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Thermal Characterization of Stoichiometrically Varied Epoxy Networks under Elevated Heating Rates via Differential Scanning Calorimetry

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ABSTRACT

This study presents a differential scanning calorimetry (DSC) investigation of epoxy thermosets formulated with varying stoichiometric resin-to-hardener ratios (1:1, 2:1, and 3:1) subjected to non-isothermal heating conditions. The influence of high heating rates of 15 °C/min for the epoxy-hardener ratio 1:1, 2:1 and 3:1 on the thermal transitions, residual cure behavior, and thermal stability was analyzed. The results demonstrate that deviations from stoichiometric balance significantly alter the thermal response of the cured networks. The 1:1 system exhibited a more uniform and complete cure with higher thermal stability, while excess amine 2:1 and excess epoxy 3:1 formulation exhibited prominent post-curing exotherms and thermodynamic instability. The glass transition occurred between 54.36 °C and 53.65°C for the ratios 2:1 and 3:1. The 1:1 ratio, among the tested stoichiometries, approximates this behavior under the applied high heating rate. Both 2:1 and 3:1 ratio demonstrated deficiencies in thermal parameters, confirming their suboptimal thermal and structural performance due to stoichiometric imbalance.

1 Introduction

Epoxy resins are widely used structural adhesives, valued for their exceptional bonding capabilities, heat, solvent, and chemical resistance, good mechanical and electrical properties, and strong adherence to many substrates [1, 2-5]. Epoxy adhesives offer a range of superior physical, chemical, electrical, and mechanical properties [6]. Epoxy adhesives are typically two-component systems, where components are mixed just before use and cure at room temperature [2]. The fundamental chemical composition often involves bisphenol A molecules with an epoxide functional group like Di glycidyl ether of bisphenol A - DGEBA and amine-based hardeners such as polyoxypropylenediamine, triethylentetramine, dicyandiamide - DICY [7-9]. The curing process involves these amines reacting with epoxide groups to form covalent bonds, leading to cross-

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linking between polymer chains and the formation of a non-crystalline hardened molecular structure. A fully-cured epoxy has achieved its full mechanical properties with no additional cross-linking possible [8].

The mechanical properties of epoxy adhesives are crucial for their application and are influenced by their composition and curing conditions. Epoxy resins are generally considered brittle materials with fracture energy values significantly lower than thermoplastics or metals. Lower crosslink density can improve toughness by allowing greater elongation before failure, while higher crosslink density improves chemical resistance and raises the glass transition temperature (T_g) but reduces strain to failure [4]. The curing conditions significantly affect mechanical properties. It is often advisable for some epoxies to undergo a final curing stage at higher temperatures than the initial cure to improve mechanical properties [2]. These adhesives are susceptible to creep, defined as the increase in deformation over time under sustained stress. This is a crucial property for long-term efficacy in strengthening systems, especially with prestressed applications [10]. The creep behaviour of epoxy adhesives can be modelled using rheological models, such as the modified Burgers model, which can predict long-term behaviour accurately up to 60% of the adhesive's tensile strength [1, 9]. Costa et al., [9] show that epoxy adhesives can withstand deformation levels twice their ultimate strain during creep tests without rupturing, indicating their ability to reorganise internal structure under sustained load. However, a loss of stiffness i.e. creep modulus has been observed with the age of the adhesive, suggesting an ageing effect on the adhesive constituents [9].

Epoxy adhesives are susceptible to environmental factors, particularly moisture and temperature, which can significantly affect their long-term performance and durability [2, 4]. They absorb water due to the presence of polar groups that attract water molecules [11]. Water molecules interact with hydroxyl groups in the epoxy network via hydrogen bonding, increasing free volume and leading to plasticization. Plasticization reduces T_g , leading to a decrease in stiffness and strength [8]. Water can act as a catalyst for the curing reaction, accelerating it up to a saturation point. However, excess water can offset this acceleration and lead to poorer mechanical properties and durability of the cured epoxy [3]. Adverse effects of water absorption include swelling like weakening adhesion and reducing strength, hydrolysis effect such as breaking chemical bonds, and corrosion of metal substrates. These effects are detrimental at humidity levels higher than 75% [2]. Water absorption occurs faster at higher conditioning temperatures, due to increased energy of water molecules and greater diffusion into the epoxy network. Moisture equilibrium is typically attained within 2 weeks of exposure [8].

