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Review Article

Analysis of Environmental Stresses on the Mechanical Properties of Laminated Glass Composites: A Review of Experimental Results and Outlook

Ufuoma Joseph Udi[1], Mustafasanie M. Yussof[1]* Felix Nkapheeyan Isa[1] and Luqman Chuah Abdullah[2]

[1]School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 USM, Nibong Tebal, Pulau Pinang, Malaysia

[2]Department of Chemical and Environmental Engineering, Faculty of Engineering, Universiti Putra Malaysia, 3400 UPM, Serdang, Selangor, Malaysia

ABSTRACT

Laminated glass composites are composed of two or more layers of glass and a thermoplastic elastomeric interlayer securely glued together in an autoclave at high temperature and pressure. This composite material which significantly enhances the performance of glass before and after breakage, is desirable for various engineering applications. The main elastomeric interlayer comprises Polyvinyl butyral (PVB), SentryGlas (SG), Ethylene-vinyl acetate (EVA), and Thermoplastic Polyethylene (TPU). These interlayer materials have different unique features which offer a variety of performance benefits for engineering purposes. However, the structural response of laminated glass composites' elements and polymeric interlayers is typically prone to structural modifications relative to temperature applications and other environmental actions such as humidity and solar irradiation. This review compares the weathering resistance of the most common interlayers used in laminated glass composites based on available experimental literature findings. The main mechanical and accelerated ageing tests of laminates with different interlayer materials are summarised, giving evidence of the impact of these environmental actions on the viscoelastic and mechanical properties of laminated glass composites plates. This research provides valuable references for predicting the long-term behaviour and risk evaluation of laminated glass composites under diverse ageing conditions.

Keywords: Ageing resistance, environmental stresses, interlayer, laminated glass composites, mechanical properties, polymeric materials

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E-mail addresses:
udiufuomajoseph@student.usm.my (Udi Ufuoma Joseph)
cemustafa@usm.my (Mustafasanie M. Yussof)
nkapheeyan@student.usm.my (Felix Nkapheenyan Isa)
chuah@upm.edu.my (Luqman Chuah Abdullah)
*Corresponding author

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INTRODUCTION

Glass is a widely used material in engineering and architectural applications due to its remarkable advantages such as desirable aesthetics, high transparency, good chemical and mechanical durability, as well as its excellent corrosion resistance and considerably small energy consumption for its manufacturing. During the formative years of glass production, the primary objective was fixated on manufacturing annealed (AN) float, representing the primary base material primarily utilised as window glass. Compared to most building materials, the strength of annealed glass is limited, with tensile resistance of up to 45 MPa (Kozlowski et al., 2018). Chemical or thermal procedures can then be employed to improve the strength of AN glass, resulting in toughened glass-tensile resistance up to 120 MPa-and is mostly employed for demanding applications like solar cell covers, façades or other load-bearing components (Kamarudin et al., 2018; Yussof et al., 2020). The structural use of glass is also receiving widespread recognition in many areas, such as aircraft and automotive industries, where laminated glass windshields may be a contributing factor to the overall vehicle crashworthiness while also being representative of the structural glass applications in buildings (Kozlowski et al., 2018).

Judging by industry market surveys, the global demand for these types of glasses is projected again to expand at a rate of 6.7% per annum over the next few years (Figure 1). Between 2012 and 2019, the global glass sector is estimated to have utilised 75 million metric tons of flat glass per year (Subagio, 2020). The construction and automotive sectors consumed a large share (70%) of the entire flat glass produced. Since flat glass usage has expanded in recent years, the proportion employed in the construction sector is expected to rise. In addition, the building sector of the Asia-Pacific region, in particular-which, has seen rapid expansion in recent years due largely to a combination of fast-growing economies, increased infrastructure expenditures, rapid urbanisation, and the sustained rise in popularity of smart city schemes-is expected to be the driving force of flat glass demand.

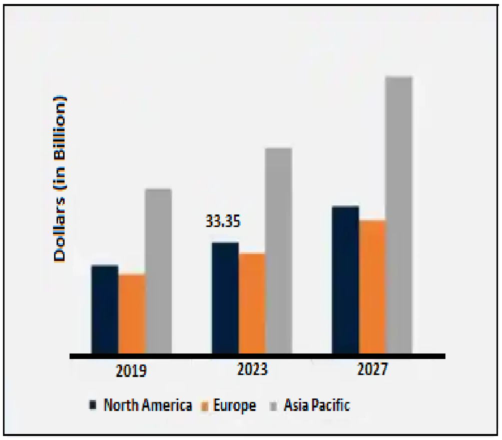

Figure 1. Global glass demand trend. Statistics from Data and Records Sheet (2021)

