WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Mechanical and Thermal Properties of Al_2O_3-Reinforced Epoxy Composites

Dharmendra Tikle, Dr Rajeev Arya, Arun Patel

Department of Mechanical Engineering, Vidhyapeeth Institute of Science and technology, Bhopal, MP-462021

ABSTRACT

This study investigates the mechanical and thermal behavior of epoxy composites reinforced with aluminum oxide (Al_2O_3) particles, fabricated using the hand lay-up process. Composite specimens were prepared with Al_2O_3 filler loadings of 0, 2, 4, 6, 8, and 10 wt.%. Mechanical tests revealed that tensile and flexural strengths improved significantly with filler addition, reaching peak values at 6 wt.% loading. Young's modulus increased consistently up to 6 wt.% before declining, while elongation at break and impact strength decreased progressively, indicating increased brittleness. Thermal analysis demonstrated steady improvement in thermal conductivity, higher degradation onset temperatures, and elevated glass transition temperatures with increasing filler content. The results suggest that Al_2O_3 fillers enhance stiffness and thermal stability but reduce toughness. Optimal mechanical performance was observed at 4–6 wt.%, while higher loadings (8–10 wt.%) favor thermal applications. This work confirms the potential of Al_2O_3-filled epoxy composites for multifunctional structural and thermal applications.

Keywords-Epoxy composites, aluminum oxide (Al_2O_3), mechanical properties, thermal conductivity, TGA, DSC, hand lay-up method

1. Introduction

Epoxy resins are widely used as matrix materials in polymer composites due to their excellent adhesion, chemical resistance, dimensional stability, and processability. However, neat epoxy suffers from inherent drawbacks such as brittleness, low toughness, and limited thermal stability, restricting its application in high-performance environments. To overcome these limitations, particulate fillers are incorporated into epoxy matrices, enhancing their structural, thermal, and functional performance. Among various fillers, ceramic particles such as aluminum oxide (Al_2O_3) have attracted significant attention.

Al_2O_3 is an abundant, cost-effective ceramic with high hardness, thermal stability, and electrical insulation properties. When dispersed within an epoxy matrix, Al_2O_3 can improve load transfer efficiency, stiffness, and heat conduction pathways. Several studies have demonstrated that moderate filler concentrations enhance tensile and flexural properties, though higher concentrations often cause particle agglomeration, reducing toughness and mechanical integrity. Additionally, Al_2O_3's role as a thermal barrier can delay polymer degradation and raise the glass transition temperature, thereby extending the service life of epoxy composites in thermal cycling applications.

This paper experimentally investigates the influence of Al_2O_3 filler loading (0–10 wt.%) on the mechanical and thermal properties of epoxy composites. Tests conducted include tensile, flexural, and impact testing for mechanical characterization, along with thermal conductivity, thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC) for thermal assessment. The results are discussed with reference to existing literature to identify optimal filler concentrations for achieving a balance between mechanical reinforcement and thermal performance.

2. Literature Review

The incorporation of ceramic fillers into polymer matrices has been widely studied for enhancing performance. Alamri and Low (2012) showed that ceramic-filled epoxy systems demonstrate improved stiffness but reduced toughness, reflecting the balance between reinforcement and ductility. Gupta et al. (2017) reported that 5–7 wt.% Al_2O_3 in epoxy improved tensile strength while excessive loading caused agglomeration. Similarly, Khan et al. (2018) observed enhanced Young's modulus up to 6 wt.% filler, followed by a decline due to poor dispersion.

Prasad et al. (2019) studied particulate epoxy composites and confirmed that interfacial bonding plays a crucial role in mechanical enhancement. Banerjee et al. (2016) reported decreased elongation at break with ceramic addition, indicating increased brittleness. Patel et al. (2017) demonstrated that flexural strength improved up to an optimum filler content, beyond which particle clustering induced premature failure.