The toughening effect observed with dispersed rubbery particles is primarily attributed to plastic deformation of the epoxy matrix, which serves as the main mechanism for energy dissipation and increased toughness. This enhanced plastic deformation arises from the interactions between the stress field that develops ahead of a propagating crack tip and the rubbery particles [6, 12]. Epoxy adhesives when polymerised, epoxy adhesives form an amorphous and highly cross-linked material, providing high modulus and failure strength [6]. These adhesives are widely valued for their strong bonding capabilities and robust mechanical, chemical, and electrical properties [6, 13, 14]. However, a significant inherent challenge is their brittleness [12, 13]. This brittleness stems from their amorphous and highly cross-linked microstructure, which, while providing high modulus and failure strength, results in poor resistance to crack initiation and growth, leading to low fracture toughness and impact strength [12-15]. The fractured surfaces of neat epoxy often appear smooth, characteristic of brittle fracture [6, 16]. To address this, various modification mechanisms are employed to enhance toughness and ductility.

The toughening primarily relies on plastic deformation of the epoxy matrix, which dissipates energy and increases toughness [12-14]. Rubbery particles, having a lower shear modulus, create tensile-stress concentrations around their equator. These act as initiation sites for multiple localised shear-yield deformations in the epoxy matrix [12, 13]. Particle cavitation like void formation within rubbery particles is crucial. It reduces stress triaxiality in the adjacent matrix, promoting further plastic deformation and plastic void growth [12, 14, 17]. Carboxyl-terminated butadiene acrylonitrile (CTBN) is a common liquid rubber used. It is pre-reacted with epoxy resin to form an adduct that undergoes in-situ phase separation during polymerisation. This forms well-dispersed spherical particles which are typically 0.5–2 μm in diameter, 15-20% volume fraction within the epoxy matrix [12, 13]. Nanoparticles, with dimensions below 100 nm, offer a unique combination of mechanical and physical properties due to their large surface area and high surface energy. They can significantly improve toughness, tensile, lap-shear, and compressive strength, and enhance thermal stability and T_g [14-18]. Nanoparticles improve toughness through mechanisms like crack bridging, nanoparticles breaking, and crack deviation [6, 19]. They can restrict crack propagation, force cracks to take a longer path, or induce plastic deformation in the matrix [6, 13, 15, 19]. Nanoparticles can influence the glass transition temperature (T_g). When homogeneously dispersed with strong interfacial properties, they may increase T_g . However, increasing nanoparticle content can also decrease T_g by filling the free volume of the epoxy resin [6, 14]. 15 wt% CuNPs improved tensile strength, 20 wt% CuNPs was found to be the proper ratio for improving thermal properties of epoxy adhesives. However, the study also notes that higher CuNP ratios could decrease thermal stability,

potentially because the metallic nanoparticles absorb heat and then act as a heat source, causing the epoxy matrix to reach its decomposition temperature. They generally increased the residual mass after degradation, but did not significantly change decomposition temperatures [6, 13]. Nano- Al_2O_3 can enhance thermal stability and char yield, particularly when surface-treated. Improvement is attributed to increased crosslinking networks, enhanced interaction between nanoparticles and polymer chains, and prevention of agglomeration. Optimal loading is crucial, as too high content above 10 wt% can lead to a decrease in thermal stability due to perturbation of the polymer's three-dimensional structure and particle agglomeration [6, 19]. Multi-walled Carbon Nanotubes (MWCNTs) have been shown to increase the thermal stability of epoxy adhesives, primarily due to their outstanding thermal conductivity and their ability to restrict the deformation of the epoxy matrix when well-dispersed. Nanoclays can contribute to a marginal increase in thermal stability by providing a barrier action that restricts the segmental motion of polymer chains within the layers, thereby minimising volatilisation [16]. A combination of MWCNTs and nanoclay can result in substantially higher thermal stability compared to neat epoxy or individual nanofillers. This is because the hybrid filler forms a hybrid network structure that acts as a physical crosslinking point, restricting polymer chain movement and delaying degradation. The activation energy of degradation for an epoxy system with both MWCNT and C30B was significantly higher than the virgin epoxy [6, 16]. Nanoparticles can influence the glass transition temperature (T_g). When homogeneously dispersed with strong interfacial properties, they may increase T_g . However, increasing nanoparticle content can also decrease T_g by filling the free volume of the epoxy resin [6, 14].