Laminated glass (LG) composites in this context, is typically haracterised by a combination of two or more glass sheets glued together by intermediate bonding polymeric material, which acts as a form of flexible shear connections (Castori & Speranzini, 2017). Polymeric materials such as Polyvinyl butyral (PVB) foils are the most commonly used in LG elements, although they can also comprise Ethylene-vinyl acetate (EVA) or SentryGlas (SG) polymers (Hála et al., 2022; Mohagheghian et al., 2018; Zemanová et al., 2022; Zhang et al., 2020). However, the mechanical and thermos-viscoelastic properties of the polymeric materials, as well as their adhesion with glass, may be affected by exposure to other environmental stresses like UV radiation, thermal cycles or humidity conditions (Martín et al., 2020; Yang et al., 2022). Adhesive and laminated connection between parts is particularly examined for ageing variables and their impact on the durability and strength of LG elements and systems. The experimental determination of the viscoelastic properties of polymeric materials is of vital importance; in particular, bonding films utilised as interlayers in laminated connections are susceptible to thermal variations required in the laminate process (Giovanna et al., 2017; Yang et al., 2022). Moreover, previous observations have indicated the potential of various deterioration factors, each with varying degrees of impact on the rheological structure of the interlayers and, as a result, on the mechanical properties of the materials; it is entirely plausible that distinct consequences dominate at various stages during in-service conditions of LG elements.

This paper proposes a critical review of the ageing consequences on the thermos-viscoelastic properties of commonly used laminated glass polymers. The research works considered in this present study are by no means exhaustive of available scholarly publications; rather, they were selected to reflect a variety of experimental techniques to the challenge of determining interlayer properties subjected to the weathering phenomena. Particular focus is devoted to the applications, mechanical characterisation, and weathering resistance of PVB, SG, and EVA-based interlayers under diverse ageing conditions. The review ends by presenting the remaining issues that should be resolved to provide better information and develop solutions for environmentally impacted LG elements in structural applications.

LAMINATED GLASS COMPOSITES AND POLYMERIC INTERLAYERS

Laminated glass composites, or laminated safety glass, represents an arrangement of usually two plies of glass glued together by foils comprising certain types of bonding films commonly known as interlayers (Joseph Udi et al., 2023). The transition from two separate materials to a composite laminate is achieved by creating the vacuum between layers, usually with vacuum bags, and then applying pressure and temperature, usually in an autoclave, in order to create a chemical bond between glass and interlayer (Centelles et al., 2021). As a general rule, the resistant cross-section of the laminate is intended to conform as a composite in reaction to the extrinsic load. Thus, there is better mechanical performance in both elastic and post-cracking phases than in a single glass pane (Alsaed & Jalham, 2012). A tacit benefit of laminated glass composites in structural applications from a mechanical perspective is that two or more glass sheets can be glued together (Biolzi et al., 2020; Hána et al., 2020; Zhao et al., 2021). Therefore, the necessary degree of strength and stiffness could be achieved by utilising standard glass thickness accessible in the market. Moreover, due to the advent of bonding films, laminated glass has been the conventional safety option in buildings for decades because the interlayer can strap glass fragments together in the event of collapse (Delincé et al., 2007; Hidallana-Gamage et al., 2015).

Bonding films usually comprise a PVB interlayer. Over the last several decades, PVB has been arguably the most prevalent interlayer used in the construction glass industry (Chen et al., 2022; Hána et al., 2019; Vedrtnam & Pawar, 2018). Following its introduction in the 1930s, innovative attempts have centred on measures to make the interlayer less expensive to manufacture, less vulnerable to irregularities during lamination, easier to handle, or to improve some of its characteristics. Many optimised PVB products with unique features such as structural function, solar reflectiveness, acoustic insulation, tighter bond, and greater adhesion to glass, as well as security and decorative functions, have appeared due to the maturity of PVB as an interlayer in laminated glass composites (Desloir et al., 2019). These advancements have enabled it to be used in automotive windshields, PV solar cells, structural glass components, security glass, and its application in laminated doors and windows (Chen et al., 2018; Kozlowski et al., 2018).

Several other interlayers could also be employed besides PVB, such as SentryGlas (SG), Ethylene-vinyl acetate (EVA), and Thermoplastic Polyethylene (TPU), which were incorporated into the laminated glass composites industry to fulfil the high-performance resistance requirement for hurricane glazing (Bennison et al., 2008). SG is an interlayer form of ionic resin or Ionoplast which provides high stiffness and transparency over a broad temperature range (elastic modulus of about 100 MPa for temperatures up to 50°C) (Bati et al., 2010; Belis et al., 2009). EVA is a sturdy foil made using a plasticised PVB. This material provides excellent flexibility, elasticity, toughness, stress-crack resistance, and clarity as an interlayer material. EVA also possesses distinctive characteristics such as high optical transmission, excellent electrical resistivity, resilience to weather conditions, and low fusion and polymerisation temperature (Pankhardt & Balázs, 2010). The chemical structure of the interlayers used in laminated glass composites is the same for all manufacturers. Nonetheless, the unique attributes of each interlayer sheet are dependent on the interlayer type, manufacturer, and composition of the interlayer sheet (Table 1) (Martín et al., 2020).