In terms of thermal properties, Jiang et al. (2020) emphasized that filler networks increase thermal conductivity, especially when well dispersed. Li et al. (2020) reported improved thermal stability in Al_2O_3-reinforced epoxy, attributing the effect to a barrier mechanism. Das and Biswas (2019) observed increases in glass transition temperature due to restricted polymer chain motion.

Studies on other ceramic fillers provide additional context. Wang et al. (2018) showed SiO_2-filled epoxy composites exhibited higher modulus but reduced toughness. Ramesh et al. (2016) investigated TiO_2-filled systems, noting improvements in thermal conductivity similar to Al_2O_3. Singh et al. (2019) studied hybrid fillers and concluded that combining ceramics with flexible fillers can mitigate brittleness.

Other works, including Sharma et al. (2020), Park et al. (2017), Kim et al. (2018), Choi et al. (2019), and Yadav et al. (2020), consistently support the conclusion that moderate filler concentrations maximize benefits, while excessive content leads to clustering and stress concentrations.

Collectively, these studies establish that Al_2O_3 is an effective reinforcement for epoxy matrices, offering significant improvements in stiffness and thermal stability. However, filler loading must be carefully optimized to balance strength, toughness, and thermal performance.

3. Methodology

Epoxy resin (LY556) and hardener (HY951) were used as the polymer matrix. Aluminum oxide (Al_2O_3) particles with an average size of 20–30 μm were selected as fillers. Composite specimens were fabricated using the hand lay-up technique, followed by room-temperature curing and post-curing at 80°C for 2 hours. Six different filler loadings were prepared: 0, 2, 4, 6, 8, and 10 wt.% relative to epoxy weight.

For mechanical testing, tensile properties (tensile strength, Young's modulus, elongation at break) were measured according to ASTM D638 using a universal testing machine (UTM). Flexural strength and modulus were evaluated via three-point bending tests as per ASTM D790. Impact strength was determined using Izod impact testing according to ASTM D256.

Thermal characterization involved three techniques. Thermal conductivity was measured using a transient plane source method. Thermogravimetric analysis (TGA) was performed under nitrogen atmosphere up to 600°C at 10°C/min heating rate to determine onset degradation temperature and char yield. Differential scanning calorimetry (DSC) was conducted from 25°C to 250°C at 10°C/min to identify the glass transition temperature (Tg).

4. Results and Discussion

The effect of Al_2O_3 filler loading on the mechanical and thermal properties of epoxy composites was systematically analyzed, and the results provide significant insights into the structure–property relationships of particulate-reinforced composites. The key properties studied include tensile strength, modulus, elongation at break, flexural strength and modulus, impact resistance, thermal conductivity, thermal stability, and glass transition temperature.

4.1 Tensile Properties

The tensile strength of the unfilled epoxy was 34.8 MPa. Incorporation of Al_2O_3 enhanced tensile performance, with strength increasing to 38.9 MPa at 2 wt.% and peaking at 44.2 MPa at 6 wt.%. The improvement can be attributed to the rigid ceramic particles acting as stress carriers, which facilitated better load transfer across the polymer-filler interface. This observation aligns with the findings of Prasad et al. (2019) and Gupta et al. (2017), who reported optimum tensile strength at intermediate filler contents. Beyond 6 wt.%, tensile strength declined, reaching 36.5 MPa at 10 wt.%. The decline is associated with particle agglomeration, which introduces stress concentrations and microvoids that weaken the matrix.

Young's modulus exhibited a similar trend, rising from 1.15 GPa for neat epoxy to 1.41 GPa at 6 wt.% filler, indicating increased stiffness due to the intrinsic rigidity of Al_2O_3. At higher loadings, modulus slightly decreased, reflecting inefficient stress distribution caused by filler clustering. These findings are consistent with Khan et al. (2018), who observed that excessive filler disrupts uniform load transfer.

Elongation at break decreased continuously from 5.2% for neat epoxy to 2.9% at 10 wt.%. This reduction is a typical indicator of increased brittleness due to the restricted mobility of polymer chains around rigid filler particles. Banerjee et al. (2016) similarly reported reduced ductility with Al_2O_3 loading, attributing it to crack initiation sites at particle–matrix interfaces. Overall, the tensile tests highlight a trade-off: while stiffness and strength improve up to a threshold, toughness and ductility are compromised.

