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Epoxy Resin Adhesives: Report on Shear Strength Retention on Glass Substrates

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Ten room-temperature-cure epoxy resin adhesives of different chemical compositions were tested for retention of shear strength after aging in the dark at 22°C (45% relative humidity (RH)) and at 75°C (dry oven, ~2-4% RH), and under high-intensity light. The tests were carried out on glass substrates. Those epoxy formulations containing a diglycidyl ether of bisphenol A resin component and a hardener composed of a modified amine showed the highest initial shear strengths of all the products tested. Although two formulations were identified as being more resistant to loss of mechanical strength upon aging than others tested, no formulation was found to lose excessive strength under the exposure conditions employed. Loss of mechanical strength upon aging should not be a major concern when using epoxy resin adhesives on glass substrates in most conservation applications.

L'évolution de la résistance au cisaillement de dix adhésifs à base de résines époxy durcissant à la température de la pièce a été étudiée. Ces adhésifs ont été soumis à un vieillissement à l'obscurité à 22 °C (45 % d'humidité relative (HR)) et à 75 °C (étuve, ~2 à 4 % HR), et sous éclairage à haute intensité. Les essais ont été effectués sur des substrats de verre. Les formulations d'époxy qui contenaient une résine à base d'éther diglycidylique de bisphénol A et un durcisseur à base d'une amine modifiée possédaient, au départ, la meilleure résistance au cisaillement. Bien que deux formulations aient été identifiées comme résistant mieux à la perte de résistance mécanique suite au vieillissement que les autres formulations testées, on a constaté qu'aucune formulation ne perdait de résistance de façon excessive dans les conditions utilisées. On ne devrait donc pas se préoccuper outre mesure de la perte de résistance mécanique causée par le vieillissement lorsque l'on utilise des adhésifs à base de résines époxy dans des applications du domaine de la conservation.

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Introduction

Many properties have been identified as being desirable or essential for a good conservation glass adhesive. The adhesive should be clear, colourless, and as close to the same refractive index as that of the glass it is expected to repair, so that the adhesive is as unobtrusive as possible. The adhesive should retain this quality, and should not discolour. The adhesive should not shrink or embrittle upon aging, and should be strong enough to perform the job adequately. The adhesive should not be tacky at room temperature, so that it avoids dust pick-up. It should be generally durable, stable, and unaffected by moisture, but should be removable upon demand. It should not release any harmful volatiles upon aging or curing, be easy to use, be quick setting, have a good shelf-life, and be inexpensive. No adhesive can satisfy all these demands. Selecting a glass adhesive has always been and continues to be a matter of compromise.

In the early years, animal glues, shellac, and cellulose nitrate were used as glass adhesives. More recently, soluble nylon, poly(vinyl acetates), poly(vinyl alcohols), poly(vinyl chlorides), poly(vinyl butyrals), acrylics, cyanoacrylates, UV-curing acrylics, silicones, polyesters, and room-temperature-cure epoxy resins have been used. Each adhesive has its good and bad points. Many of the traditionally used adhesives are highly coloured, shrink, and embrittle with time.[1] Most of the synthetic adhesives, although offering some improvements on these properties, suffer cure shrinkage, have dissimilar refractive indices from that of glass, or are very weak. The room-temperature-cure epoxy resin adhesives afford a good alternative because they possess, in particular, the following desirable properties:

1) They have good refractive index-matching properties, which makes their glue lines essentially invisible.

2) They have low shrinkage on curing, which is beneficial because it alleviates stress on the glass.

3) They are known to be very polar adhesives. This is necessary for glass, and results in strong adhesive bonds.[2] In fact, epoxy resins have probably the strongest adhesion and cohesion of all the adhesives mentioned, traditional or modern.

On the negative side, the following points should be noted:

1) Most epoxy resin adhesives are irreversible. Some, however, have been shown to swell in various solvents, which affords some mechanical removability.[3,4]

2) Many epoxy resin adhesives tend to discolour with time, but some epoxy resins have been identified that have less tendency to yellow than others under natural dark aging at 22°C and under high-intensity light aging.[5,6]

The loss of mechanical strength upon aging of epoxy resin adhesives has been little studied in the conservation field. Strength retention after aging has been investigated by others, but the majority of research studies are concerned with formulations that do not find acceptance in conservation practice, and that are performed on substrates other than glass. For example, the aerospace industry has investigated mechanical failure of epoxy-aluminium and epoxy-steel bonds at elevated temperatures.[7,8] Unfortunately, such studies were carried out on *elevated*-temperature-cure epoxy resin adhesives whose chemical composition differs from *room*-temperature-cure epoxy resin adhesives. Consequently, their findings are not directly relevant to room-temperature-cure epoxy formulations that are used in conservation.