However, as highlighted by several scholars, a typical feature of these elastomeric materials is that these films are usually governed by their viscous nature in addition to their distinct constitutive principles; thus, they are typically prone to chemical modifications relative to the ambient conditions they are exposed to over time (Hartwell & Overend, 2020; Kothe & Weller, 2014; Louter et al., 2012; Ranocchiai et al., 2016, 2018). Hence, the mechanical and thermos-viscoelastic properties of the polymeric materials, as well as their adhesion with glass or another substrate such as steel, may be affected by exposure

Table 1
Main properties of laminated glass composites interlayers (PVB, SG, and EVA) (Martín et al., 2020)

Parameter		PVB	SG	EVA
Price	€/m²	4.02–4.82	n.a.	1.74–1.91
Coefficient of thermal expansion	10^{-5} cm/cm°C	22–40	10–15	160–190
Water absorption (ASTM D-570)	wt.%	3.6	n.a.	0.15–0.5
Density	kg/m³	915–1070	950	945–955
Ultimate tensile strength	MPa	20.8	34.5	9.5–10
Poisson's ratio	–	0.5	0.442–0.500*	0.47–0.49
Transmittance	%	88–89	n.a.	90–92
Elongation at failure	%	190–350	400	880–930
Glass transmission temperature	ºC	8–42	55	–77 to –69
Yellowness index	–	12.5	2.5	1.9
Young modulus	MPa	2–5	300–480	7–9
Joining technique	–	Lamination, UV curing	Lamination	Vacuum Lamination, autoclave, or vacuum bags

* Directly proportional to time and temperature

to other environmental stresses like UV radiation, thermal cycles or humidity conditions (Andreozzi et al., 2015; Centelles, Castro et al., 2020) The coupling capability between the different components may also be altered by additional factors such as failure of the bonding layer, material degradation or delamination (Figure 2). Thus, the interlayer properties, in addition to the weathering resistance and durability, have an enormous influence on the overall structural integrity of LG composites. On account of that, LG composites and polymeric materials have garnered significant attention in recent years. The behaviour of polymeric interlayers, and thus LG composites systems can be evaluated in three ways: experimental research, numerical simulation, or theoretical study.

The mechanical behaviour of LG composites could be determined experimentally using Dynamic Mechanical Analysis (DMA) (Giovanna et al., 2017; Hána et al., 2020; Lu et al., 2021), which enables a thorough characterisation of the viscoelastic properties of the interlayers. The viscoelastic properties of polymers employed in interlayer LG composites can be analysed using a variety of experimental approaches. The ISO-6721-1

(2019) presents numerous dynamic procedures to experimentally determine the mechanical properties of polymeric materials; the draft standard EN 16613 (2013) offers three different test procedures to address specific issues pertaining to various types of polymeric materials. Moreover, many researchers have proposed different experimental techniques for simulating ageing action on LG composites in order to define thermos-viscoelastic properties and to properly reflect the short and long-term behaviour of LG composites using an effective modulus of elasticity which is dependent on the working temperature and time loading (Giovanna et al., 2017). In any case, observations from the literature findings have demonstrated that the shear stiffness of interlayers used in LG composites differs so much from the stiffness of component glass that minor inconsistency in determining this property results in significant deviations in evaluating the bending behaviour of LG composites. However, the many different methods proposed in the literature to determine the viscoelastic properties of polymeric materials make it difficult to compare results. In the following sections, we aim to highlight the disparities to identify the peculiarities associated with determining thermos-viscoelastic and mechanical properties of LG composites due to environmental stresses, summarising what different researchers agree on; and outlining the potential direction for future studies.

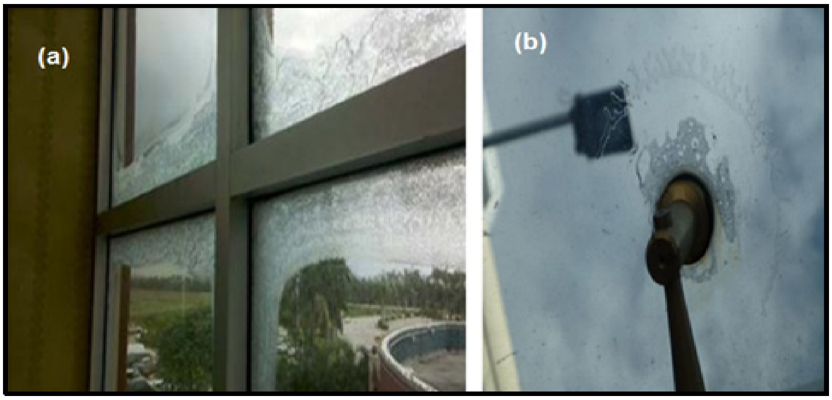

Figure 2. Delamination of LG panels (a) framed window glass (b) Point fixed glass (CPNI EBP 04/13, 2013)

EXPERIMENTAL RESEARCH ON PROPERTIES OF LG INTERLAYERS

The thermos-viscoelastic properties of polymeric materials used in LG composites are vital in evaluating the structural response of LG composites, and therefore, knowledge of its long-term behaviour is essential for the fail-safe design of structural components utilising LG elements to avert disastrous failures. Consequently, it is paramount that the structure meets serviceability conditions, ensuring that unexpected failure of any glass component does not cause the entire structure to collapse and that a minimum load-bearing capacity is maintained pending evacuation or replacement. In this regard, numerous attempts have been made to characterise polymeric materials' material properties and ascertain their long-term performance under diverse ageing scenarios. In the following sections, particular emphasis will be on consequential and more recent experimental results to adequately describe the material properties of commonly used polymeric interlayers under varying environmental stress conditions and provide useful data for structural LG design involving long-term effects.