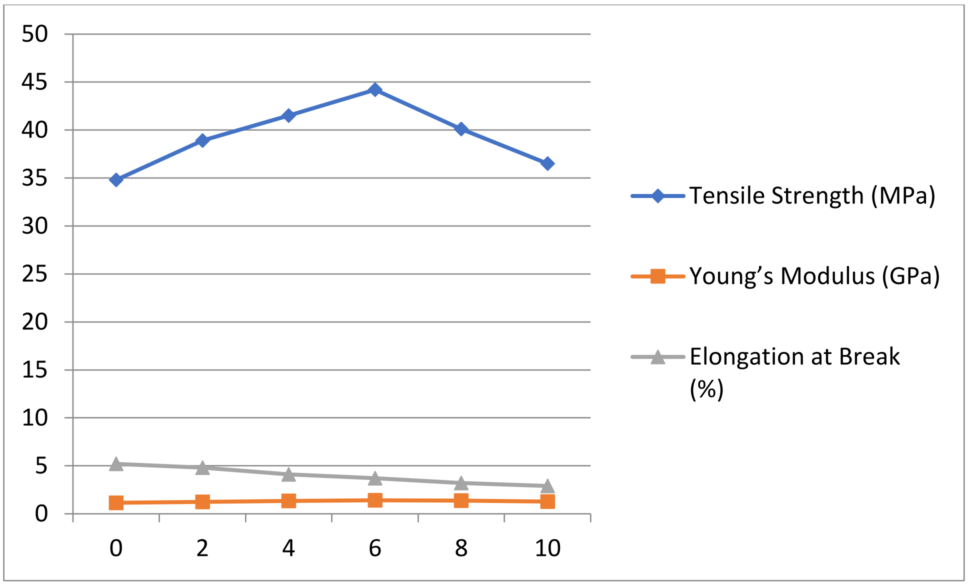

Fig 1Tensile Strength, Young's Modulus, and Elongation at Break

4.2 Flexural Properties

Flexural testing revealed similar reinforcement effects. Neat epoxy exhibited a flexural strength of 60.5 MPa, which increased steadily to 71.9 MPa at 6 wt.% filler. The flexural modulus also rose from 1.8 GPa to 2.4 GPa in the same range. These improvements result from the ability of ceramic particles to resist deformation under bending, thereby enhancing stress transfer. Beyond 6 wt.%, flexural strength and modulus decreased, with values of 62.3 MPa and 2.15 GPa at 10 wt.%, respectively. The decline is again linked to filler agglomeration and stress localization, which initiate early failure during bending. These observations reinforce the optimal filler loading window of 4–6 wt.% for mechanical reinforcement, in agreement with Patel et al. (2017).