It is generally assumed that epoxy resins have high strength and that most will retain sufficient strength, even after severe aging, to satisfy any conservation requirement. This study sets out to investigate this assumption. This paper reports the results of shear strength tests carried out on selected formulations of room-temperature-cure epoxy resins on glass substrates. This, of course, is a test of adhesive strength between the glass and epoxy resin as opposed to a test of cohesive strength which would involve an adhesive film, not substrates. Shear strength was chosen not only because it was a convenient test, but also because it simulated many of the forces that could be acting on glass joints found in conservation. Tests were carried out before and after thermal dark aging at 75°C (dry oven, ~2-4% relative humidity (RH)), high-intensity light aging, and natural dark aging at 22°C (45% RH).

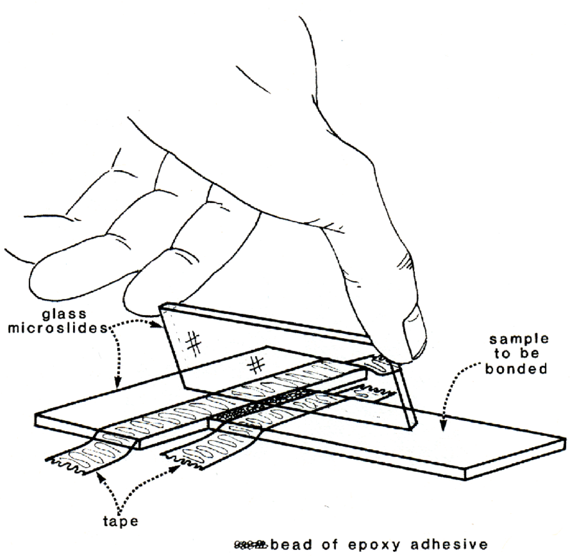

Figure 1. Set up for ensuring an even, reproducible bead of adhesive in bond area.

Experimental

Ten room-temperature-cure epoxy resin adhesives (**Table I**) were selected for this study. At the time of selection in 1981, the adhesives were chosen because they displayed the least tendency to yellow under natural dark aging at 22°C. With the passage of time and the collection of more reliable yellowing data, other formulations have superseded the original adhesives as having the least tendency to yellow.[5,6] Most of the formulations chosen in 1981 for shear strength testing display a moderate tendency to yellow with time rather than a slight tendency as was first thought.

Epoxy resin adhesive components were weighed and mixed according to each manufacturer's recommendations. Glass microslides (75 x 25 x 1 mm) were used as test substrates. All slides were degreased with acetone prior to application of the adhesive. To ensure that an even, reproducible bead of adhesive was applied to the bond area on the microslide, a mould (1 mm wide) was made with tape as shown in **Figure 1**. Adhesive was applied to the microslide by dragging another microslide along the tape mould. When the tape was removed, a bead of adhesive 1 mm wide and of the same thickness as the tape remained. This microslide was bonded to a second microslide using an apparatus (**Figure 2a** and **2b**) designed to ensure that the bond areas would be uniform from sample to sample (25 x 1 mm) and that trapped air bubbles in the adhesive bead would be expelled. The air bubbles were expelled by even pressure from a wooden bar (**Figure 2b**). The wooden bar sat by its own weight (wooden bar weight: ~71 g — could vary by ~2%; dimensions: 25.5 x 3.0 x 1.4 cm) on the top slide over the bond area. Five apparati were employed so that enough samples (60) for a complete test run for one aging condition could be made from one potting mixture of adhesive, thus eliminating potting mixture errors in the comparison. Samples remained in the bonding apparati for 24 hours before they were removed and labelled. Samples were allowed to sit undisturbed in the dark for an additional seven days to ensure a complete cure.