Effect of Environmental Stresses

The first consequential studies on the impact of environmental stresses on the properties of structural glass systems came to light towards the end of the 1950s because of the enormous usage of glass materials as windowpanes. However, many of these research efforts focused on the investigation of thermal stress breakage–indicative of the leading cause of fracture in window glass (Bedon, 2017; Wang, 2020). It is common knowledge that polymeric materials are susceptible to weathering agents and may alter their rheological properties. Hence, the durability of LG elements and their polymeric interlayers against environmental stresses is of significant concern in ensuring its practicability for safety design purposes. The causes and processes of glass weathering have been extensively studied for several decades. Weathering can occur as a result of either mechanical or chemical action on a glass plate. Mechanical action can be caused as a result of wind debris or abrasion (Datsiou & Overend, 2017). In contrast, chemical action is due chiefly to the effects of environmental parameters such as temperature, atmospheric water vapour (relative humidity), or UV radiation.

Accelerated ageing tests-which are used to expedite the process of natural weathering-can is employed to investigate the effects of each weathering agent on polymeric interlayers. It can be achieved by combining weathering agents in environmental chambers-such as controlled temperature or high humidity-or other ageing processes to simulate a realistic natural weathering process (Datsiou & Overend, 2016; Lombardo et al., 2005; Reiß et al., 2019). Different weathering processes may produce varying degrees of modifications in interlayer properties, and for this reason, it is vital to utilise standard procedures (ISO-6721-1, 2019) so that different results can be compared. In the following paragraphs, the different experimental ageing techniques, standard and non-standard techniques reported in the literature, are identified, categorised, and summarised. Many experimental research available in the literature has shown that weathering has a considerable impact on the physicochemical properties of polymeric materials as well as the mechanism of degradation of LG composites in general.

For example, Kothe and Weller (2014) described an experimental campaign in which LG units having different polymeric interlayers like PVB, TPU, SG, and EVA were exposed to environmental stresses such as UV radiation, corrosion by saline fog, and a combination of humidity and temperature produced in an environmental chamber. While the authors reported considerable delamination on the edges of tested specimens after 21 days of exposure to UV radiation, the material behaviour of the interlayers did not exhibit significant changes up to the glass transition temperature compared to un-weathered specimens. Prior to this, Serafinavicius et al. (2014) investigated the weathering resistance of LG units glued with different polymeric materials, i.e., SG, EVA, and PVB, on exposure to different weathering agents in a climatic chamber. Long-term bending tests at different temperature conditions indicated that PVB interlayers had the highest mid-span deflection results at the highest temperature conditions, while SG interlayers posted the lowest deflection results at various temperatures. Humidity was also shown to have the least impact on the middle span deflection of tested specimens.

However, the maximum displacement values could not be compared due to the unreported load level in the creep tests. In a different study, Andreozzi et al. (2015) conducted an articulated experimental campaign wherein laminates with PVB interlayers were subjected to different artificial ageing processes and tested with DMA. In doing so, a thorough thermo-viscoelastic behaviour of the polymeric material was obtained both before and after the ageing processes. Delamination was observed only on specimens exposed to humidity-220 days in total in a thermostatic bath—over an extended period. It was also shown that thermal cycles performed under well-defined conditions and ISO-12543-4 (2021) have no significant effect on the rheological response of the PVB material. However, UV radiation was observed to have modified the rheological structure of the material, as evidenced by the modification of the interlayer master curves. These modifications have a direct impact on the long-term performance of LG composites. Changes were also observed in the bulk response of the polymeric material, concluding that further experimental research is needed to separately analyse these features.

In a more recent study, Centelles, Castro et al. (2020) evaluated the influence of various polymeric materials-PVB, Saflex, SG, and EVASAFE-on the bond behaviour of LG units after being exposed to different levels of environmental stresses, i.e., humidity, UV radiation, and thermal cycles. Results from the study gave evidence and under prior literature findings (Andreozzi et al., 2015; Delincé et al., 2007) of a loss in adhesion in PVB specimens on exposure to humidity conditions, as well as producing a stiffer material after exposure to UV and thermal cycles (Figure 3). EVASAFE and SG specimens, however, showed better resistance performance to weathering actions. In another study, the same authors (Centelles, Martín, et al., 2020) reported high moisture absorption in PVB and SG laminates compared to EVA and TPU laminated specimens after immersing said specimens in a thermostatic bath and following ISO-62 (2008) and ISO-175 (2010) over an extended period (367 h in total). The study concluded that SG and PVB with minimum plasticiser are the best choices for LG composites in structural applications due partly to their maximum

