

Evaluation of Bipolar Plate Bonding Adhesives with the Aim of Increasing PEM Fuel Cell Power Density

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Abstract

One of the strategies to increase the power density of fuel cells is reducing the thickness of composite bipolar plates. However, considering the brittle nature of these plates, a reduction in thickness may result in fracture under applied loading. The use of adhesives for sealing, instead of elastomeric gaskets on the cooling side of bipolar plates, enables bonding of the anode and cathode plates together, thereby improving mechanical strength. Consequently, applying adhesives can significantly enhance the power density of the fuel cell. In this study, the performance of structural (epoxy-phenolic) and non-structural (fluorinated vinyl ester) adhesives was evaluated under fuel cell operating conditions. Essential properties such as adhesion strength, effective sealing, ease of preparation and application, thermal stability, and chemical resistance in the acidic fuel cell environment were investigated. The results revealed that epoxy-phenolic adhesives, due to their high shear strength, negligible weight loss, dense cross-linked structure, and the presence of phenolic rings, are more suitable for structural applications. In contrast, fluorinated vinyl ester adhesives exhibited zero weight loss under the same conditions and excellent chemical resistance, but lower mechanical strength. Specifically, EP-Ph10 exhibited a lap shear strength of 10.2 MPa, while VES-PFO5 showed 8.4 MPa. Chemical resistance tests indicated < 0.5% weight loss for EP-P, EP-Ph5, EP-Ph10, VES, and VES-PFO5, whereas EP-D showed approximately 2.0% weight loss in H₂SO₄ and ~ 3.0% in HF after 30 days.

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1 Introduction

Polymer electrolyte membrane fuel cells (PEMFCs) are an energy generation technology that produces electricity with high efficiency through the direct combination of hydrogen fuel and oxidant, without generating environmental or acoustic pollution. One of the fundamental issues currently under investigation by fuel cell manufacturers is increasing the power density of fuel cells. This objective can be addressed through various strategies, including optimizing the design of fuel cell components, improving the performance of the membrane electrode assembly (MEA), using metallic bipolar plates, and employing thinner composite bipolar plates. Reducing the thickness of composite bipolar plates is an effective approach to enhancing power density; however, due to the brittle nature of these plates, a reduction in thickness can lead to fracture under the compressive loads imposed by the clamping system. Improving the flexural strength of composite bipolar plates through modification of the employed compounds has been one research direction in this area. Another promising approach is to reconsider the type of sealing materials used in PEMFCs.

Sealing is one of the most critical aspects in fuel cell design. In conventional fuel cells, elastomeric gaskets are commonly employed to prevent leakage of hydrogen, oxygen, and coolant between cell components as well as to the external environment [1]. Replacing elastomeric gaskets with adhesives on the cooling side of bipolar plates reduces the required groove depth for sealing and consequently decreases the necessary thickness of bipolar plates. These adhesives also bond the anode and cathode plates together, thereby increasing the mechanical strength of the assembled plates. Thus, the application of sealing adhesives on the cooling side of composite bipolar plates can significantly enhance the power density of the fuel cell.

In conventional PEM fuel cell stacks, elastomeric gaskets are employed to seal the cooling channels, which requires the application of a compressive load to ensure leak-tight operation. This local compressive stress not only increases the mechanical requirements imposed on the bipolar plates but also limits the potential for reducing plate thickness, as insufficient stiffness may result in bending, cracking, or channel deformation during operation. In contrast, when a structural adhesive layer is used to bond the cooling-side plates, the need for sealing compression is eliminated. The two plates behave as a single mechanically integrated laminate, significantly increasing flexural stiffness and reducing the susceptibility to localized mechanical failure.

As a result, the bipolar plate can be manufactured at a lower thickness without compromising structural integrity, which directly leads to reduced stack volume and mass. Since PEMFC power output scales with active area rather than plate thickness, this reduction in structural volume increases the volumetric power density (WL^{-1}) of the stack. Therefore, adhesive-bonded bipolar plate assemblies provide a structural pathway to enhance power density not through electrochemical improvement, but through geometric optimization and load redistribution within the stack architecture.

The sealing materials must remain functional under the acidic operating environment of fuel cells. Accordingly, the use of adhesives with reliable sealing capability and chemical resistance has recently gained more attention [2]. The chemical bonds formed between the adhesive and the substrate can generate strong interfacial adhesion between the two bipolar plates and prevent leakage. Additional advantages of adhesives compared with conventional gaskets include the elimination of the need for high contact pressure during operation [3].

The selection of suitable adhesives is strongly influenced by the type of polymeric binder used in the composite bipolar plates. Since pure graphite is brittle, and grinding it for plate fabrication requires complex and costly processes, graphite-based composites with polymeric binders are preferred for cost-effective production. The polymeric binder may be either thermoplastic or thermosetting [4]. Among the most commonly used thermosetting binders in composite bipolar plates are epoxy, vinyl ester, polyester, phenol-formaldehyde, and phenolic resins, while widely applied thermoplastics include polypropylene, polyphenylene sulfide, polytetrafluoroethylene derivatives, polycarbonate, and high-density polyethylene [4–8]. Therefore, the adhesive used to join graphite-based composite bipolar plates must be selected to ensure strong bonding with the binder. Moreover, the binder type is important because the adhesive should at least match the chemical resistance of the binder against fuel cell reactants and by-products.

Relatively few studies have addressed the application of different adhesives for this purpose. Most research is limited to epoxy- and silicone-based adhesives, despite the crucial long-term importance of sealing performance. Clearly, improving the design protocols and testing methodologies for sealing materials could lead to improved overall fuel cell performance.

