure 12 and Figure 13. Both adhesives achieved excellent visual properties. Adhesives stayed transparent and no additional cracks or bubbles appeared. Delamination proved to be problematic, as is shown especially in Figure 13 right. It is important to note that delamination is only visible from a specific angle. Delamination was more visible in specimens with acrylate adhesive, where delamination occurred on approximately 25 – 75 % of the bonded surface. In the case of the epoxy adhesive, delamination was observed on no more than 10 % of the bonded surface.

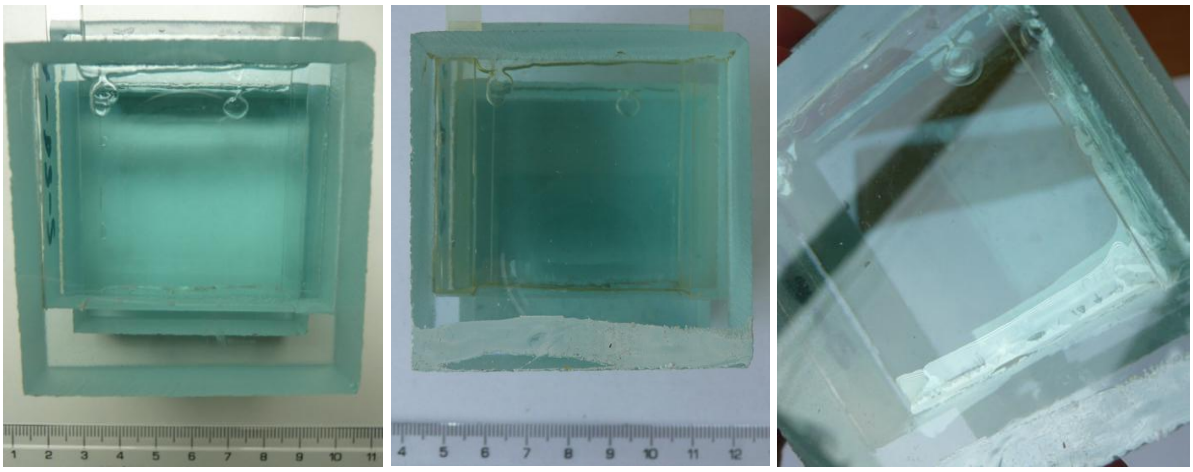

Fig. 12 - Specimen with epoxy adhesive before artificial ageing (left), after artificial ageing (middle), detail of the specimen after artificial ageing (right)

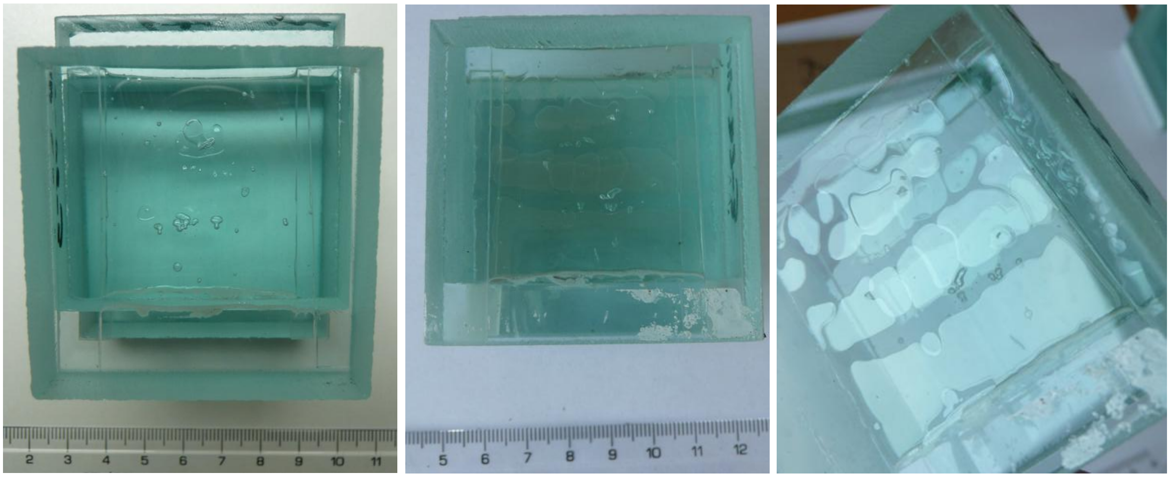

Fig. 13 - Specimen with acrylate adhesive before artificial ageing (left), after artificial ageing (middle), detail of the specimen after artificial ageing (right)