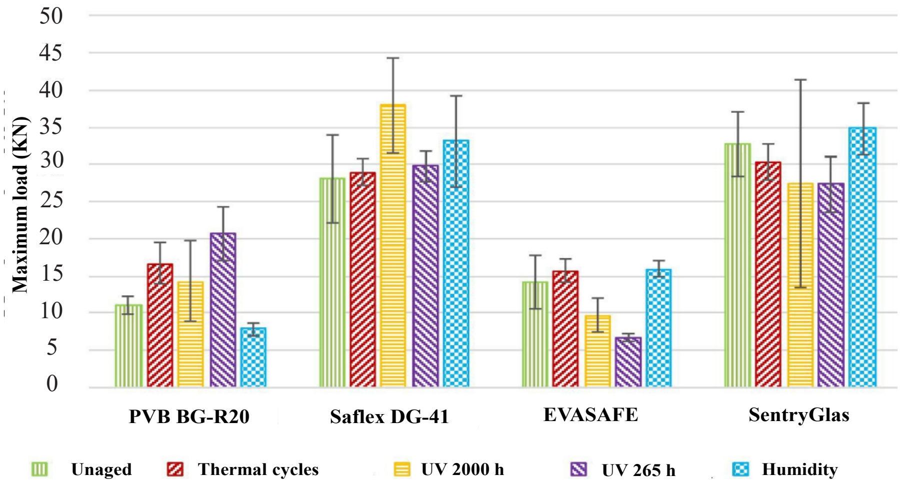

Figure 3. Weathering consequences on LG pane with different interlayer materials (Centelles, Castro et al., 2020)

stresses and high initial stiffness when not exposed to humidity conditions. The authors, however, emphasised that the performance of polymeric materials for LG composites may differ after the laminating processes, suggesting more dynamic experiments at various temperature levels to investigate the thermo-viscoelastic behaviour of these polymeric materials.

Note that, even though a significant number of experimental tests have been performed and the findings are obtainable, these studies are difficult to compare, not only because the artificial ageing processes were performed using different procedures but also because the experiments are frequently superimposing dissimilar environmental stresses in order to determine an effective rheological parameter. It is also worth highlighting a significant difference between LG composites exposed to a controlled environmental chamber (such as controlled humidity and temperature) and the exterior environment. The external environment exposes the glass to various levels of solar radiation, periodic condensation of water films due to humidity cycles, and the deposition of aerosol particles on the glass. All of these factors can influence the rate of alteration of the polymeric materials, hence, a different mechanism in the deterioration of LG composites.

Although several experimental studies have focused on the degradation of LG panes and interlayers as a constructional material due to environmental stresses, limited literature efforts are still available on the outdoor natural weathering of laminated glass (Table 2). As far as the authors know, outdoor weathering of LG composites has been performed only by Ensslen (2007). The author reported an extensive experimental evaluation on the behaviour of circular LG units 100 x 100 mm and 300 x 300 mm, their nominal sizes glued together by PVB foils and exposed to environmental stresses. Some samples were exposed to weathering processes in humidity and temperature mixed conditions in a climatic chamber, another set of samples were exposed to UV radiation in a solarium, while others were simply exposed to outdoor environmental conditions for up to two years at various climatic locations. The monotonic shear test was used to compare specimens that had been weathered artificially to those that had been subjected to the outdoor environment. In general, results from the study demonstrated large increments in moisture absorption of artificially aged specimens but no significant increase in moisture absorption of naturally weathered specimens. Shear test results indicated that a stiffer and more brittle PVB foil, as well as adhesion loss and delamination at the edges of LG units, could also be observed in artificially aged specimens.

On the other hand, the naturally weathered specimens showed only minor derivations in overall shear performance. However, at low test speeds, it could also be observed at the edge of specimens naturally weathered in extreme climatic conditions. The actual behaviour of such glasses, as expected from the test conditions, was closely linked to local instabilities, i.e., buckling, thus, requiring more rigorous experimental analysis of naturally weathered LG units and systems.

Mechanical Characterisation

The mechanical performance of LG composites and systems relies on the deformability of the constituent polymeric material; hence, mechanical analysis cannot be achieved without considering interlayer cohesive behaviour (Hooper et al., 2012; Mohagheghian et al., 2018; Zhang et al., 2019). Furthermore, as such, the experimental techniques developed to evaluate the mechanical response of the polymeric interlayer alone and the LG composite, in general, are quite diverse and dissimilar in the existing literature. Testing methods to evaluate the mechanical properties of LG composite include most notably, the four-point bending test (Delincé et al., 2007; Louter et al., 2012; Serafinavičius et al., 2013), shear test (Centelles, Castro et al., 2020; Serafinavicius et al., 2013), peel test (Louter et al., 2012), and pull-out test (Louter et al., 2012).

Taking into account the complete LG composites, for example, Delincé et al. (2007) were among the first to conduct an extensive experimental campaign to study the effect of artificial weathering on the shear-bond properties of LG panels 1100 x 360 mm their nominal sizes with PVB and SG interlayers using two different types of mechanical tests, i.e., shear test and bending tests. Observations from the shear tests indicated that while the level of adhesion of the LG panels decreased slightly after the weathering processes, there was a slight increase in stiffness. However, the reverse trend was observed from the bending tests, in addition to the SG and PVB specimens having quite a similar failure behaviour in terms of adhesion of broken glass pieces to the interlayer. Similar observations were also noted by Serafinavicius et al. (2013), who also reported experimental results of four-point tests conducted on laminates glued with various polymeric materials PVB, SG, and EVA after imposing sustained loading at different temperature ranges, i.e., 20°C, 30°C, and 40°C. Monolithic tempered glass sheets were also included in the set of experiments. The authors gave evidence and under prior findings (Delincé et al., 2007; Louter et al., 2012; Serafinavičius et al., 2013) that while all the tested LG specimens have a similar level of influence on the resistance and behaviour of LG composites, laminates with SG interlayer (maximum failure load at 7.8 kN) could be considered safer at the same residual stiffness of failed glass panels. The maximum load for PVB specimens was 6.5 kN (first load at failure of the bottom of the glass sheet) at a maximum displacement of about 50 mm. The maximum load of EVA specimens was similar to that of the PVB specimens (6.7 kN), but the displacement was much smaller at the same failure load (Figure 4). Nonetheless, the findings demonstrated how the interlayers' viscoelastic behaviour influences the coupling capability of LG panels.