Ten samples (in some cases 11) of each adhesive were then subjected to a shear strength test using an Instron Tensile Strength Tester equipped with a specially designed jig to hold

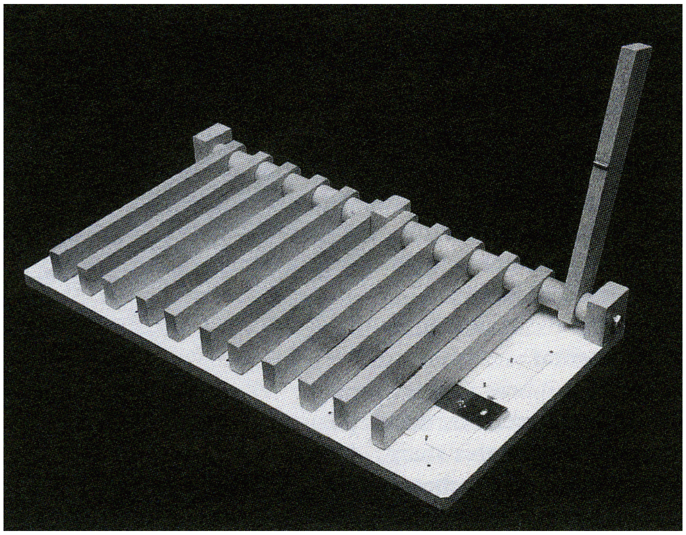

Figure 2a. Apparatus for bonding samples uniformly.

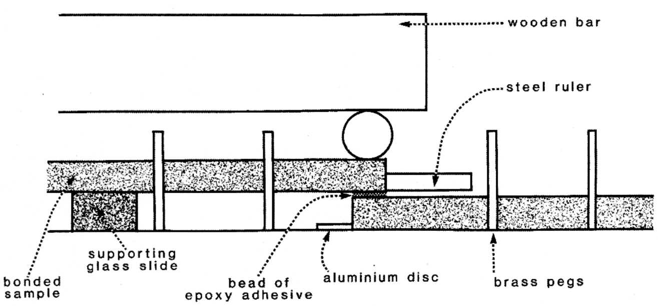

Figure 2b. Cross-sectional view of apparatus for bonding samples. Wooden bar sits by its own weight on top slide over bond area. This helps to expel air bubbles with the same pressure (by weight) on every bond. Brass pegs align slides. Steel ruler holds upper slide in place. Aluminium disc holds lower slide in place.

and break the samples in the compressive mode (**Figure 3**). As already mentioned, samples were broken in shear compression for two reasons — because this simulated many of the forces that could be acting on glass joints, and because of the convenience. In trial tests of butt-joined samples broken in the tensile mode, the glass substrates failed before the glued joints did. Since glass is stronger under compression than in tension, the experiment was designed for the compressive mode. This required that the samples be lap-bonded and shear-stressed rather than butt-joined and tensile-stressed. Employing a compressive shear test eliminated the majority of glass substrate breakage.

The remaining test samples were then subjected either to: i) thermal dark aging at 75°C (dry oven, ~2-4% RH) for 2000 hours; ii) high-intensity light aging in an Atlas Weather-Ometer equipped with a 6500 watt xenon arc lamp and infrared absorbing filters (having an ultraviolet intensity of 350 μW/lm, a light intensity of 100,000 lux, a temperature of 22 ± 1°C, and an RH of 50 ± 5%) for 1000 hours; or iii) natural dark aging at 22°C (45% RH) for four years. At timed intervals (every 500 hours for thermal dark aging at 75°C, every 250 hours for high-intensity light aging, and every six months to a year for natural dark aging at 22°C), between 5 and 12 (in the majority of cases, 10) samples were removed from the exposure condition and were subjected to the shear strength test.

The shear strength for each sample was calculated, along with sample means and standard errors of the sample mean. All results were subjected to a statistical analysis to determine significant changes in shear strength after aging. To compare the sample means with the mean of the maximum strength attained, a 95% confidence interval for the difference in means was calculated. If the confidence interval did not include zero, then the difference between the two means was considered "statistically significant." If the confidence interval included zero, then the difference between the two means was considered "not statistically significant."

When samples were broken in the compressive shear mode, it was found that the majority of breaks occurred at the epoxy-glass interface. Values for samples displaying cohesive substrate failure (glass breakage) were included in the mean only if the value was greater than or equal to the mean calculated without the value included.

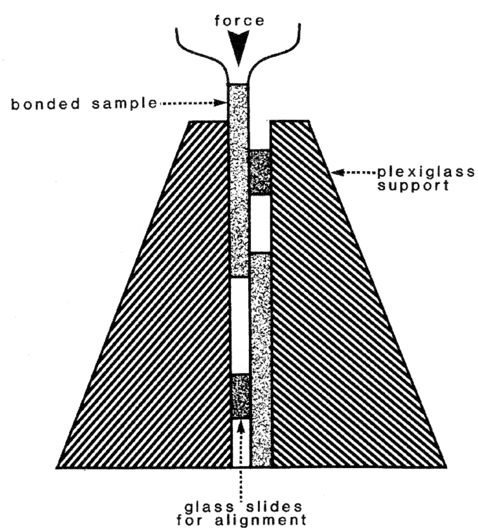

Figure 3. Cross-sectional view of sample holder modification to the Instron Tensile Strength Tester for breaking samples in the compressive mode.