Epoxy adhesive also achieved excellent ageing resistance in terms of mechanical properties. Average shear strength after artificial ageing increased to 106.6 % of average shear strength of the reference set; see Table 7. Specimens failed by rupture of glass. A combined failure mode was observed in only two specimens, characterised by dominant substrate failure; see Figure 14. However, the shear strength of these two specimens was similar as specimens which failed only due to rupture of glass; see Figure 15. The standard deviation for epoxy adhesive after artificial ageing is only 0.40 MPa which is much lower according to the reference set; see Table 7 and Figure 16. Specimen after the shear test failed by rupture of glass is in the Figure 17.

Tab. 7 - Reference set and set of specimens exposed to artificial ageing

Adhesive	Average shear strength τ [MPa]	Standard deviation [MPa]	Dominant failure mode	$\tau_i/\tau_{i,ref}$ [%]
Epoxy - ref	4.55	1.80	S*	100.0 %
Epoxy - DVS	4.86	0.40	S*	106.6 %
Acrylate - ref	10.17	0.52	S*	100.0 %
Acrylate - DVS	5.09	4.94	AA-S*	50.1 %

S* - substrate failure mode, A-SS* - combined failure mode with dominant substrate failure

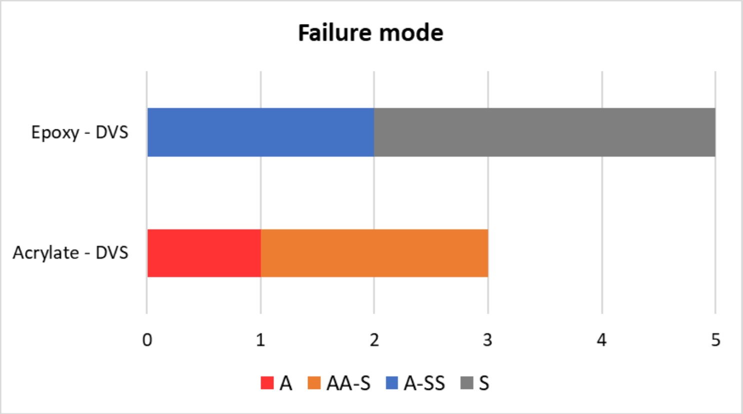

Fig. 14 - Failure mode of specimens in set exposed to artificial ageing (A - adhesion failure, AA-S - combined failure mode with dominant adhesion failure, A-SS - combined failure mode with dominant substrate failure, S - substrate failure)