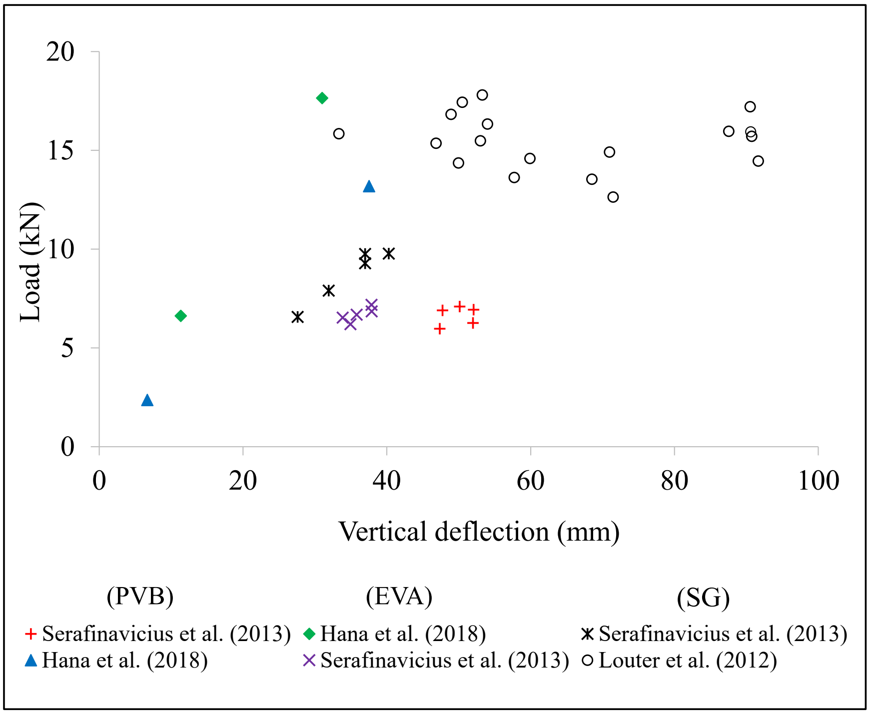

Figure 4. Load deflection relationship from four-point bending test of LG specimens with different interlayers as derived from experimental literature

Sable et al. (2019) and Hána et al. (2018) also tested LG units in a short-term controlled four-point bending test under constant temperature with three different interlayers, i.e., PVB, SG, and EVA. The authors demonstrated that the maximum load and stiffness were impacted by the type of polymeric material and the fracture pattern and breakage mechanisms. In the study by Hána et al. (2018), their experiments indicated that LG units with EVA polymers not only revealed larger ultimate load values (Figure 4) but also demonstrated higher bending stiffness than laminates with PVB polymers. However, Sable et al. (2019) noted that the stiffness of LG units with EVA polymers was comparable with PVB specimens, and EVA materials could be utilised in the same settings as PVB polymers, requiring further detailed investigations of these tests and materials. For the sake of clarity, Figure 4 presents a comparison among experimental literature results. The comparison is made in terms of laminates with PVB, EVA, and SG interlayers used in each campaign. The comparison is only made among results with similar test conditions (four-point bending tests). As shown in Figure 4, the distribution of LG strength is highly scattered, mainly due to the different geometry and material properties used for the different campaigns.

In studying the mechanical response of a polymer material, one can usually categorise experiments into two regimes in terms of strain rate and dynamic modulus: Uniaxial tensile strength tests (Belis et al., 2009; Centelles, Martín et al., 2020; Chen et al., 2018; Hooper et al., 2012; Liu et al., 2012; Sable et al., 2017; Zhang et al., 2015) and dynamic mechanical analysis (Andreozzi et al., 2015; Liu et al., 2014; Lu et al., 2021; Pelayo et al., 2017). In characterising the strain rate-dependent behaviour, for example, Liu et al. (2012) described an articulated campaign for both compression and tensile strength tests of PVB laminates using four different strain rates, i.e., 10, 50, 100, and 200 mm/min. The authors observed that while the PVB behaviour can be best described as viscoelastic under compression loads in both dynamic and quasi-static scenarios, however, under tensile loading, the material can be described as viscoelastic in quasi-static loadings and elastic-plastic in dynamic loadings. Observations from the study indicated that, while increasing strain rates made little difference in the failure stresses (16.9, 16.5, 16.5, 14.5 MPa, respectively), the failure strain decreased from 1.8 to 2.8, a 36% drop. The authors also defined and divided the PVB constitutive model into three regimes: linear-elastic stage, bi-exponent stage and failure stage.