Surface treatment of nanoparticles with silanes or diisocyanate is beneficial for improving thermal conductivity and stability. This is achieved by reducing thermal contact resistance and improving the interface between the filler and the matrix, which helps in better dispersion and load transfer. However, over-coating with silane or high activity of certain agents (like TDI) can negatively impact thermal conductivity by creating a thermal barrier [6, 20].

2 Methodology

The methodology of the above-mentioned research follows a formulated range of epoxy resin and hardener combinations from Fig. 1, ensuring that the stoichiometric ratios are meticulously controlled. This is generally entails adjusting the epoxy-to-hardener equivalent ratios such as 1:1, 2:1, and 3:1 epoxy: hardener to investigate the effects of off-stoichiometry including both epoxy-rich and hardener-rich formulations on thermal characteristics. The samples are precisely measured to the specified quantities of epoxy resin, hardener into individual containers. The samples are carefully combined the elements to achieve uniformity. Mechanical stirring, potentially enhanced by mild heating, followed by degassing under vacuum, are essential procedures for the removal of air bubbles.



Fig. 1 –Epoxy Resin and Hardener

2.1 Testing

The testing method utilizes a dynamic heating protocol for thermal characterization. This process entails raising the samples from a temperature significantly lower than their anticipated glass transition temperature (T_g) to a level considerably higher than their decomposition temperature, or to a temperature adequate for observing all pertinent transitions. Differential Scanning Calorimetry (DSC) examines curing behaviour, glass transition temperature (T_g), and reaction heat [6, 16, 21-25].

3 Results and Discussions

The DSC thermograms of varied epoxy ratio at 15 °C/min heating rate are depicted in Fig. 2, 3 and 4. Thermal stability can be described by the initial decrement temperature (IDT), where a higher IDT indicates greater thermal stability [6, 23]. The decomposition temperature signifies the limit of a material's thermal stability [13]. When epoxy's temperature momentarily exceeds T_g , post-curing can occur, leading to increased cross-linking and a subsequent increase in T_g [2, 8]. Elevated conditioning temperatures can provide additional energy for cross-linking, increasing conversion [8]. Young's modulus generally decreases with increasing temperatures during tests, but may increase at sub-zero temperatures. Tensile strength and Young's modulus are closely correlated, generally increasing or decreasing together [2]. The comparative thermal stability of the epoxy with varying ratios is depicted in table 1.