Results and Discussion

Initial Shear Strengths

The average shear strength of each epoxy formulation prior to aging is given in **Table I**. In general, the adhesives containing a modified amine-type hardener (Epoweld 3672, Tra-Cast 3012, and Maraglas R658/H558) were the strongest, followed by two adhesives — one with a hardener composed of a blend or adduct of polyoxyethylene with a primary aliphatic polyamine (Hysol TE6175/HD3561), and the other with a hardener containing a mixture of triethylenetetramine, tetraethylenepentamine, and higher polymeric ethylene amines (Araldite 502/HY956). The remaining adhesives showed lower strengths.

According to Skeist,[2] bond strengths for glass adhesives in the order of:

1.5 to 3 MPa are considered to be quite **low**;
3 to 7 MPa are considered to be **low but sufficient**;
7 to 8 MPa are considered to be **fair**; and
8 to 38 MPa are considered to be **high**.

This would indicate that the *initial* strength of epoxy resin adhesives tested in this study is high (11-33 MPa) for glass substrates.

Table I also gives some insight into potting mixture and batch to batch differences (differences between columns). All samples within each aging condition were made from the same potting mixture but different potting mixtures were used for each aging condition. In actual fact, the samples for the 75°C aging and high-intensity light aging were made in April/May 1981 from the same batch of adhesive. The natural dark aging samples were made in August 1981 from, in most cases, a new batch of adhesive. One can see that agreement between initial shear strengths for the 75°C aging and high-intensity light aging (potting mixture differences) are better than for the natural dark aging and other two aging conditions (batch to batch differences).

Thermal Dark Aging at 75°C

The results of thermal dark aging at 75°C are given in **Table II** and **Figure 4**. After aging at 75°C, all epoxy formulations had increased in strength and had reached a maximum between 500 and 1500 hours, depending on the formulation. After maximum strength was attained, subsequent aging resulted in a loss of strength from the maximum which might or might not be statistically significant. No formulation lost strength below the initial strength, even after 2000 hours of aging.

Table I: Initial Shear Strengths of Epoxy Resin Adhesives Prior to Aging

Hardener Composition of Epoxy*	Epoxy	Initial Shear Strength (MPa)			
		Thermal Aging at 75°C	High-Intensity Light Aging	Natural Dark Aging at 22°C	Average
Modified amine (primary amine groups, aliphatic CH_2 chains and ether linkages - no aromatics)	Epoweld 3672	28 se 1	34 se 2	24 se 4	29 se 2
	Tra-Cast 3012	34 se 3	35 se 2	28 se 4	33 se 2
	Maraglas R658/H558	33 se 1	33 se 2	24 se 2	30 se 1
Triethylenetetramine	Araldite 6010/HY951	12 se 0	13 se 1	11 se 2	12 se 1
	Homalite 1100	12 se 1	16 se 1	9 se 2	13 se 1
	Araldite 502/HY951	9 se 1	14 se 1	11 se 3	11 se 1
Triethylenetetramine, tetraethylenepentamine, and higher polymeric ethylene amines	Araldite 502/HY956	22 se 2	24 se 2	11 se 2	19 se 2
A blend or adduct of polyoxyethylene and primary aliphatic polyamine	Hysol TE6175/HD3561	29 se 2	35 se 2	15 se 2	27 se 2
Polyamine-epoxy resin adduct	Devcon-2-ton	15 se 1	15 se 1	15 se 2	15 se 1
Amino-amide adducted with phenyl glycidyl ether - no free epoxide	Canus 1000/68	16 se 1	13 se 2	7 se 2	12 se 1

* All resin components were a diglycidyl ether of bisphenol A;[5] se = standard error of the sample mean.

After 2000 hours of thermal dark aging at 75°C, epoxy formulations Epoweld 3672, Araldite 6010/HY951, Araldite 502/HY956, Hysol TE6175/HD3561, and Canus 1000/68 showed no statistically significant decrease in strength when compared to the maximum strength attained.