A similar observation was also noted in (Belis et al., 2009), where the failure behaviour of LG sheets with SG interlayers was experimentally investigated. Results from the tensile tests loading speed ranging from 5 mm/min to 100 mm/min indicated an elastic-plastic material behaviour at failure (approximately 350%), which was affected by strain rates. Despite the relatively good material properties of the interlayer, the post-failure behaviour following prior studies was below expectations (i.e., failure strength above 32 N/mm^2). However, the observed failure mechanism varied significantly from that of LG with PVB interlayer tested in prior studies. In complement, Zhang et al. (2015) conducted tensile tests on LG specimens with SG interlayers, ranging from low (10 mm/min to 100 mm/min) to high (0.1 m/s to 20 m/s) strain rates. Observation from the test results indicated that, while the failure strain at low rates varied from 22 MPa to 47 MPa, the specimens were less ductile with an increasing strain rate. The authors also derived the initial modulus of the

LG specimens with SG interlayers, and this value was found at 200-300 MPa at low strain rates and reduced to approximately 150 MPa at the high strain rate. The study concluded that the SentryGlas interlayer indicated a viscous material behaviour under uniaxial tension.

Centelles, Martín et al. (2020) also studied the tensile behaviour of LG units glued together with different polymer materials such as PVB (three different variations), EVASAFE, SG, and TPU. Following the standard set in ASTM D638 (2014) and ISO-527 (2006), tests were conducted under constant displacement rates of 10 mm/min, 50 mm/min, and 100 mm/min. In general, the authors gave evidence of similar stress-strain curves for PVB and SG laminates, with a softening zone preceded by an initial non-linear small region and a second region with smaller stiffness than the initial region. Whilst the TPU specimens had an initial elastic region coupled with a progressive softening and finally a linear region until breakage, the EVASAFE specimens proved to be the most ductile among all tested specimens. Figure 5 presents a comparison among experimental literature results. The comparison is made in terms of laminates with PVB and SG interlayers used in the different campaigns. The comparison is only made among results with similar test conditions (uniaxial tensile strength tests) and similar strain rates (10 mm/min). Remarkably and despite the different geometry and material properties, a similar trend is observed for most of the experimental results considered for the normalised tensile strength.

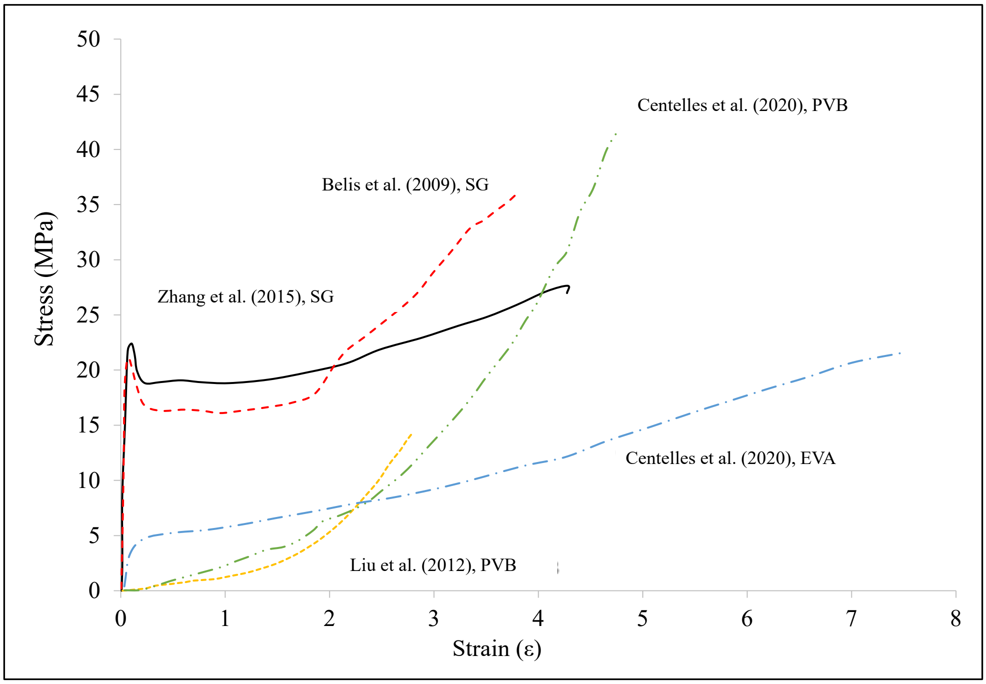

Figure 5. The stress-strain behaviour of LG interlayers in uniaxial tension test derived from experimental literature

In the case of DMA, several experiments have been conducted to study the time-temperature-dependent behaviour and hence the mechanical properties of LG interlayers. For example, Andreozzi et al. (2014) used the DMA technique to report that the PVB interlayer is in the glass transition region between 0°C and 50°C. Furthermore, as such, its dynamic modulus shows significant variations in temperature and vibration frequency. By contrast, an experiment by Liu et al. (2014) indicated that in the glassy and rubbery state, PVB shows brittleness and little variations in the dynamic modulus with temperature and vibration frequency variations. Using an identical technique, Pelayo et al. (2017) observed that the glass transition zone of standard PVB begins from 8-10°C. Thus, more studies on DMA analysis on LG interlayers, particularly for SG and EVA interlayers, are needed to verify the mechanical response of LG interlayers under different temperature conditions.