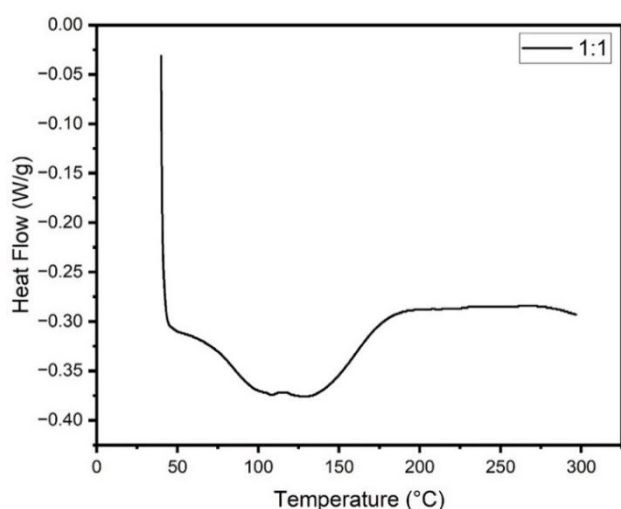


Fig. 2–DSC Thermogram of Epoxy 1:1 at 15 °C/min

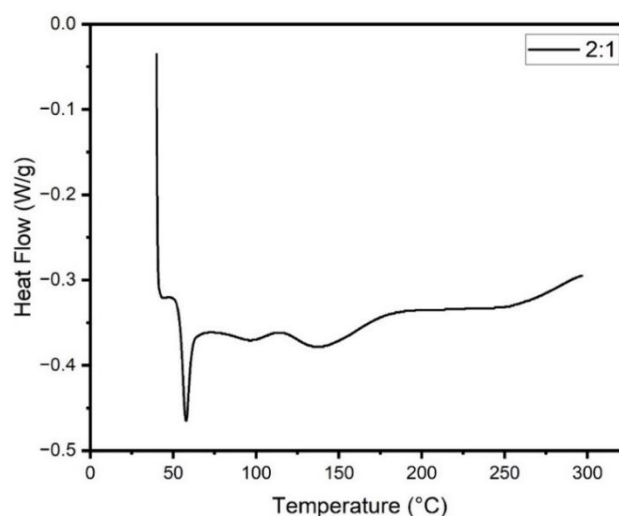


Fig. 3–DSC Thermogram of Epoxy 2:1 at 15 °C/min

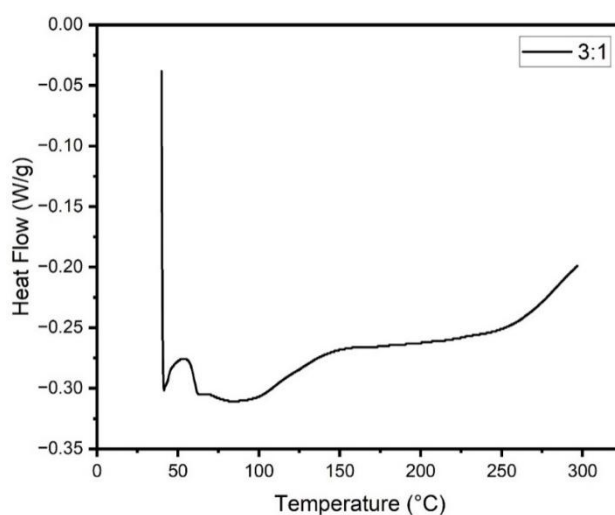


Fig. 4–DSC Thermogram of Epoxy 3:1 at 15 °C/min

Table 1 –Comparative Thermal Stability

Formulation	Heating Rate (°C/min)	Glass Transition Temperature T_g (°C)	Residual Exotherm (°C)	Thermal Stability	Network Quality
1:1	15	54.36	150–200	High	High (stoichiometric)
2:1	15	54.36	130–180	Moderate	Incomplete (amine-rich)
3:1	15	43.63	100–250	Low	Poor (resin-rich)

Table 2–Summarized Thermal Stability Parameters

Parameter	Definition	Influence on Stability	Observed Trend
T_g (°C)	Glass transition temp	Higher $T_g \rightarrow$ more stable	Highest in 1:1
ΔH cure (J/g)	Residual curing enthalpy	Lower $\Delta H \rightarrow$ more cured $\rightarrow$ more stable	Lowest in 1:1
Post- T_g Slope	Slope of baseline	Flat = stable, Curved = active	Flat in 1:1, rising in 3:1
T_d (°C)	Degradation onset	Higher $T_d \rightarrow$ stable	Implicit in 1:1 (above 300°C)
Crosslink Density	Degree of network connectivity	Higher $\rightarrow$ greater stability	Implied high in 1:1
Homogeneity	T_g breadth and number of transitions	Single T_g = stable network	1:1 > 2:1 > 3:1

3.1 Glass Transition Temperature (T_g)

The T_g is a critical property, representing the temperature at which epoxy transitions from a hard, relatively brittle state to a rubber-like state [2, 8]. T_g is dependent on polymer chain mobility, which is influenced by cross-linking density and free volume [8]. T_g is a critical thermal property that limits the usable temperature range of an adhesive [6, 13, 14]. The glass transition temperature (T_g) is a critical indicator of polymer network rigidity and thermal endurance. It marks the temperature range over which the epoxy network transitions from a glassy, rigid state to a rubbery, flexible one due to the onset of segmental chain mobility. Higher cross-linking density leads to higher T_g [8]. In highly crosslinked systems, T_g tends to be higher and sharper, reflecting restricted molecular motion. In the current study from Fig. 5(a), the 1:1 stoichiometric formulation exhibited a broad but elevated T_g window from approximately 60°C to 120°C, signifying a well-developed three-dimensional network with substantial crosslinking. By contrast, from Fig. 5 (b), (c) the 2:1 and 3:1 system demonstrated lower T_g onsets (~55°C), suggesting either residual chain mobility or plasticization due to unreacted constituents. The broad T_g in these off-stoichiometric systems indicates a wider distribution of molecular environments and heterogeneous network formation, both of which reduce thermal stability under operational heating conditions.