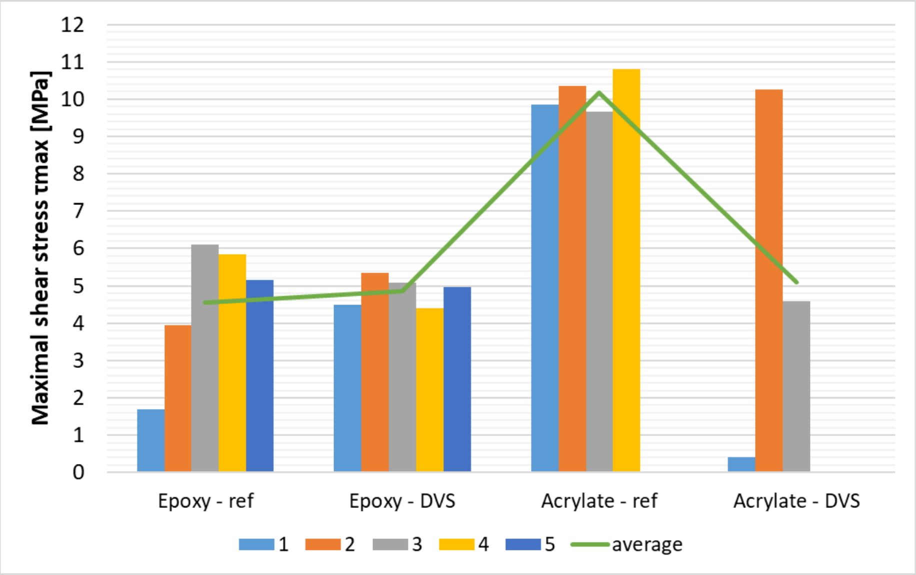

Fig. 15 - Shear strength of individual specimens in the reference set and set exposed to artificial ageing

Specimens with acrylate adhesive showed very different results; see Figure 15 and Table 7. One specimen achieved extremely high shear strength, more than 10 MPa which is similar to shear strength in reference set. One specimen showed extremely low shear strength, less than 0.5 MPa. This specimen failed due to loss of adhesion; see Figure 14. And the third specimen failed at shear stress 4.6 MPa which is app. average of shear strength of specimens in the set exposed to artificial ageing. High differences in shear strength with acrylate adhesive are also evident in Figure 16.

Specimens with higher shear strength failed in combined failure mode with dominant adhesion failure; see Figure 14 and Figure 18.

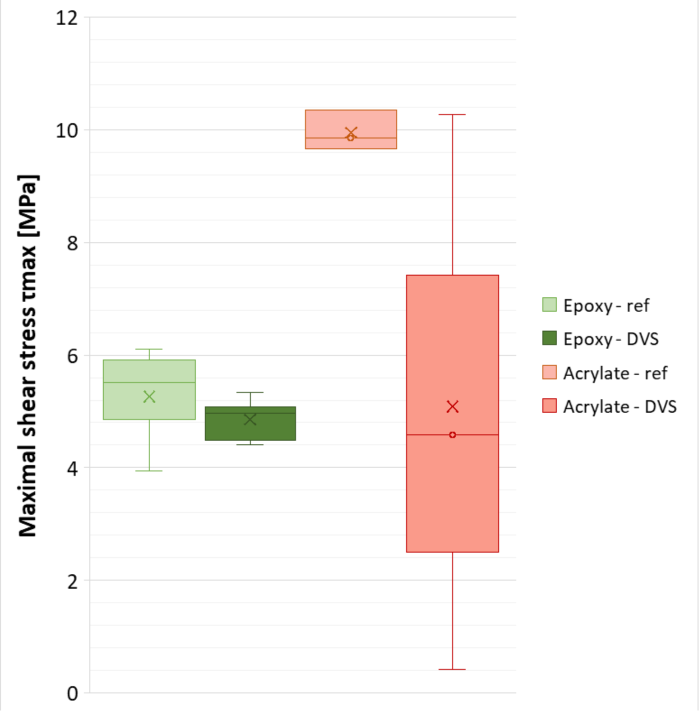

Fig. 16 - Shear strength of individual specimens in the reference set and set exposed to artificial ageing

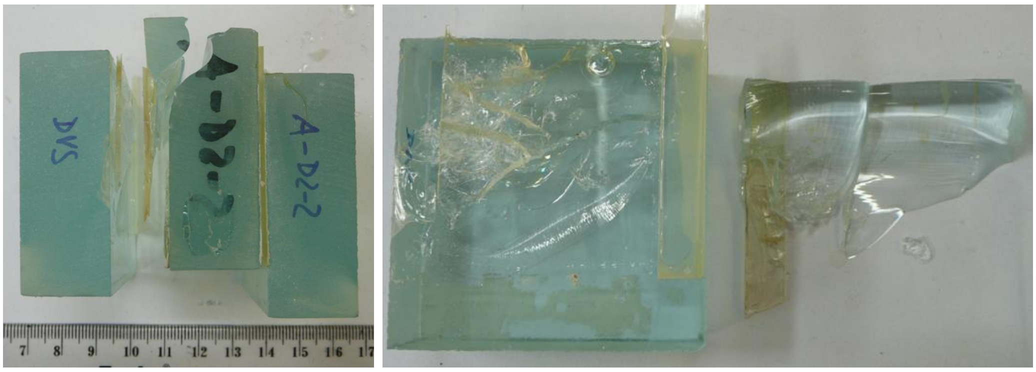

Fig. 17 - Specimen with epoxy adhesive exposed to artificial ageing after shear test - substrate failure