Extensive studies have been conducted on epoxy resins for laminating and bonding graphite-based composites [9,10]. However, the use of epoxy resins specifically for laminating graphite-based bipolar plates in fuel cells is still limited. In 2019, Rzczkowski et

al. [3] used epoxy adhesives to laminate both modified and unmodified polypropylene/graphite composite plates in fuel cells. They employed surface tension measurements of graphite composites to verify suitability for adhesive bonding. The mechanical properties of PP/graphite composites joined with adhesives were determined by lap shear tests. Their results indicated that the lap shear strength increased with higher graphite content in the composite plates, which was attributed to stronger adhesive-substrate bonding and increased stiffness of the base material, thereby reducing peak stresses within the adhesive layer.

Stammen et al. [11] highlighted that the use of adhesives is necessary for cost-effective fuel cell manufacturing in the medium term. They fabricated bipolar plates from polypropylene/carbon black/graphite mixtures and considered conductive adhesives to withstand the operating environment. On the coolant side, they reported service temperatures of 80 °C in deionized (DI) water or typical ethylene glycol mixtures. Gas permeation was also evaluated as a key factor in safe fuel cell operation. Four adhesives were investigated, including carbon black/tin-filled epoxy, polyolefin hot-melt adhesive with carbon black/tin, carbon-filled pressure-sensitive adhesive, and silver-filled two-component epoxy. Adhesives must not negatively affect electrochemical performance in terms of conductivity and impermeability. Aging tests in DI water at 80 °C for 500 h revealed no weight loss in single-component epoxy or polyolefin adhesives, with slight weight gain attributed to water absorption. Importantly, these adhesives showed better hydrogen barrier properties compared to previously applied silicone elastomer gaskets, with highly cross-linked epoxies performing particularly well.

Wang et al. [12] used phenol-formaldehyde (PF)-based resins as adhesives for bonding graphite materials. They reported that PF resin is a suitable adhesive for graphite due to chemical compatibility and high adhesion strength, but its bonding strength decreases significantly after thermal treatment above 300 °C.

Wang et al. [13] developed modified phenol-formaldehyde resin adhesives containing boron carbide and fumed silica for graphite and carbon bonding. They found that fumed silica nanoparticles improved flexural strength of the adhesive, while boron oxides enhanced bonding properties through chemical interactions with graphite substrates. Moreover, the formation of borosilicate phases improved viscosity, stability, and heat resistance above 800 °C, with adhesive structure remaining compact and uniform even at 1500 °C.

Kim et al. [2] measured the adhesion strength of a silicone adhesive between a Nafion membrane and a carbon fiber/epoxy composite bipolar plate. They

fabricated an anode bipolar plate/membrane assembly bonded with silicone adhesive to address hydrogen leakage. The measured lap shear and tensile bond strengths were 1.5 MPa and 1.9 MPa, respectively. Gas sealing was also confirmed, with no pressure drop after applying 0.3 MPa air pressure for 1 h under a 0.5 MPa compression load.

In 2019, Rzeczkowski et al. [14] examined novel sealing solutions for bipolar plates. Their work focused on epoxy adhesives with various fillers, urethanes, and their bonding with graphite/PP/EPDM composites. They studied aging effects under moisture and acidic solvents at elevated temperatures. Other approaches include the use of microencapsulated adhesives, which overcome pot-life limitations of conventional adhesives, as reported by Blunk et al. [15]. Similarly, epoxy adhesives were employed for metallic bipolar plates [16]. Industrial hot-melt adhesives (M300 type, based on methyl hydroxyethyl cellulose) were also tested by Sekine et al. [17], showing promising sealing and chemical resistance in fuel cell environments.

A review of previous research indicates that comprehensive comparative studies on adhesive bonding and sealing properties for different adhesives in fuel cells, particularly graphite-based composites, are lacking. Epoxy-phenolic adhesives, due to their dense cross-linked structure and aromatic groups, exhibit excellent thermal stability but require improvement under strongly acidic environments. Conversely, fluorinated vinyl ester adhesives (VES-PFO) demonstrate exceptional chemical resistance due to their unique chemical structure, but suffer from relatively lower mechanical strength. This contrast highlights the necessity of designing multifunctional adhesive formulations.

This study demonstrates and quantifies this structural advantage by evaluating the mechanical and chemical performance of two classes of structural adhesives – epoxy-phenolic and fluorinated vinyl ester – under conditions relevant to PEMFC operation, presenting a scalable approach for lightweight, compact, and mechanically robust bipolar plate design. For this, novel adhesive formulations were developed with the aim of ensuring strong adhesion between fuel cell components while maintaining effective sealing properties. Additionally, the adhesive must be easy to prepare and apply, and capable of providing durable chemical resistance in the acidic environment of fuel cells. Therefore, chemically resistant adhesives, focusing on epoxy-phenolic and fluorinated vinyl ester systems, were investigated. Epoxy, epoxy-phenolic, unsaturated polyester, fluorine-modified unsaturated polyester, silicone, and latex-based adhesives were compared. The present study is significant for several reasons. Firstly, phenolic resins, although strong adhesives, are inher-

ently brittle; combining them with epoxy resins enables simultaneous utilization of the advantages of both systems. Secondly, the incorporation of fluorinated agents into polyester resins improves chemical resistance by providing high cross-linking density and strong C-F bonds. Finally, latex-based adhesives, although elastomeric, offer ease of application and chemical resistance when cured with phenolic resins.

By presenting comprehensive experimental data, this study aims to fill the knowledge gap regarding the relationship between molecular structure, cross-linking density, and adhesive performance under complex operating conditions, ultimately identifying the optimal adhesive system for fuel cell applications.

2 Materials and Methods

In this section, the preparation procedures of the adhesives and the methodology of various tests to evaluate their sealing efficiency, thermal stability, and chemical resistance are described. First, the raw materials used for each adhesive and their roles are presented. Then,

the detailed preparation process for each adhesive is explained, followed by the testing procedures.

2.1 Adhesive preparation

The raw materials required for each adhesive and their functions are summarized in Table 1.

The epoxy resin (average molecular weight: 390 g/mol, grade E06) was supplied by Khuzestan Petrochemical Co. The curing agents PACM and DETA, perfluoro-1-octene (PFO), triethylamine (TEA), phenolic resin (CTK), vinyl ester resin, cobalt solution, and benzoyl peroxide were purchased from Sigma-Aldrich and industrial suppliers.