Table 2

Impact of environmental stresses on LG panes: Summary of some selected experimental research studies

Reference	Year	Interlayer type	Stress condition	Test Evaluation
Kothe and Weller	2014	PVB, EVA, SG, TPU	UV radiation, Corrosion, Temperature, Humidity	Visual inspection, Dynamic mechanical analysis
Andreozzi et al.	2015	PVB	Humidity, UV radiation, Temperature	Visual inspection, Dynamic torsion tests
Serafinavičius et al.	2013	PVB, EVA, SG	UV radiation, Temperature, Humidity	Long-term bending tests
Ensslen	2007	PVB	Temperature, Humidity, UV radiation, Natural outdoor weathering	Visual inspection, Shear Test
Louter et al.	2012	SG	Temperature, humidity, thermal cycling	Four-point bending tests
Hána et al.	2018	EVA, PVB	Controlled temperature	Short-term four-point bending tests
Sable et al.	2019	EVA, PVB, SG	Controlled temperature	Four-point bending tests
Centelles, Martín et al.	2020	PVB, EVASAFE, SG, TPU	Temperature, Humidity, UV radiation, Load–duration: 10, 50, 100 mm/min	Uniaxial tensile strength test
Centelles, Castro et al.	2020	PVB, Saflex, SG, and EVASAFE	Humidity, Thermal cycles, UV radiation	Double-lap shear tests

Table 2 *(Continue)*

Reference	Year	Interlayer type	Stress condition	Test Evaluation
Liu et al.	2012	PVB	Load–duration: 10, 50, 100, 200 mm/min	Uniaxial tensile strength test
Belis et al.	2009	SG	Load–duration: 5, 10, 20, 50, 100 mm/min	Uniaxial tensile strength test
Zhang et al.	2015	SG	Load–duration: Low speed; 10, 100, 250, 500, 750, 1000 mm/min High speed; 0.1, 0.5, 1, 2, 3, 5, 7, 10, 15, 20 m/s.	Uniaxial tensile strength test

CONCLUDING REMARKS AND OUTLOOK

In many applications, laminated glass composites elements are repetitively exposed to environmental stresses as well as frequent mechanical and chemical cleaning procedures, which can lead to changes in the rheological properties of the interlayer. Hence, the efficiency of the products decreases with age. Such deterioration and ageing processes are mainly determined by various environmental stress conditions such as relative humidity, thermal cycles and UV radiation. This paper presents the assessment of laminated glass composites against such ageing scenarios based on available literature findings. Only experimental studies are included in the comparison to make it more practical and consistent.

By reviewing major and other recent experimental works, several remaining questions are summarized from the authors' viewpoint. The artificial ageing actions documented in the literature and reviewed in this present study are often not comparable because the procedures were performed using different ageing processes and frequently superimposing different weathering scenarios. In addition, when mechanical tests were conducted, the goal was frequently to compare specimens exposed to different types and intensities of environmental stresses and not to determine an effective rheological parameter. As a result, it is quite difficult to compare experimental data reported by different authors. The ISO -12543-4 (2021) addresses the durability of LG composites, however, it lacks sufficient evaluation methodologies to investigate the impact of environmental stresses on the interlayers' optical, mechanical, and adhesive capabilities. It can be deduced that for comparison among weathering experiments of LG elements with diverse interlayers, a unified technique must be devised.

Nonetheless, significant inferences can be drawn from the summaries of what different scholars reported in their studies. Different researchers agree that UV radiation appears to have the most significant consequences, particularly for PVB materials, as a stiffer material is produced after the ageing action. However, more detailed experimental tests to investigate the damages produced by UV radiation on various LG interlayers are required, so as to identify possible diverse deterioration mechanisms in these interlayers. Humidity affects the interlayer in two ways; high absorption in the polymers which also acts as a plasticizer and also delivering a softer bulk property, which may inadvertently compromise its adhesion to glass. Based on the above, more detailed investigations are required to determine the impact of environmental stresses on the occurrence of bubbling and delamination phenomena. Temperature effects require further examination, since thermal variations may have quite diverse impacts on the various types of interlayers, depending on the transition temperature of each interlayer. The findings reported by different authors do not appear to be indicative of this phenomenon.

Lastly, the tremendous advancement in technology within the LG industry is already witnessing rapid growth in the production and supply chain of innovative polymeric materials in the glazing market. Irrespective of the interlayer type, LG elements are exposed to different environmental conditions, loading scenarios or working temperatures and this may affect how they respond and behave in LG systems. The weathering effect on its mechanical performance should be continually investigated in order to gain better knowledge of LG composites under environmental stress conditions. In addition, artificial ageing techniques currently have a great deal of inconsistency in estimating the long-term performance of LG composites, owing to the lack of an artificial ageing mechanism that is consistent with the real-world accumulated damages. In light of these considerations, further monitoring and tests of naturally weathered LG elements and systems are still required to aid in the prediction of weathering resistance, risk assessment, and safety of laminated glass composites in structural applications.

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