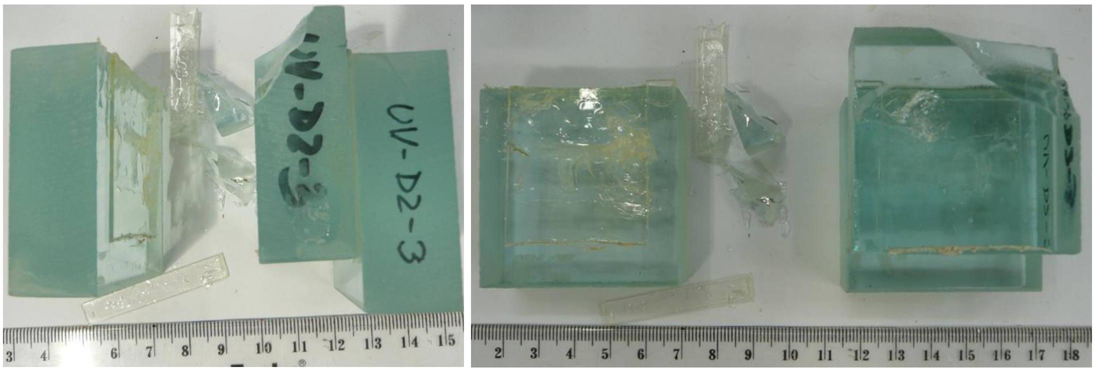

Fig. 18 - Specimen with acrylate adhesive exposed to artificial ageing after shear test - combined failure mode with dominant adhesion failure

During the testing, the deformation and subsequent displacement of the centre glass were measured. Average displacement of the center glass was calculated using Equation 2.

$$\overline{u_c} = \overline{u_t} - \overline{u_z} \,, \tag{2}$$

where $\overline{u_c}$ is average displacement of the central glass pane [mm], $\overline{u_t}$ is average displacement of the specimen [mm], and $\overline{u_z}$ is average compression of the pad [mm].

Subsequently, the shear strain was determined from Equation 3.

$$\gamma = \frac{\overline{u_c}}{\overline{t}} \,, \tag{3}$$

where γ is shear strain [-], and $\overline{t}$ is the average thickness of the adhesive layer [mm].

It was not possible to compile a relevant stress-strain diagram for epoxy adhesive due to the very low deformation and the influence of the elastic pads. The stress-strain diagram for acrylic adhesive is illustrated in Figure 19. In this instance, the curve exhibits a wavy pattern; however, the trend is evident in the graph. The shear modulus of the aged specimens was found to be lower than that of the specimens in the reference set.