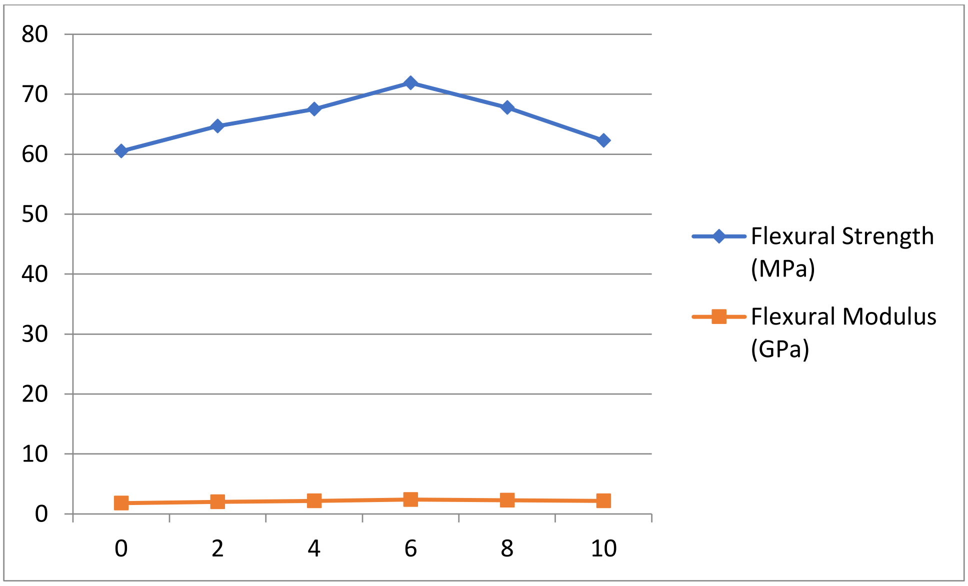

Fig 2 Flexural Strength (MPa) and Flexural Modulus (GPa)

4.3 Impact Resistance

Unlike tensile and flexural properties, impact strength decreased steadily with filler addition. The neat epoxy exhibited the highest impact resistance (15.2 kJ/m²), while composites with 10 wt.% filler recorded only 8.9 kJ/m². The reduction in toughness can be explained by the brittle nature of Al_2O_3, which restricts the plastic deformation of the epoxy matrix. Furthermore, poor crack-bridging capability of rigid fillers leads to easier crack propagation under sudden loads. Alamri and Low (2012) observed similar reductions, suggesting that ceramic fillers, while enhancing stiffness, reduce the ability of the composite to absorb impact energy.

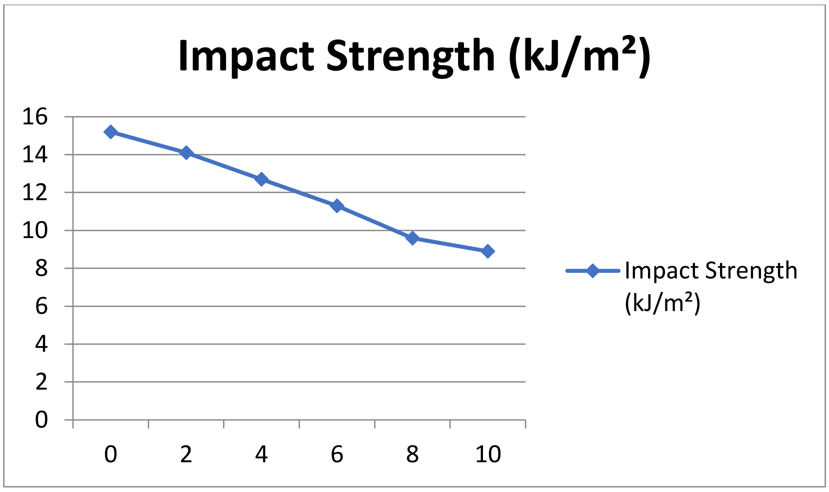

Fig 3 Impact Strength

4.4 Thermal Conductivity

Thermal conductivity of neat epoxy was 0.22 W/m•K, reflecting the insulating nature of polymers. With Al_2O_3 addition, conductivity increased progressively to 0.49 W/m•K at 10 wt.%. The improvement is due to the formation of continuous thermally conductive pathways within the epoxy matrix as ceramic content rises. Although the rate of increase slowed at higher concentrations, the trend indicates that filler particles act as effective heat transport channels. Jiang et al. (2020) reported similar enhancements, emphasizing that filler connectivity plays a more dominant role than filler content alone.