Epoxy adhesives without fillers were prepared by physically mixing the resin with the curing agent in precise proportions, followed by addition of TEA as accelerator to accelerate curing. For epoxy-phenolic adhesives, the preparation was similar, except that finely ground phenolic resin was incorporated during addition of PACM to epoxy resin, ensuring homogeneous dispersion. Curing was performed in an oven at 120 °C for 1 h.

Table 1. Raw materials used for the adhesives.

Material	Raw material	Role	Notes
Epoxy	Epoxy	Resin	EEW: 182-194 g/mol
	Diaminodicyclohexylmethane (PACM, -4.4)	Hardener	Cycloaliphatic amine, M_w : 210.365 g/mol
	Triethanolamine (TEA)	Accelerator	Tertiary amine
Epoxy-phenolic (Novolac)	Epoxy	Resin	EEW: 182-194 g/mol
	Diaminodicyclohexylmethane (PACM, -4.4)	Hardener	Cycloaliphatic amine, M_w : 210.365 g/mol
	Triethanolamine (TEA)	Accelerator	Tertiary amine
	p-tert-Butylphenol-formaldehyde resole	Phenolic resin	-
Silicone	PDMS	Resin	M_w : 2000 g/mol
	TEOS	Hardener	208.33 g/mol
Chemo-sil (industrial adhesive)	Chemlok (Chemo-sil) industrial adhesive	Resin	-
Unsaturated polyester (UPR)	Vinyl ester resin	Resin	M_w : 400-500 g/mol
	Cobalt promoter	Accelerator	White powder
	Benzoyl peroxide (BPO)	Curing agent	10% solution
Fluorinated unsaturated polyester (F-UPR)	Vinyl ester resin	Resin	M_w : 400-500 g/mol
	Cobalt promoter	Accelerator	White powder
	Benzoyl peroxide (BPO)	Curing agent	10% solution
	Perfluorooctane (PFO)	Fluorinated agent	13-fluorinated liquid

Vinyl ester adhesives, both with and without fluorinated agents, were prepared according to the ratios in Table 2. Initially, vinyl ester resin, cobalt accelerator, and fluorinated agent (if applicable) were mixed thoroughly. Then, benzoyl peroxide (BPO) was added. To

overcome the very short pot life of these systems, microcapsules containing BPO were used, enabling curing to occur only after adhesive application and compression of the plates. Complete curing was performed in an oven at 50 °C for 1 h.

Table 2. Formulation ratios of the adhesives.

Base	Sample code	Raw material	Role	Parts per hundred resin (phr)
Epoxy	EP-D	Epoxy	Resin	100
		Diethylenetriamine (DETA)	Hardener	11
		Triethanolamine (TEA)	Accelerator	1-2
	EP-P	Epoxy	Resin	100
		Diaminodicyclohexylmethane (PACM, −4.4)	Hardener	28
		Triethanolamine (TEA)	Accelerator	1-2
Epoxy-phenolic (Novolac)	EP-Ph5	Epoxy	Resin	100
		Diaminodicyclohexylmethane (PACM, −4.4)	Hardener	28
		Triethanolamine (TEA)	Accelerator	1-2
		p-tert-Butylphenol-formaldehyde resole (CK)	Phenolic curing agent	5
	EP-Ph10	Epoxy	Resin	100
		Diaminodicyclohexylmethane (PACM, −4.4)	Hardener	28
		Triethanolamine (TEA)	Accelerator	1-2
		p-tert-Butylphenol-formaldehyde resole (CK)	Phenolic curing agent	10
	VES	Vinyl ester resin	Resin	100
		Cobalt promoter	Accelerator	1
		Microcapsulated benzoyl peroxide (BPO)	Curing agent	5
Vinyl ester resin (fluorinated and non-fluorinated)	VES-PFO5	Vinyl ester resin	Resin	100
		Cobalt promoter	Accelerator	1
		Benzoyl peroxide (BPO)	Curing agent	5
		Perfluorooctane (PFO)	Fluorinated agent	5

For EP-Ph10 samples, after mixing all ingredients according to Table 2, the adhesive was applied and cured in an oven at 100 °C for 1 h (Figure 1).

2.2 Standard tests on adhesives

In this section, the procedures for lap shear strength testing, pot life measurement, thermal resistance evaluation, fuel cell simulation, and chemical resistance tests are described. Lap shear strength test was conducted under conditions similar to ASTM D1002. Composite strips with dimensions of $1.8 \times 7 \text{ cm}^2$ were prepared (Figure 2).

The preparation procedure is demonstrated in Figure 3, included degreasing with acetone (Figure 3a), marking the adhesive application area (Figure 3b), applying the adhesive with a thickness of about 500 μm over an area of $1.27 \times 1.8 \text{ cm}^2$ (Figure 3c), bonding two composite strips at a 180° angle with sufficient clamping pressure (Figure 3d), curing in an oven (Figure 3e) according to the conditions in Table 2.

The bonded strips were tested using a Santam STM-20 universal tensile testing machine, with a

crosshead speed of 1.3 mm/min under a 180° pulling angle. Each sample was tested in triplicate.

Pot life is an important parameter in adhesive systems, representing the usable working time after mixing. It was measured according to ISO 9514, defined as the time required for the viscosity of a 250 g sample to increase by 100% compared to its initial viscosity. Pot life was determined using a SubCASE pot life tester and a Brookfield Yr-1 rheometer.

After curing in an 80 °C oven, adhesive samples were tested using thermogravimetric analysis (TGA) to evaluate thermal degradation behavior. Tests were conducted with a TGA-PL 1500 instrument (UK) under nitrogen atmosphere at a heating rate of 10 °C/min from 25 to 700 °C. To simulate the harsh acidic environment of a fuel cell, an accelerated durability test (ADT) solution was prepared by dissolving 48% HF and 98% H_2SO_4 in deionized water to yield 1 M H_2SO_4 with 10 ppm HF. The test was carried out at 60 °C and 80 °C, close to practical operating conditions of PEMFCs.