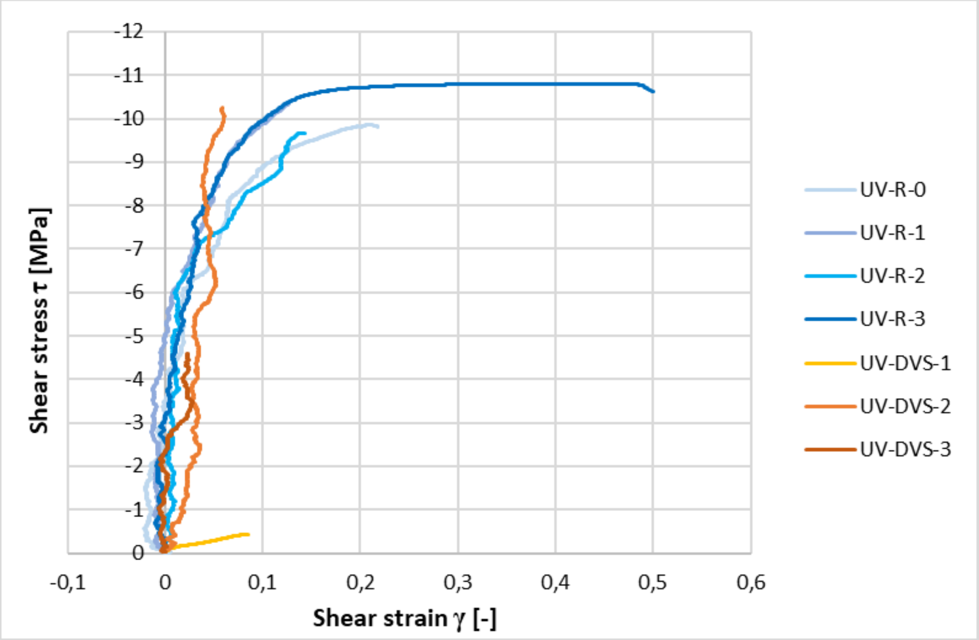

Fig. 19 - Stress-strain diagram of UV acrylate adhesive

Table 8 summarizes the experimental observations and key performance parameters for both adhesives. It highlights the differences in workability, visual appearance after ageing, resulting shear strength, and observed failure modes across the tested specimens.

Tab. 8 - Experimental observations and comparative assessment of adhesives

Adhesive	Epoxy	Acrylate
Bonding challenges	Proper sealing of the specimens due to low viscosity of the adhesive	Lighting/curing of the bonding area, shrinkage of the adhesive
Average shear strength (reference set)	4.55 MPa	10.17 MPa
Typical failure mode (reference set)	Substrate failure	Substrate failure
Ageing trend	Stability over time	Highly variable ageing resistance
Visual stability	Excellent	Stable colour, frequent delamination
Average shear strength (artificial ageing)	4.86 MPa	5.09 MPa
Typical failure mode (artificial ageing)	Substrate failure	Combined adhesive-substrate failure with dominant adhesive failure

DISCUSSION

Similar geometry, and mechanical test was performed in different researches [26, 27]. The punch test is convenient due to low tensile strength of glass. Substrate failure is not an appropriate mode of failure during the testing of bonded specimens. The substrate failure mode does not reveal the actual strength of the adhesive itself; rather, it provides an indication of the strength of the substrate. The testing of glass specimens is an issue that is complicated by the material's inherent brittleness and its sensitivity to stress peaks. In the majority of cases, the glass failed; thus, the ultimate strength of the adhesive could not be fully determined, but the results established the minimum stress level the bond can withstand without failure.

Specimens with epoxy adhesive

In the reference set, the epoxy adhesive showed a high standard deviation. This was caused by the low shear strength of specimens that failed due to loss of adhesion. The weaker was the adhesion, the lower was the resulting shear strength. However, this premature loss of adhesion occurred in only two out of five specimens. Therefore, it cannot be generally concluded that the Araldite adhesive has insufficient adhesion to glass. Nevertheless, there are studies indicating that epoxies may have issues with adhesion to glass [28]. For a more reliable assessment, higher number of shear tests should be performed.

Specimens with epoxy adhesive after artificial ageing failed due to breakage of glass or in combined failure mode but with dominant substrate failure. According to the literature [8, 9], artificial ageing, especially effect of water, may lead to a loss of adhesion. Thus, another possible reason for the insufficient adhesion to glass may be related to limited experience with the bonding process. This interpretation is supported by the fact that the specimens bonded in the reference set belonged to the first specimens prepared, where insufficient adhesion was also most pronounced.

Epoxy adhesive after artificial ageing achieved higher average shear strength compered to reference set (106.6 %). But, reduction of shear strength was expected. If specimens with lower adhesion are removed from the reference set, then there was a slight decrease in strength after laboratory ageing. However, there are studies where shear strength increased after laboratory ageing [12, 13]. The authors attributed this to the post-cure process or to water adsorption due to high temperatures during ageing, i.e., partial restoration of properties (recovery).