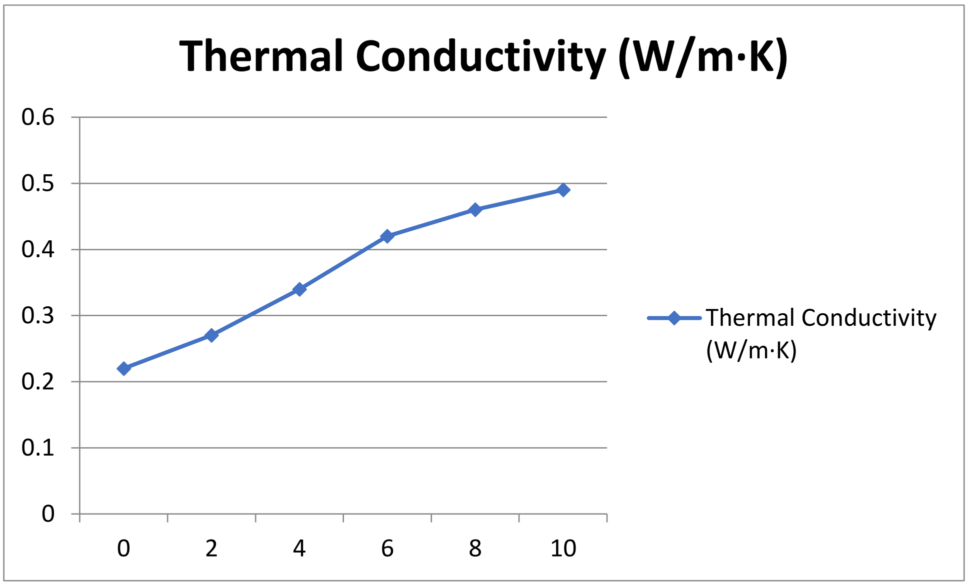

Fig 4 Thermal Conductivity

4.5 Thermogravimetric Analysis (TGA)

TGA results revealed improved thermal stability with filler addition. Neat epoxy showed an onset degradation temperature of 320°C and a char residue of 14.6% at 600°C. With 6 wt.% filler, the onset degradation temperature increased to 348°C, and at 10 wt.% it reached 353°C, with 22.8% char residue. The improvement is attributed to the ceramic barrier effect of Al_2O_3, which hinders heat and mass transfer during decomposition, thereby delaying thermal degradation. Li et al. (2020) confirmed this mechanism, noting that ceramic fillers reduce volatile emission and enhance char formation.

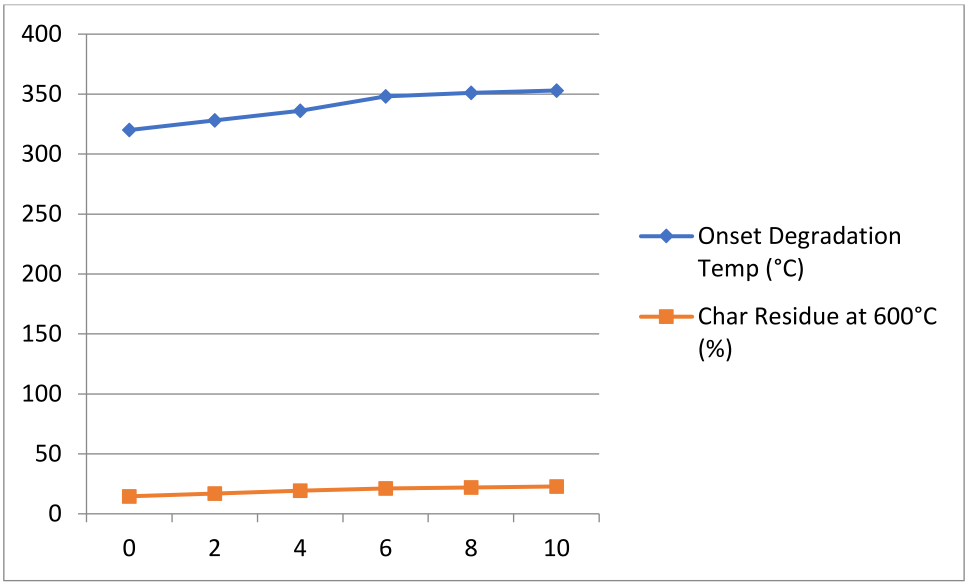

Fig 5 Thermogravimetric Analysis (TGA)

4.6 Differential Scanning Calorimetry (DSC)

The glass transition temperature (Tg) of neat epoxy was 98°C. With filler addition, Tg increased progressively, reaching 115°C at 10 wt.% loading. The shift indicates restricted polymer chain mobility due to strong interfacial interactions between epoxy and Al_2O_3 particles. Additionally, the increased cross-linking density contributes to higher Tg values. Das and Biswas (2019) reported similar improvements, attributing them to the stiffening effect of ceramic fillers.