To evaluate chemical stability, adhesive specimens of defined weight and dimensions were immersed in

0.05 M H_2SO_4 (pH 1), 0.001 M H_2SO_4 (pH 3), 0.1 M HF (pH 1), and 0.001 M HF (pH 3) for 70 h and 30 days at room temperature, following ASTM D471. After immersion, samples were dried and weight changes were measured. The weight change was calculated using the following equation:

$$\text{Change in mass, \%} = \frac{M_2 - M_1}{M_1} \times 100 \quad (1)$$

where M_1 is the initial weight and M_2 is the post-immersion weight. Samples showing less than 1% weight change were considered to have high chemical resistance. Each test was repeated three times for reliability.

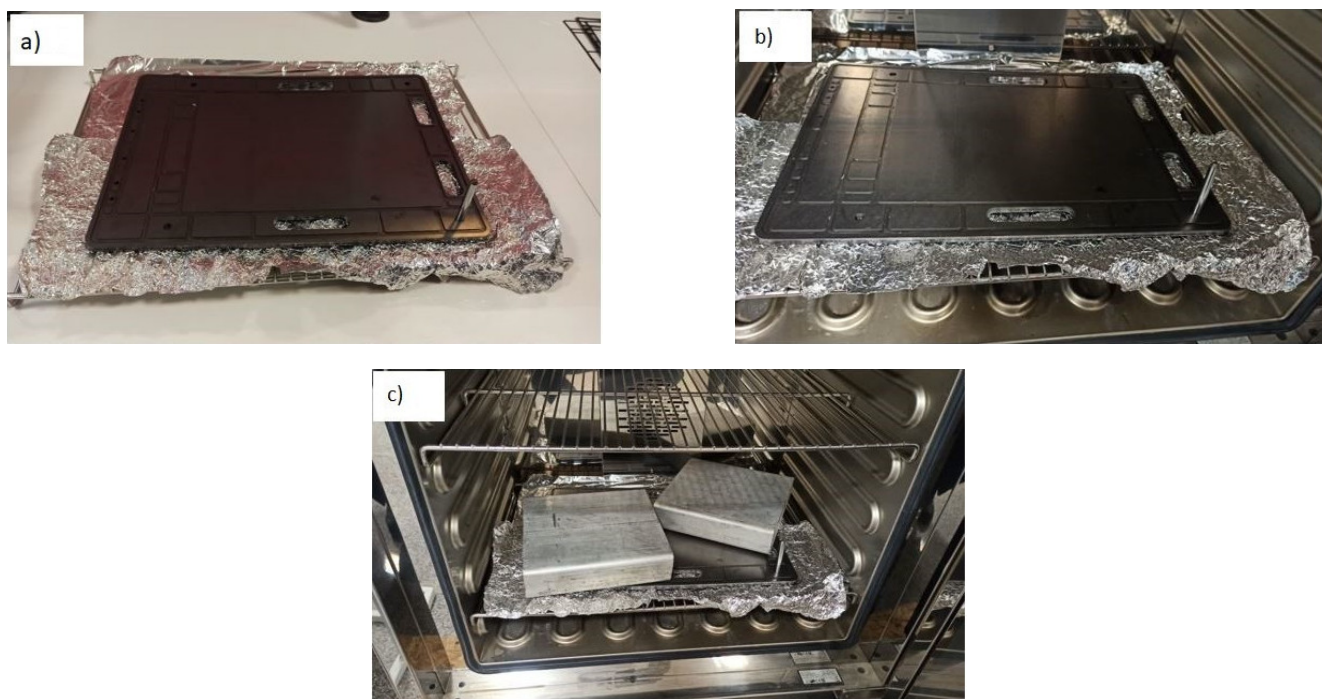


Fig. 1. Steps of preparing EP-Ph10 and curing at 100 °C.

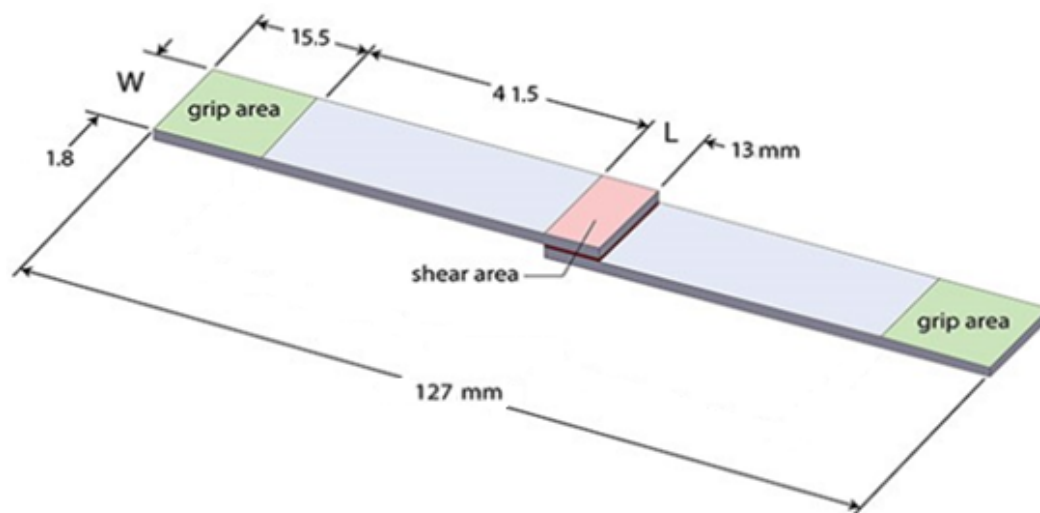


Fig. 2. Dimensions of composite strips for lap shear strength test.