Specimens with acrylate adhesive

Acrylate adhesive achieved excellent results in the reference set accompanied by a low standard deviation. The low standard deviation may be related to the good quality of bonding, characterized by a minimal presence of air bubbles. During bonding, adhesive shrinkage was observed, which is a common issue associated with UV-cured adhesives [5, 11]. In this study, an adhesive with very low shrinkage was selected. Owing to the relatively thick bond line (1 mm), compared to the more commonly used thinner joints of only a few tenths of a millimetres, the effect of shrinkage was more pronounced. Nevertheless, the specimens were bonded with only a minimal occurrence of bubbles and cracks.

The laboratory ageing results proved to be more problematic than expected. Only three specimens were tested, and each specimen exhibited different behaviour, which significantly complicates the evaluation. The observed failure modes included loss of adhesion or a combined failure mode with dominant adhesion loss. Compared to the epoxy adhesive, specimens with the acrylate adhesive for laboratory ageing were bonded first. This bonding and curing approach differs substantially from that of two-component epoxy adhesives and may require a certain level of experience and skill. The durability of the joint may therefore have been influenced by the quality of the bonding process; however, further tests would be required to verify this assumption. The present results are consistent with observations reported in the literature, indicating that adhesion may be weakened during ageing, particularly under water exposure [8, 9, 29]. It should also be noted that one specimen after artificial ageing achieved approximately the same shear strength as the specimens in the reference set. Given that only three specimens were subjected to laboratory ageing and their results exhibited considerable variability, any conclusions drawn from these tests must be interpreted with caution.

CONCLUSION

This paper focused on all process of experimental testing bonded specimens - bonding of the specimens, artificial ageing and shear test.

Although scientific articles typically do not provide a detailed description of the bonding process, the present study has shown that the quality and consistency of specimen bonding play a critical role in the reliability of the obtained results. Consequently, the present work has highlighted specific challenges encountered during bonding with both two-component epoxy and UV-cured acrylate adhesives. In particular, adequate sealing of the bond line proved to be necessary to prevent leakage of the highly fluid adhesive prior to curing, a requirement typical for low-viscosity adhesive systems. The acrylate adhesive required careful bottom-up curing to prevent the formation of bubbles and to maintain the integrity of the bonded layer, taking into account adhesive shrinkage during the curing process.

The selection of an appropriate ageing method represents a major challenge. In this study, laboratory ageing according to DVS 1618 was applied, followed by additional UV radiation exposure, in order to simulate a range of external environmental influences relevant to real construction applications. The selected laboratory ageing procedure is considered to have a significant degrading effect on the specimens. The epoxy adhesive demonstrated a high resistance to the applied laboratory ageing procedure. The average shear strength obtained after laboratory ageing was slightly higher than that of the reference set (106.6 %). However, this result may have been influenced by the presence of low adhesion in two specimens in the reference set.

In contrast, specimens bonded with the acrylate adhesive exhibited, on average, significantly lower shear strength after ageing compared to the reference set, which was primarily associated with complete or partial loss of adhesion. While only three acrylate specimens were subjected to laboratory ageing, their behaviour varied considerably, reflecting varying extents of adhesion loss and delamination. These adhesion-related defects were subsequently manifested in the shear test results.

After the ageing process, both adhesives demonstrated excellent visual stability, with no signs of yellowing. Nevertheless, several specimens exhibited indications of delamination. This loss of adhesion was subsequently reflected in the results of shear tests. Further investigation would be necessary to confirm assumptions regarding adhesion failure in relation to bonding quality. Despite these limitations, both adhesives demonstrate a high potential for application in structural glass assemblies.

ACKNOWLEDGEMENTS

This work was supported by the Czech Science Foundation, grant number GA22-14105S and Student Grant Competition of Czech Technical University, grant number SGS18/169/OHK1/3T/11.

I would also like to express my gratitude to the technician Tomáš Vorlíček from Henkel, who assisted in selecting the adhesive and provided me with comprehensive instruction on its application.

Gen AI:

For language improvement and editing support, DeepL and DeepL Write was used. NotebookLM was used for reformulation and assistance with citations in the Introduction section. Additionally, Consensus was utilized for literature search and citation assistance.

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