Aging in the oven at 75°C caused all the epoxy resins to increase in strength significantly (60 to 240%). This dramatic increase was not seen under any other aging conditions. It is unlikely that any of the epoxies would increase in strength to this level even given time under natural dark aging at 22°C. Heating causes greater mobility at the molecular level and likely more crosslinking than would ever occur if not heated (room temperature conditions). Without aging at 3 to 5 different elevated temperatures and extrapolating to room temperature conditions using the Arrhenius equation, it is difficult to use the 75°C oven aging to predict future performance of any of the epoxies at room conditions. However, sometimes epoxy potting mixtures or bonds are heated to promote faster curing. It is likely that these bonds will be significantly stronger than bonds formed under room temperature conditions.

During aging at 75°C, most of the epoxies decreased in strength after a maximum was attained but none decreased to their original strength even after 2000 hours. Rough extrapolation of the data reveals that it might take 4 months to 1 year of aging at 75°C before the epoxies would return to their original strength and 6 months to 3 years of aging at 75°C before they would decrease to no strength at all (0-3 MPa). How this relates to room temperature conditions is unknown.

High-Intensity Light Aging

The results for high-intensity light aging are presented in **Table III** and **Figure 5**. After 1000 hours of high-intensity (100,000 lux, 350 μW/lm) light aging, three of the epoxies had increased in strength, two had decreased in strength, and five had increased in strength then subsequently had decreased. Of these last seven that lost strength, most lost strength to their original value before the end of the 1000 hours of aging (300-900 hours). Rough extrapolation reveals that they would lose all their strength (0-3 MPa) in 1500-2200 hours in the Weather-Ometer.

The light aging was continuous for 1000 hours. Most museum lighting is at lower intensity and intermittent. If one expressed the times above in terms of intermittent (10hours/day, 6 days/week; ~3000 hours/year) lighting at lower intensity (200 lux, 350 μW/lm), this would give estimates that the epoxies would lose strength to their original value in 60 to 250 years and would lose all their strength (0-3 MPa) in 300 to 400 years. These estimates are conservative in that the UV component (350 μW/lm) is high. Extrapolation to lower UV levels is complex

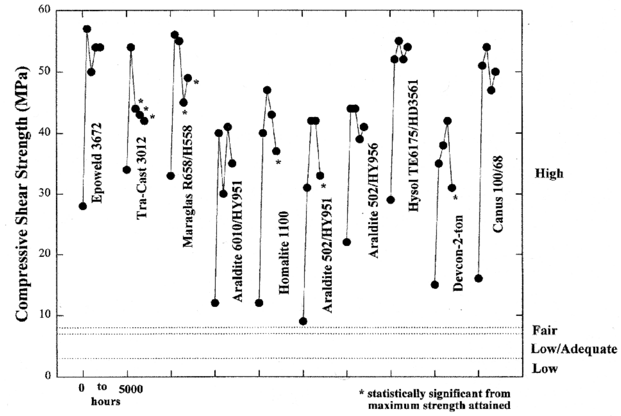

Figure 4. The effect of thermal dark aging at 75°C on various epoxy resin adhesives.

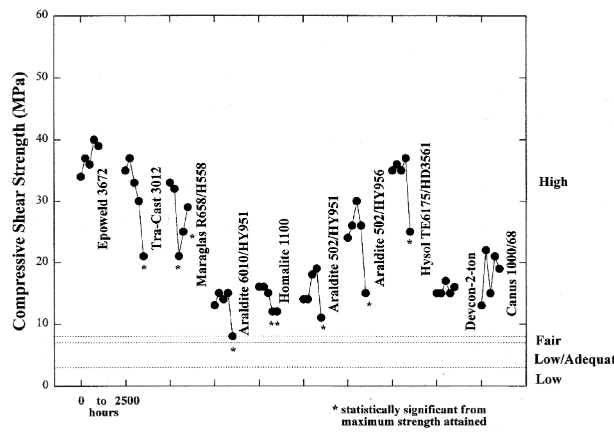

Figure 5. The effect of high-intensity light aging on various epoxy resin adhesives.