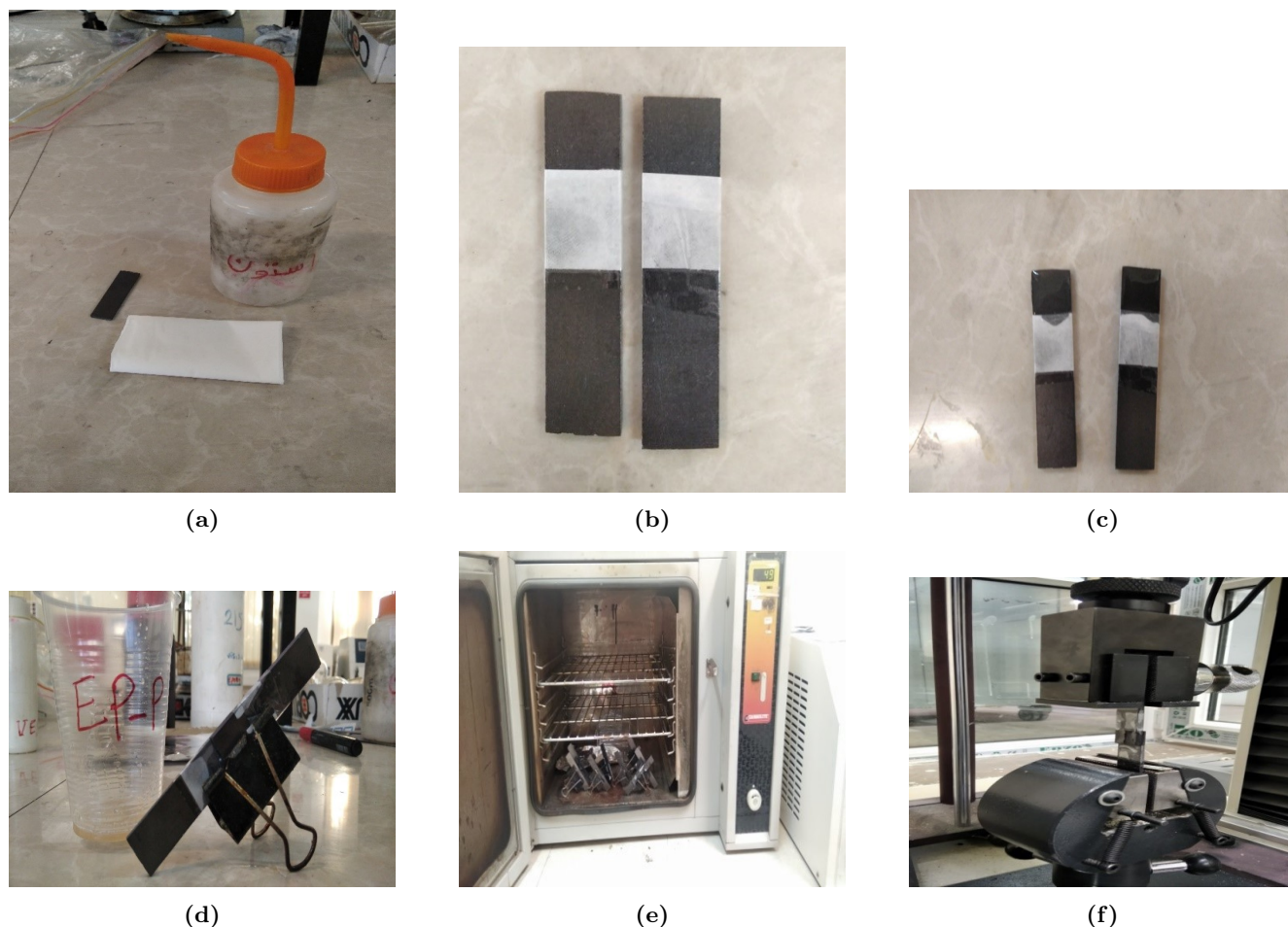


Fig. 3. Steps for preparing bonded composite strips for lap shear testing.

3 Results and Discussion

In this section, the results of lap shear strength, pot life, chemical resistance, thermal resistance, surface morphology, sealing performance, and fuel cell environment simulation are presented and discussed.

3.1 Lap shear strength

The lap shear strength test showed that all adhesives exhibited shear strength values above 1 MPa. The exact adhesive strengths on composite strips could not be measured beyond this level, because the composite strips themselves fractured while the adhesive joints remained intact (Figure 4).

To further evaluate the adhesives, lap shear tests were also performed on aluminum strips. Figure 5 shows the modulus and shear strength at fracture for all adhesives applied to aluminum substrates.



Fig. 4. Complete fracture of composite strips during lap shear testing.

Results indicated that epoxy-based adhesives demonstrated the highest strength and modulus. The presence of aromatic rings in epoxy structure contributes to both high chemical resistance and high elastic modulus due to reduced chain mobility and increased relaxation times. Quantitatively, EP-Ph10 = 10.2 MPa and 3.7 GPa, EP-Ph5 = 10.2 MPa and 3.4 GPa, EP-P = 9.6 MPa and 2.5 GPa, EP-D = 8.9 MPa and 2.2 GPa, VES-PFO5 = 8.4 MPa and 2.7 GPa, and VES = 8.3 MPa and 2.7 GPa.