3.2 Residual Cure Exotherm (ΔH cure)

The presence and magnitude of a post-glass transition exothermic peak in DSC thermograms serve as a measure of residual curing activity, expressed as the residual cure enthalpy. This value represents the latent chemical reactivity within the system due to unreacted epoxy or amine groups. Ideally, a fully cured epoxy system will exhibit little to no exothermic activity in this region. From table 1, the 1:1 formulation produced a minimal post-curing peak in the range of 150–200°C, suggesting near-complete reaction and high conversion during the initial curing process. In contrast, the 2:1 and 3:1 system displayed significant exothermic peaks, particularly the 3:1 system with a pronounced release extending up to 250°C. This behavior confirms the presence of substantial unreacted monomers and implies inadequate curing during the initial processing phase. A large ΔH cure is associated with reduced thermal reliability, as continued curing during service may lead to dimensional changes, localized stress build-up, or even thermal runaway in tightly confined applications.

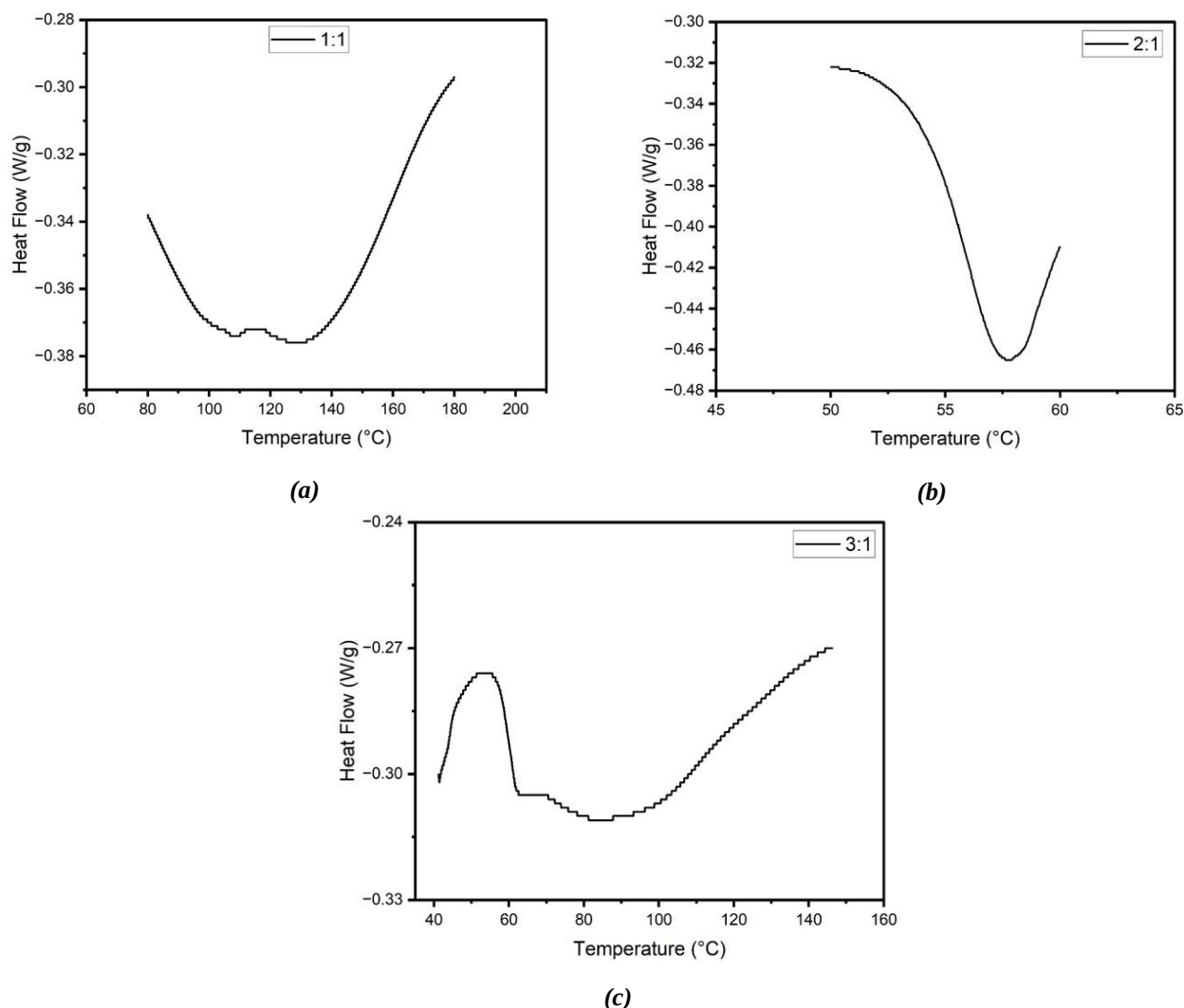


Fig. 5–Glass Transition Regions of Epoxy (a) 1:1 (b) 2:1 (c) 3:1

3.3 Post- T_g Heat Flow Baseline Behavior

The stability of the heat flow baseline after the T_g region provides additional insight into the thermodynamic equilibrium of the polymer network. A flat and steady baseline indicates thermal inertness and completion of all major transition and reaction events. The 1:1 formulation exhibited such a characteristic, with a smooth post- T_g baseline consistent with a stable and well-cured network. On the other hand, both the 2:1 and 3:1 system displayed rising or fluctuating baselines, indicative of ongoing secondary transitions such as enthalpic relaxation, late-stage curing, or segmental rearrangement. These deviations reflect the presence of mobile species or loosely constrained chains, both of which can compromise the material's thermal stability and dimensional accuracy during long-term thermal cycling.

3.4 Crosslink Density