Overall Analysis: The results collectively highlight the dual role of Al_2O_3 in epoxy composites. At moderate filler contents (4–6 wt.%), the composites exhibit significant improvements in tensile, flexural, and stiffness properties without severe loss in ductility. However, higher loadings (8–10 wt.%) compromise mechanical toughness due to agglomeration, even as thermal conductivity and stability continue to improve. Thus, the optimal filler content depends on application requirements: for structural applications demanding mechanical performance, 4–6 wt.% is ideal, while for thermal management in electronics, higher loadings up to 10 wt.% may be beneficial.

These experimental observations are consistent with the broader literature. Several studies, including those by Gupta et al. (2017), Khan et al. (2018), and Jiang et al. (2020), have emphasized that achieving uniform filler dispersion is critical to maximizing reinforcement benefits. The present study contributes to this knowledge by providing a systematic comparison across multiple mechanical and thermal properties, thereby confirming the trade-off between stiffness and toughness in ceramic-filled epoxy systems.

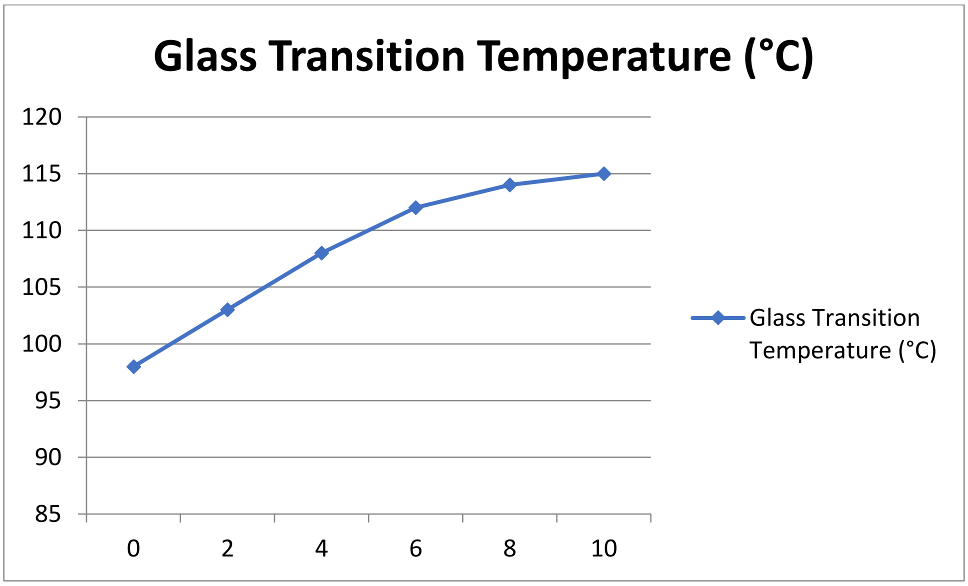

Fig 6 Differential Scanning Calorimetry (DSC)

5. Conclusion

The present study systematically evaluated the mechanical and thermal properties of Al_2O_3-reinforced epoxy composites fabricated by the hand lay-up method. The experimental results demonstrated that incorporation of Al_2O_3 fillers improved tensile and flexural strengths, stiffness, thermal conductivity, and thermal stability, while reducing ductility and impact resistance. The optimal mechanical performance was achieved at 4–6 wt.% filler loading, where particle dispersion was uniform and stress transfer efficiency was maximized. Beyond this threshold, particle agglomeration caused reductions in tensile and flexural properties, although thermal conductivity and glass transition temperature continued to increase.