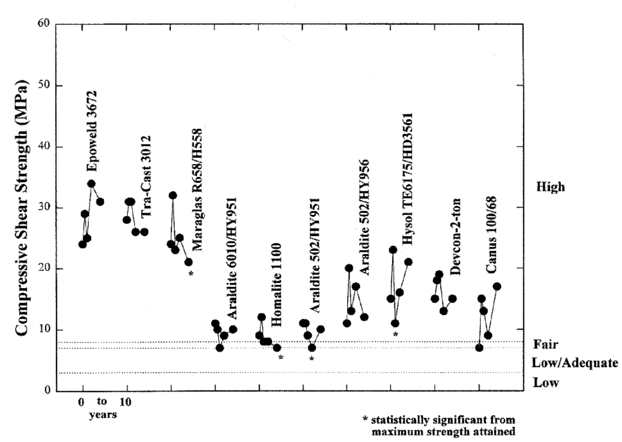

Figure 6. The effect of natural dark aging at 22°C on various epoxy resin adhesives.

Table II: Results of Thermal Dark Aging at 75°C

Epoxy	0 hours	~ 500 hours	~ 1000 hours	~ 1500 hours	~ 2000 hours
Epoweld 3672	28 se 1	57 se 3 (max)	50 se 2 (12)	54 se 2 (6)	54 se 2 (5)
Tra-Cast 3012	34 se 3	54 se 1 (max)	44 se 3 (20)*	43 se 3 (21)*	42 se 3 (23)*
Maraglass R658/H558	33 se 1	56 se 2 (max)	55 se 2 (2)	45 se 4 (20)*	49 se 2 (13)*
Araldite 6010/HY951	12 se 0	40 se 3	30 se 4	41 se 5 (max)	35 se 5 (13)
Homalite 1100	12 se 1	40 se 3	47 se 2 (max)	43 se 3 (7)	37 se 3 (20)*
Araldite 502/HY951	9 se 1	31 se 3	42 se 2	42 se 1 (max)	33 se 2 (21)*
Araldite 502/HY956	22 se 2	44 se 3	44 se 3 (max)	39 se 5 (13)	41 se 4 (7)
Hysol TE 6175/HD3561	29 se 2	52 se 3	55 se 1 (max)	52 se 5 (5)	54 se 3 (2)
Devcon-2-ton	15 se 1	35 se 4	38 se 3	42 se 3 (max)	31 se 3 (26)*
Canus 1000/68	16 se 1	51 se 2	54 se 2 (max)	47 se 4 (13)	50 se 2 (8)

Table III: Results of High-Intensity Light Aging

Epoxy	0 hours	~ 250 hours	~ 500 hours	~ 750 hours	~ 1000 hours
Epoweld 3672	34 se 2	37 se 3	36 se 3	40 se 4 (max)	39 se 5 (2)
Tra-Cast 3012	35 se 2	37 se 2 (max)	33 se 1 (10)	30 se 3 (18)	21 se 2 (42)*
Maraglass R658/H558	33 se 2 (max)	32 se 3 (3)	21 se 2 (35)*	25 se 2 (24)*	29 se 2 (10)
Araldite 6010/HY951	13 se 1	15 se 1 (max)	14 se 1 (8)	15 se 1 (5)	8 se 1 (45)*
Homalite 1100	16 se 1	16 se 1 (max)	15 se 0 (5)	12 se 1 (26)*	12 se 1 (23)*
Araldite 502/HY951	14 se 1	14 se 1	18 se 1	19 se 1 (max)	11 se 1 (41)*
Araldite 502/HY956	24 se 2	26 se 2	30 se 2 (max)	26 se 2 (15)	15 se 2 (49)*
Hysol TE 6175/HD3561	35 se 2	36 se 3	35 se 2	37 se 3 (max)	25 se 2 (31)*
Devcon-2-ton	15 se 1	15 se 2	17 se 2 (max)	15 se 2 (11)	16 se 2 (4)
Canus 1000/68	13 se 2	22 se 2 (max)	15 se 2 (30)	21 se 2 (5)	19 se 2 (11)

Table IV: Results of Natural Dark Aging at 22°C

Epoxy	0 hours	~ 0.5 year	~ 1 year	~ 2 years	~ 4 years
Epoweld 3672	24 se 4	29 se 3	25 se 3	34 se 1 (max)	31 se 3 (9)
Tra-Cast 3012	28 se 4	31 se 4 (max)	31 se 3 (2)	26 se 1 (15)	26 se 3 (15)
Maraglass R658/H558	24 se 2	32 se 3 (max)	23 se 3 (28)	25 se 3 (21)	21 se 2 (34)*
Araldite 6010/HY951	11 se 2 (max)	10 se 2 (5)	7 se 1 (40)	9 se 1 (14)	10 se 1 (13)
Homalite 1100	9 se 2	12 se 1 (max)	8 se 1 (30)*	8 se 2 (32)	7 se 1 (39)*
Araldite 502/HY951	11 se 3	11 se 2 (max)	9 se 2 (25)	7 se 1 (42)*	10 se 1 (12)
Araldite 502/HY956	11 se 2	20 se 3 (max)	13 se 1 (38)	17 se 3 (18)	12 se 2 (40)
Hysol TE 6175/HD3561	15 se 2	23 se 3 (max)	11 se 1 (52)*	16 se 2 (30)	21 se 3 (6)
Devcon-2-ton	15 se 2	18 se 2	19 se 2 (max)	13 se 2 (31)	15 se 2 (20)
Canus 1000/68	7 se 1	15 se 3	13 se 1	9 se 1	17 se 2