Crosslink density, though not directly measurable through DSC, can be qualitatively inferred by examining the T_g position and ΔH cure. A tightly crosslinked network typically presents with a high T_g and low residual enthalpy. The 1:1 epoxy fulfilled this condition, suggesting optimal stoichiometry and maximal formation of a three-dimensional network. In comparison, both the 2:1 (amine-rich) and 3:1 (resin-rich) formulations showed suboptimal thermal parameters, indicative of reduced crosslink density. Excess amine leads to unreacted terminal groups and dangling chain ends, while excess resin limits network connectivity due to insufficient crosslinking agents. In both cases, the network becomes thermally vulnerable, with lower modulus and increased susceptibility to degradation.

3.5 Network Homogeneity and Phase Structure

The breadth and multiplicity of T_g transitions provide insight into the structural homogeneity of the epoxy matrix. A single, sharp T_g is typically indicative of a uniformly cured network, while a broad or multi-step transition suggests heterogeneous curing, phase separation, or the presence of microdomains with varying mobility. The DSC curve for the 1:1 formulation displayed a continuous and coherent T_g transition, pointing to a homogenous molecular architecture. In contrast, the 2:1 formulation showed overlapping shoulders in the T_g region, possibly due to regions of hardener over-concentration leading to uneven network formation. The 3:1 system, on the other hand, showed not only a broad T_g but also a high-temperature exotherm, further confirming phase heterogeneity and incomplete reaction. The summarized thermal stability parameters are depicted in table 2. These inhomogeneities often translate to poor dimensional stability, variable mechanical performance, and inconsistent thermal response under operational conditions.

4 Conclusion

The analysis of all DSC derived thermal parameters T_g , residual curing enthalpy, post T_g baseline, inferred decomposition onset, and network uniformity provides a comprehensive picture of the thermal stability of the epoxy systems. There is a delayed transition region in the 1:1 ratio. The higher crosslink density resulted in the increase in thermal resistance and reduced segmental motion. The heating rate was observed to modulate the thermal resolution of transitions, influencing the observed glass transition temperature (T_g) and exothermic event localization.