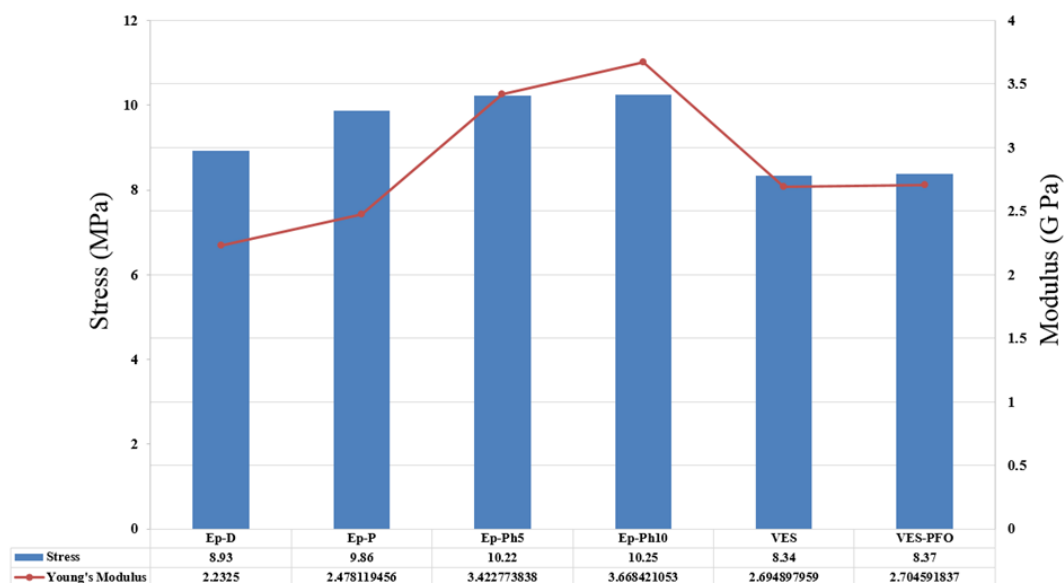


Fig. 5. Modulus and strength at fracture for different adhesives on aluminum strips.

Comparing EP-D and EP-P samples revealed that the cycloaliphatic segments of PACM hardener enhanced mechanical properties compared with the linear amine hardener in EP-D. Consequently, EP-P also showed a higher glass transition temperature. Incorporation of phenolic resol resin into epoxy (EP-Ph5, EP-Ph10) further improved modulus and shear strength due to the high number of aromatic rings, which increased cross-link density and chain rigidity. However, no significant difference was observed between EP-Ph5 and EP-Ph10.

Vinyl ester adhesives (VES, VES-PFO5) showed

lower strength than epoxy adhesives, though their modulus values were comparable. The high cross-link density and limited free volume of vinyl ester systems reduced chain relaxation time, increasing modulus but limiting elongation. Addition of fluorinated side chains (VES-PFO5) did not significantly affect mechanical strength but was expected to improve chemical resistance.

Strain at fracture for different adhesives is shown in Figure 6. As expected, both epoxy and vinyl ester adhesives showed very low elongation at break ($< 1\%$) due to their rigid cross-linked networks.

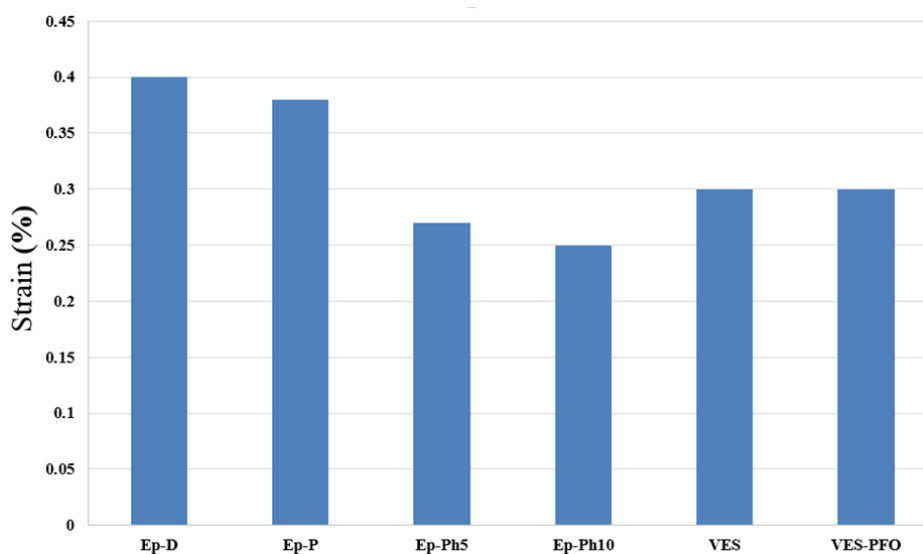


Fig. 6. Strain at fracture for different adhesives.

3.2 Pot life

Pot life values of adhesives are summarized in Table 3. Vinyl ester adhesives polymerize via radical mechanisms with inherently fast reaction rates, giving them

very short pot life. To overcome this, encapsulated BPO was used, so that curing only began after microcapsules were ruptured under pressure during plate assembly. In such systems, pot life is practically undefined.

Table 3. Pot life of adhesives.

Code	Ep-D	Ep-P	Ep-Ph5	Ep-Ph10	VES		VES-PFO	
					bpo	m-bpo	bpo	m-bpo
Pot life	15-25 min	25-40 min	> 1 h	> 1 h	1-10 min	> 1 h	1-10 min	≫ 1 h

3.3 Chemical resistance

Chemical resistance tests in H_2SO_4 and HF solutions at different concentrations showed that: EP-D exhibited < 0.5% weight loss after 70 h, ~ 2.0% weight loss in H_2SO_4 (pH 1), and ~ 3.0% weight loss in HF (pH 1) after 30 days. EP-P, EP-Ph5, EP-Ph10, VES, and VES-PFO5 all demonstrated < 0.5% weight loss under the same conditions, indicating excellent chemical stability.

VES and VES-PFO: Both showed no measurable weight loss in either H_2SO_4 or HF, even after 30 days. The dense 3D network and chemical stability of fluorinated groups contributed to exceptional resistance. VES-PFO was expected to outperform under harsher conditions due to strong C–F bonds. Overall, all adhesives showed high resistance at pH 3, while EP-D was less stable at pH 1 over extended periods. Table 4 summarizes mechanical and chemical performance of different adhesives.

Table 4. Roughness parameters from AFM images.