se = standard error of the sample mean; max = maximum strength attained; numbers in brackets indicate percent decrease from maximum strength attained; * indicates a statistically significant difference from the maximum strength attained.

and dependent on the spectral distribution. It will not be attempted here. Nevertheless, these estimated times are relatively long.

Only three formulations — Epoweld 3672, Devcon-2-ton, and Canus 1000/68 — did not show a loss in strength *below* the initial strength after 1000 hours of high-intensity light aging. As well, these same three epoxies showed no statistically significant decrease in strength from the maximum strength.

Natural Dark Aging at 22°C

The natural dark aging results can be seen in **Table IV** and **Figure 6**. Under natural dark aging at 22°C, two of the epoxies increased in strength, two decreased in strength, and six increased in strength then subsequently decreased. Of these last eight that lost strength, most lost strength to their original value before the end of the 4 years (0.5-2.5 years). Rough extrapolation reveals that they would lose all their strength (0-3 MPa) in 8 to 26 years. This is a shorter time frame than the estimate given above for failure under light aging, but about the same time or long after (depending on the illumination) these adhesives might yellow intolerably and require the glass to be re-repaired. It should be pointed out that this rough estimate, and all others mentioned, are based on two or three points only and thus reflect a high degree of uncertainty. Further work would be required to achieve more reliable estimates.

Three formulations — Epoweld 3672, Araldite 502/HY956, and Canus 1000/68 — did not show a loss in strength below the initial strength after four years of natural dark aging.

Epoxy formulations Epoweld 3672, Tra-Cast 3012, Araldite 6010/HY951, Araldite 502/HY956, and Devcon-2-ton showed no statistically significant decrease from the maximum strength attained as a result of natural dark aging at 22°C. After the same aging conditions, Canus 1000/68 was still increasing in strength. No decrease from the original strength was observed for Canus 1000/68.

Overall

Given the nature of the data, it is difficult to predict with any certainty the time under normal museum conditions that strength loss will occur to any of the tested products. However, it can be said that no epoxy formulation tested lost an excessive amount of strength even after aging for 2000 hours in the dark at 75°C, for 1000 hours under high-intensity light exposure, or for four years in the dark at 22°C. Although the majority of formulations tested had decreased in strength from a maximum after aging, the lowest strength observed was at least 7 MPa. This, according to Skeist,[2] would still be an adequate bonding strength for glass.

It must be pointed out that the tests were carried out on *new* glass microscope slides. It is uncertain what effect glass of different compositions or of different states of degradation might have on the performance of these epoxy resins. As a further limitation, it must be noted that new glass was the *only* substrate studied and, thus, extrapolating the results to other substrates is not recommended. As a final note, it should be pointed out that aging under humid conditions was not investigated. This aspect should be assessed in more detail.

A summary of all the results under the various aging conditions is given in **Table V**. The results show that after dark aging at 22°C or 75°C, epoxy formulations Epoweld 3672, Araldite 6010/HY951, and Araldite 502/HY956 displayed no statistically significant decreases in strength from the maximum attained. Canus 1000/68 showed no statistically significant decrease after thermal dark aging at 75°C. After four years of natural dark aging at 22°C, the strength of Canus 1000/68 was still increasing. Similarly, Epoweld 3672, Devcon-2-ton, and Canus 1000/68 showed no statistically significant decrease after high-intensity light aging. Epoweld 3672 was the only formulation that showed resistance to loss of shear strength after *both* thermal and high-intensity light aging. Canus 1000/68 appears to perform equally well (a maximum strength had not been reached under natural dark aging).