The stoichiometrically balanced 1:1 formulation consistently outperformed the off-stoichiometric systems, demonstrating the highest thermal resistance, most complete cure, and most uniform network structure.

The 2:1 and 3:1 formulation were found to be thermally inferior, primarily due to stoichiometric imbalance resulting in residual reactivity, phase heterogeneity, and lower crosslink density.

These findings reinforce the importance of precise resin-to-hardener ratios and optimized thermal curing protocols in achieving thermally robust epoxy thermosets for high performance applications.

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REFERENCES

- [1]- W. Liu, Q. Qiu, J. Wang, Z. Huo, H. Sun, Curing kinetics and properties of epoxy resin–fluorenyl diamine systems. *Polymer*, 49(20) (2008) 4399–4405. <https://doi.org/10.1016/j.polymer.2008.08.004>
- [2]- M. Kujawa, P. Paczos, Ł. Smakosz, A. Piasecki, F. Jan, K. Winkelmann, V.A. Eremeyev, Impact of thermal and humidity conditions on structural epoxy adhesives during medium-term exposure. *Int. J. Adhes. Adhes.*, 139 (2025) 103981. <https://doi.org/10.1016/j.ijadhadh.2025.103981>
- [3]- P.S. Shin, D.J. Kwon, J.H. Kim, S.I. Lee, K.L. DeVries, J.M. Park, Interfacial properties and water resistance of epoxy and CNT-epoxy adhesives on GFRP composites. *Compos. Sci. Technol.*, 142 (2017) 98–106. <https://doi.org/10.1016/j.compscitech.2017.01.026>
- [4]- P. Jojibabu, Y.X. Zhang, B.G. Prusty, A review of research advances in epoxy-based nanocomposites as adhesive materials. *Int. J. Adhes. Adhes.*, 96 (2020) 102454. <https://doi.org/10.1016/j.ijadhadh.2019.102454>
- [5]- S. Han, Q. Meng, S. Araby, T. Liu, M. Demiral, Mechanical and electrical properties of graphene and carbon nanotube reinforced epoxy adhesives: Experimental and numerical analysis. *Compos. Part A Appl. Sci. Manuf.*, 120 (2019) 116–126. <https://doi.org/10.1016/j.compositesa.2019.02.027>
- [6]- P. Tranchard, S. Duquesne, F. Samyn, B. Estebe, S. Bourbigot, Kinetic analysis of the thermal decomposition of a carbon fibre-reinforced epoxy resin laminate. *J. Anal. Appl. Pyrolysis*, 126 (2017) 14–21. <https://doi.org/10.1016/j.jaap.2017.07.002>
- [7]- M.P. Zanni-Deffarges, M.E.R. Shanahan, Diffusion of water into an epoxy adhesive: comparison between bulk behaviour and adhesive joints. *Int. J. Adhes. Adhes.*, 15(3) (1995) 137–142. [https://doi.org/10.1016/0143-7496\(95\)91624-F](https://doi.org/10.1016/0143-7496(95)91624-F)