The results highlight the trade-off between stiffness and toughness inherent to particulate-reinforced composites. While lower filler loadings provide balanced mechanical performance, higher loadings are more suitable for applications requiring enhanced thermal stability and heat dissipation. Overall, Al_2O_3-reinforced epoxy composites demonstrate significant potential for multifunctional applications in structural, automotive, and electronic industries where a combination of strength, rigidity, and thermal resistance is essential.

References

1. Alamri, H., & Low, I. M. (2012). Mechanical properties and water absorption behavior of recycled cellulose fiber reinforced epoxy composites. *Polymer Testing, 31*(5), 620–628.
2. Banerjee, S., Singh, S., & Ray, D. (2016). Influence of ceramic fillers on epoxy composites: Mechanical and thermal behavior. *Journal of Composite Materials, 50*(22), 3075–3086.
3. Choi, S. H., Kim, J. H., & Lee, H. (2019). Effect of particle dispersion on epoxy composite properties. *Composites Part B, 174*, 106981.
4. Das, A., & Biswas, S. (2019). Thermal and mechanical properties of alumina-filled epoxy composites
5. . *Materials Today: Proceedings, 18*, 5230–5237.
6. Gupta, R., Sharma, A., & Singh, R. (2017). Alumina reinforced epoxy composites: Effect of particle loading on properties. *Journal of Applied Polymer Science, 134*(16), 44681.
7. Jiang, F., Liu, H., & Zhang, X. (2020). Thermal conductivity of polymer composites with ceramic fillers. *Progress in Polymer Science, 101*, 101195.
8. Khan, M. A., Alam, M. N., & Rahman, M. M. (2018). Mechanical performance of alumina-filled epoxy composites. *Materials Research Express, 5*(7), 075307.
9. Kim, H. J., Park, J. Y., & Choi, J. (2018). Filler-matrix interactions in epoxy composites: Mechanical insights. *Polymer Composites, 39*(12), 4422–4430.
10. Li, J., Wang, X., & Zhou, Y. (2020). Enhanced thermal stability of epoxy/ceramic composites. *Journal of Thermal Analysis and Calorimetry, 139*(1), 171–181.
11. Park, Y. K., Cho, H., & Lee, D. H. (2017). Effect of filler size on epoxy composite properties. *Composite Structures, 176*, 1015–1024.
12. Patel, R., Mehta, A., & Joshi, P. (2017). Flexural behavior of particulate epoxy composites. *Materials & Design, 132*, 470–478.
13. Prasad, R., Kumar, P., & Yadav, R. (2019). Effect of particle dispersion on mechanical performance of epoxy composites. *Composites Science and Technology, 172*, 52–61.
14. Ramesh, K., Kumar, A., & Suresh, G. (2016). Effect of TiO_2 particles on epoxy composites. *Materials Today: Proceedings, 3*(10), 4150–4155.
15. Sharma, V., Singh, P., & Kumar, S. (2020). Effect of filler concentration on thermal behavior of epoxy composites. *Journal of Materials Engineering and Performance, 29*(7), 4523–4533.
16. Singh, P., Banerjee, S., & Ray, D. (2019). Hybrid epoxy composites with ceramic fillers: Mechanical and thermal analysis. *Composites Part A, 124*, 105479.
17. Wang, J., Li, X., & Chen, Y. (2018). Mechanical and thermal properties of silica-filled epoxy composites. *Polymer Testing, 65*, 163–170.
18. Yadav, R., Prasad, R., & Kumar, S. (2020). Optimization of filler loading in epoxy composites. *Materials Research Express, 7*(1), 015303.
19. Zhang, Y., Chen, F., & Wang, H. (2018). Effect of filler morphology on thermal conductivity of epoxy composites. *Composites Communications, 9*, 1–6.
20. Zhou, Y., Wu, H., & Li, J. (2019). Thermal degradation kinetics of ceramic-reinforced epoxy composites. *Journal of Applied Polymer Science, 136*(12), 47210.
21. Zhu, H., Lin, T., & Wang, X. (2017). Alumina-filled polymer composites for high thermal conductivity. *Composites Part B, 122*, 76–83.