Table V: Summary of Results

Epoxy	Natural Dark Aging at 22°C	Thermal Dark Aging at 75°C	High-Intensity-Light Aging
Epoweld 3672	NC	NC	NC
Tra-Cast 3012	NC	*	*
Maraglas R658/H558	*	*	*
Araldite 6010/HY951	NC	NC	*
Homalite 1100	*	*	*
Araldite 502/HY951	*	*	*
Araldite 502/HY956	NC	NC	*
Hysol TE6175/HD3561	*	NC	*
Devcon-2-ton	NC	*	NC
Canus 1000/68	no max yet	NC	NC

NC indicates there was no statistically significant change from the maximum strength attained; * indicates there was a statistically significant decrease from the maximum strength attained; max = maximum strength attained.

Conclusions

The results of this study indicate that the initial strength of the epoxy resin adhesives tested is high (all over 11 MPa) for new glass substrates. Initial strength appears to vary according to the chemical composition of the epoxy adhesive. Of the epoxy adhesives tested, those containing a modified amine-type hardener displayed by far the highest initial shear strengths.

Epoweld 3672 and Canus 1000/68 were identified as the most resistant adhesives to loss of strength after both thermal and high-intensity light aging. Loss of strength upon aging should not prove to be a major concern for the use of these epoxy resin adhesives on glass substrates since no epoxy formulation tested lost an excessive amount of strength under the aging conditions employed. However, it must be kept in mind that only *new* glass was used in this testing. Degraded glass or glass of differing composition may alter the results.

Acknowledgements

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Materials

Araldite 502/HY951, Araldite 502/HY956, and Araldite 6010/HY951: Ciba-Geigy Ltd., 205 boul. Bouchard, Dorval, Quebec, H9S lBl, Canada, (514)631-4841.

Canus 1000/68: Canus Plastics Ltd., 300 Lisgar Street, Ottawa, Ontario, K2P 0E2, Canada, (613)232-2657.

Devcon-2-ton: Devcon Canada Ltd., 22 Golden Gate Court, Scarborough, Ontario, M5H 3Z6, Canada, (416)291-1678.

Epoweld 3672: Hardman Inc., Belleville, New Jersey 07109, U.S.A., (201)751-3000.

Homalite 1100: SGL Homalite, A Division of SGL Industries Inc., 11 Brookside Drive, Wilmington, Delaware 19804, U.S.A., (302)652-3686.

Hysol TE6175/HD3561: Hysol (Canada) Ltd., 345 Finchdene Square, Scarborough, Ontario, M1X 1B9, Canada, (416)298-9395.

Maraglas R658/H558: Acme Chemicals & Insulation Co., Division of Allied Products Corp., Box 1404, New Haven, Connecticut 06505, U.S.A., (203)562-2171.

Tra-Cast 3012: Tra-Con Inc., 55 North Street, Medford, Massachussets 02155, U.S.A., (617)391-5550.

References

1. Davison, S., "A Review of Adhesives and Consolidants Used on Glass Antiquities," *Adhesives and Consolidants*, Preprints of the Contributions to the Paris Congress, 2-8 September 1984 (London: International Institute for Conservation of Historic and Artistic Works, 1984), pp. 191-194.

2. Skeist, I., editor, *Handbook of Adhesives*, (Huntington, New York: Robert E. Krieger Publishing Co., 1962), pp. 523-533.

3. Rémillard, F., "Adhésifs à base de résines époxy: étude de solubilisation," *Journal of the International Institute for Conservation - Canadian Group*, vol. 14, 1989, pp. 12-17.

4. Rémillard, F., *The Effect of Solvents on Epoxy Resin Adhesives*, Master of Art Conservation Research Project (Kingston, Ontario: Queen's University, September 1984).

5. Down, Jane L., "The Yellowing of Epoxy Resin Adhesives: Report on Natural Aging," *Studies in Conservation*, vol. 29, 1984, pp. 63-76.

6. Down, Jane L., "The Yellowing of Epoxy Resin Adhesives: Report on High Intensity Light Aging," *Studies in Conservation*, vol. 31, 1986, pp. 159-170.

7. Black, J.M. and Blomquist, R.F., "A Study of the Deterioration of Adhesives in Metal Bonds at High Temperatures," *Wright Air Development Center Technical Report 55-330*, (Springfield, Ohio: Carpenter Litho & Printing Co., March 1956), pp. 1-41.

8. Black, J.M. and Blomquist, R.F., "Relationship of Polymer Structure to Thermal Deterioration of Adhesive Bonds in Metal Joints," *National Aeronautics and Space Administration Technical Note D-108*, (Washington, DC: National Aeronautics and Space Administration, August 1959), pp. 1-35.