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- [8]- B.P. Blackburn, J. Tatar, E.P. Douglas, H.R. Hamilton, Effects of hygrothermal conditioning on epoxy adhesives used in FRP composites. *Constr. Build. Mater.*, 96 (2015) 679–689. <https://doi.org/10.1016/j.conbuildmat.2015.08.056>
- [9]- I. Costa, J. Barros, Tensile creep of a structural epoxy adhesive: Experimental and analytical characterization. *Int. J. Adhes. Adhes.*, 59 (2015) 115–124. <https://doi.org/10.1016/j.ijadhadh.2015.02.006>
- [10]- C.W. Feng, C.W. Keong, Y.P. Hsueh, Y.Y. Wang, H.J. Sue, Modeling of long-term creep behavior of structural epoxy adhesives. *Int. J. Adhes. Adhes.*, 25(5) (2005) 427–436. <https://doi.org/10.1016/j.ijadhadh.2004.11.009>
- [11]- K.B. Armstrong, Long-term durability in water of aluminium alloy adhesive joints bonded with epoxy adhesives. *Int. J. Adhes. Adhes.*, 17(2) (1997) 89–105. [https://doi.org/10.1016/S0143-7496\(96\)00038-3](https://doi.org/10.1016/S0143-7496(96)00038-3)
- [12]- A.J. Kinloch, Toughening epoxy adhesives to meet today's challenges. *MRS Bull.*, 28(6) (2003) 445–448. <https://doi.org/10.1557/mrs2003.126>
- [13]- N. Ataberk, The effect of Cu nanoparticle adding on to epoxy-based adhesive and adhesion properties. *Sci. Rep.*, 10(1) (2020) 11038. <https://doi.org/10.1038/s41598-020-68162-4>
- [14]- Z. Ahmadi, Nanostructured epoxy adhesives: A review. *Prog. Org. Coat.*, 135 (2019) 449–453. <https://doi.org/10.1016/j.porgcoat.2019.06.028>
- [15]- A. Nemati Giv, M.R. Ayatollahi, S.H. Ghaffari, L.F. da Silva, Effect of reinforcements at different scales on mechanical properties of epoxy adhesives and adhesive joints: a review. *J. Adhes.*, 94(13) (2018) 1082–1121. <https://doi.org/10.1080/00218464.2018.1452736>
- [16]- R. Aradhana, S. Mohanty, S.K. Nayak, High performance epoxy nanocomposite adhesive: Effect of nanofillers on adhesive strength, curing and degradation kinetics. *Int. J. Adhes. Adhes.*, 84 (2018) 238–249. <https://doi.org/10.1016/j.ijadhadh.2018.03.013>
- [17]- F. González Garcia, M.E. Leyva, M.G. Oliveira, A.A.A. De Queiroz, A.Z. Simoes, Influence of chemical structure of hardener on mechanical and adhesive properties of epoxy polymers. *J. Appl. Polym. Sci.*, 117(4) (2010) 2213–2219. <https://doi.org/10.1002/app.31892>
- [18]- C. Chen, B. Li, M. Kanari, D. Lu, Epoxy adhesives. *Adhesives and Adhesive Joints in Industry Applications*, 3 (2019). <https://doi.org/10.5772/intechopen.86387>
- [19]- J. Fu, L. Shi, D. Zhang, Q. Zhong, Y. Chen, Effect of nanoparticles on the performance of thermally conductive epoxy adhesives. *Polym. Eng. Sci.*, 50(9) (2010) 1809–1819. <https://doi.org/10.1002/pen.21705>
- [20]- L. Zhai, G. Ling, J. Li, Y. Wang, The effect of nanoparticles on the adhesion of epoxy adhesive. *Mater. Lett.*, 60(25–26) (2006) 3031–3033. <https://doi.org/10.1016/j.matlet.2006.02.038>
- [21]- N.A. Razack, L.A. Varghese, The effect of various hardeners on the mechanical and thermal properties of epoxy resin. *Int. J. Eng. Res. Technol.*, 3(1.10) (2014) 17577.
- [22]- S.G. Prolongo, G. del Rosario, A. Ureña, Comparative study on the adhesive properties of different epoxy resins. *Int. J. Adhes. Adhes.*, 26(3) (2006) 125–132. <https://doi.org/10.1016/j.ijadhadh.2005.02.004>
- [23]- A. Rudawska, M. Worzakowska, E. Bociąga, E. Olewnik-Kruszkowska, Investigation of selected properties of adhesive compositions based on epoxy resins. *Int. J. Adhes. Adhes.*, 92 (2019) 23–36. <https://doi.org/10.1016/j.ijadhadh.2019.04.008>
- [24]- B.J. Anderson, Thermal stability of high temperature epoxy adhesives by thermogravimetric and adhesive strength measurements. *Polym. Degrad. Stab.*, 96(10) (2011) 1874–1881. <https://doi.org/10.1016/j.polymdegradstab.2011.07.010>
- [25]- B.K. Kandola, B. Biswas, D. Price, A.R. Horrocks, Studies on the effect of different levels of toughener and flame retardants on thermal stability of epoxy resin. *Polym. Degrad. Stab.*, 95(2) (2010) 144–152. <https://doi.org/10.1016/j.polymdegradstab.2009.11.040>