Adhesive	Shear Strength (MPa)	Weight Loss 30 days (H_2SO_4 , pH $\approx$ 1)	Weight Loss 30 days (HF, pH $\approx$ 1)
EP-Ph10	10.2	< 0.5%	< 0.5%
EP-Ph5	10.2	< 0.5%	< 0.5%
EP-P	9.6	< 0.5%	< 0.5%
VES-PFO5	8.4	< 0.5%	< 0.5%
VES	8.3	< 0.5%	< 0.5%
EP-D	8.9	~ 2.0%	~ 3.0%

3.4 Thermal resistance

Thermogravimetric analysis results are shown in Figure 7. All samples showed < 5% weight loss below 120 °C, attributed to moisture, solvent residues, and low molecular weight species. VES and VES-PFO showed gradual weight loss between 300–350 °C due to carbon chain degradation. A secondary weight loss

in VES-PFO near 400 °C corresponded to decomposition of C–F bonds. Epoxy systems degraded mainly between 350–450 °C, with secondary degradation at 450–550 °C for EP-Ph5 and EP-Ph10, associated with phenolic cross-link decomposition. Epoxy-phenolic systems exhibited superior thermal stability compared with neat epoxy and vinyl ester adhesives, confirming the stabilizing effect of phenolic groups.

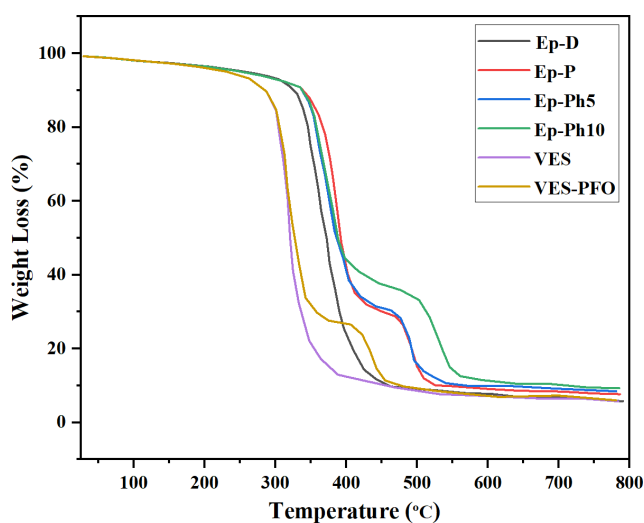


Fig. 7. TGA curves of different adhesives.

3.5 Surface morphology

The dispersion state and fracture morphology of adhesives EP, EP-P, EP-Ph5, and EP-Ph10 are shown in Figure 8 at a 20 μm scale. EP matrix displayed a smooth, compact surface typical of brittle fracture. EP-Ph5 showed a rough fracture surface with numerous micro-voids across the surface, indicating strong interfacial interactions.

Incorporation of phenolic chains into epoxy created layered structures, suggesting cross-linking between epoxy and phenolic components. VES and VES-PFO exhibited smoother fracture surfaces compared to

epoxy-phenolic adhesives, consistent with lower hardness and toughness.

AFM analysis further confirmed these observations (Figure 9, Table 5). VES and VES-PFO exhibited smoother surfaces with lower roughness (R , S_y , S_a), whereas EP-Ph5 and EP-Ph10 showed higher roughness, leading to increased surface energy and hydrophilicity.

Table 5. Roughness parameters from AFM images.

Sample	S_y (nm)	R (nm)	S_a (μm^2)
EP	212.4	58	172
EP-P	200.6	54	168
EP-Ph5	360.5	72	240
EP-Ph10	380.3	76	261
VES	180	46	120
VES-PFO	140.4	41	117

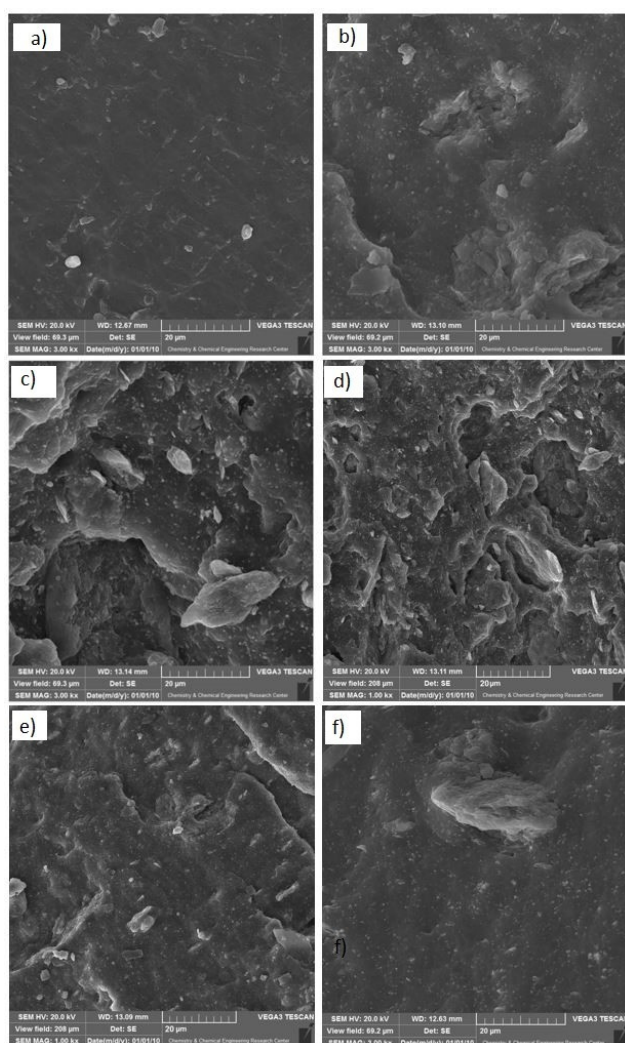


Fig. 8. Fracture surface morphology of adhesives: (a) EP, (b) EP-P, (c) EP-Ph5, (d) EP-Ph10, (e) VES, (f) VES-PFO.

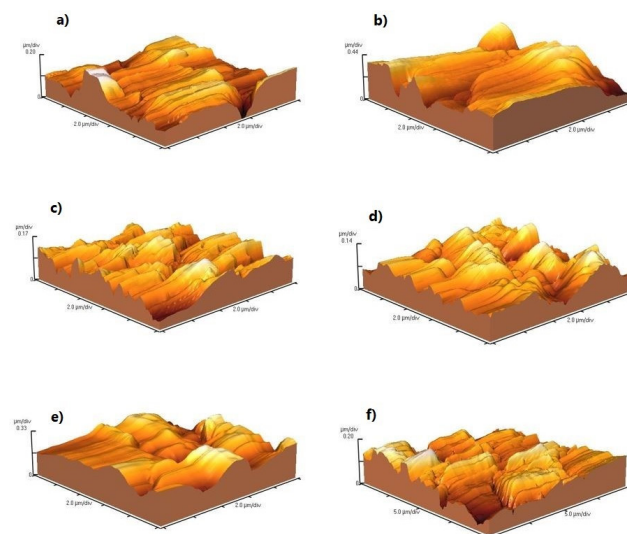


Fig. 9. AFM images of adhesives: (a) EP, (b) EP-P, (c) EP-Ph5, (d) EP-Ph10, (e) VES, (f) VES-PFO.

3.6 Thermal resistance

This test evaluated gas leakage resistance of adhesives. For EP-Ph10, samples were subjected to 2 bar N_2 pressure for 10 min. The pressure dropped only by 0.03 bar, demonstrating excellent sealing performance.

3.7 Thermal resistance

To simulate fuel cell conditions, adhesives were exposed to an acidic environment containing H_2SO_4 (1 M) and HF (10 ppm), with $\text{pH} < 1$, at 23°C and 80°C . Although real PEMFCs typically operate at pH 3–3.5, harsher conditions were applied to accelerate degradation.

Figure 10 shows the weight loss of different adhesives over 43 days. EP-Ph10 demonstrated the lowest weight loss ($\sim 2\%$), confirming that the presence of phenolic groups and strong epoxy-phenolic interactions enhanced stability.

4 Conclusion

In this study, the performance of adhesives based on epoxy (EP-D, EP-P), epoxy modified with phenolic resin (EP-Ph5, EP-Ph10), unsaturated polyester (VES), and fluorinated unsaturated polyester (VES-PFO5) was evaluated for potential use in fuel cells. Key parameters considered included adhesion strength, effective sealing, ease of preparation and application, and long-term chemical stability. Various tests such as lap shear strength, pot life, chemical resistance, thermal resistance, surface morphology, sealing, and fuel cell

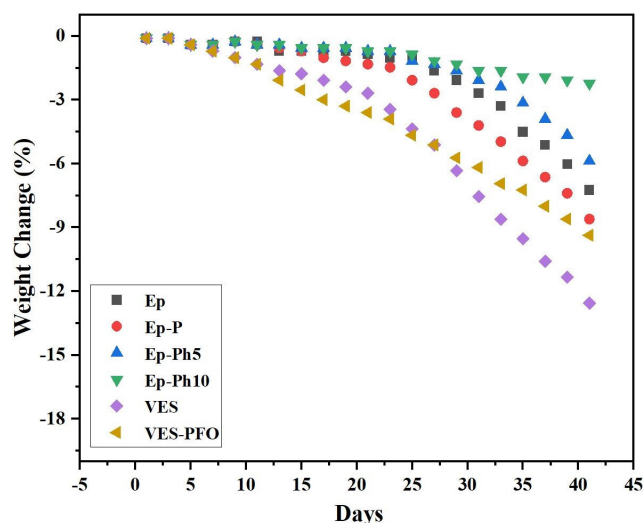


Fig. 10. Accelerated durability test (ADT) results for EP, EP-P, EP-Ph5, EP-Ph10, VES, and VES-PFO.

environment simulation were carried out. The results demonstrated the superior performance of epoxy-phenolic adhesives, particularly EP-Ph10, under fuel cell operating conditions. Lap shear tests showed that epoxy adhesives containing aromatic and cycloaliphatic structures (EP-P, EP-Ph5, EP-Ph10) provided the highest strength due to their dense cross-linked networks. Vinyl ester adhesives (VES, VES-PFO) exhibited 20–30% lower strength but maintained comparable modulus, making them suitable for applications with limited dynamic stress. Chemical resistance tests revealed that epoxy-phenolic adhesives experienced negligible weight loss ($< 1\%$) even after 30 days in acidic environments, while EP-D showed 2–3% weight loss at pH 1. Vinyl ester adhesives, especially VES-PFO, showed excellent resistance due to dense cross-linking and the presence of strong C-F bonds.

Thermogravimetric analysis confirmed that epoxy-phenolic systems had higher thermal stability compared to neat epoxy and vinyl ester adhesives, attributed to the stabilizing role of phenolic groups. Surface morphology tests indicated rougher and more porous fracture surfaces in EP-Ph10, associated with strong epoxy-phenolic interactions, while vinyl ester adhesives exhibited smoother and harder surfaces. Sealing tests under 2 bar nitrogen showed only a 0.03 bar pressure drop for EP-Ph10, confirming its suitability as a sealing adhesive. In accelerated fuel cell simulation tests (pH 1, 23–80 °C, 43 days), EP-Ph10 again demonstrated the lowest weight loss ($\sim 2\%$), highlighting its excellent balance of mechanical strength, chemical/thermal stability, and sealing capability. Therefore, epoxy-phenolic adhesives with high phenolic content (such as EP-Ph10) are the optimal choice for fuel cell

applications, providing a superior combination of mechanical strength, thermal-chemical stability, and sealing performance. Quantitative evaluation confirmed that EP-Ph10 provided the highest performance, with 10.2 MPa shear strength and $< 0.5\%$ weight loss after 30 days, while EP-D showed $\sim 2.0\%$ loss in H_2SO_4 and $\sim 3.0\%$ in HF, representing comparatively lower chemical stability.

Declaration

Conflict of interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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