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تأثير الحشوات النانوية الهجينة المكونة من الفيرايت والجرافين وأكسيد الجرافين على الخواص الميكانيكية لمتراكبات الإيبوكسي النانوية

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المستخلص:

تم في هذا الدراسة تحضير متراكبات من الإيبوكسي تحتوي على حشوات هجينة مكونة من أكسيد الحديد (Fe_2O_3) مع الجرافين أو أوكسيد الجرافين، باستخدام طريقة الصب اليدوي وعند أربع نسب وزنية مختلفة هي ١% و٣% و٥% و٧%. وكان الهدف من ذلك دراسة تأثير تغير نسبة الحشوة الهجينة في الخواص الميكانيكية لمادة الإيبوكسي. ولتحقيق هذا الهدف، تم إجراء ثلاث اختبارات ميكانيكية قياسية هي: اختبار الشد باستخدام جهاز الفحص الشامل (UTM)، واختبار الصدمة، واختبار الصلادة من نوع Shore D.

أظهرت النتائج أن العينة المدعمة بأكسيد الحديد وأوكسيد الجرافين بنسبة ٧% حققت أعلى قيم لمعامل يونك والصلادة، في حين سجلت العينة ذات نسبة التدعيم ٥% أعلى مقاومة للشد والصدم. كما بينت النتائج أن الحشوة الهجينة أثرت بصورة واضحة في السلوك الميكانيكي لمصفوفة الإيبوكسي المتصلبة عند جميع نسب التدعيم المدروسة.

ويُعزى هذا التحسن إلى التآزر بين الطور المغناطيسي المتمثل بأكسيد الحديد والصفائح النانوية الكربونية، مما ساعد على تحسين انتقال الإجهاد عبر السطح البيني بين الحشوة والمصفوفة البوليمرية. ونتيجة لذلك، ازدادت كل من مقاومة الشد والصلابة مع زيادة نسبة الحشوة حتى حد معين. إلا أن هذا الاتجاه بدأ بالتراجع عند التراكيز الأعلى، حيث تميل الجسيمات النانوية

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إلى التكتل ويصبح توزيعها داخل المصفوفة أقل تجانساً، الأمر الذي يؤدي إلى فقدان جزء من التحسن المتحقق في الخواص الميكانيكية.

لذلك، فإن التحكم في نسبة الحشوة وجودة تشتتها داخل المصفوفة يُعد عاملاً أساسياً لتحقيق توازن مناسب بين الصلابة والمتانة. وفي ضوء هذه النتائج، يمكن اعتبار المتراكبات الإيبوكسية الهجينة المحضرة في هذه الدراسة مواد واعدة للتطبيقات الإنشائية والهندسية التي تتطلب صلابة عالية مع قدرة جيدة على مقاومة الاحمال والصدمات.

الكلمات المفتاحية: مركبات نانوية إيبوكسية، الفرايت، أكسيد الكرافين، الخواص الميكانيكية، المركبات النانوية الهجينة

Effect of Hybrid Ferrite–Graphene–Graphene Oxide Reinforcement on the Mechanical Behavior of Epoxy Nanocomposites

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ABSTRACT

Epoxy nanocomposites that contain a hybrid filler made of ferrite (Fe_2O_3) together with either graphene or graphene oxide were prepared in the present work by simple casting at four loading levels: 1, 3, 5 and 7 wt%. The aim was to track how the resin's mechanical response changes as the hybrid filler fraction varies. Three standard measurements were used: a uniaxial tensile test on a universal testing machine, an Izod-type impact test with a calibrated hammer, and Shore D hardness. The 7% ferrite-graphene oxide sample achieved the highest Young's modulus and hardness, while the 5% sample achieved the highest tensile and impact resistance. Across the four loadings, the hybrid filler clearly modified the

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mechanical behaviour of the cured resin. A coupling between the magnetic oxide phase and the carbon nanosheet appears to assist load transfer through the matrix–filler interface; as a consequence, both tensile strength and stiffness rose with filler content up to a certain limit. Above that limit, the trend reversed: the filler tends to agglomerate, dispersion becomes uneven, and part of the early gain in performance is lost. Filler ratio and dispersion quality therefore must be controlled together to preserve a balance between rigidity and toughness. Under such conditions, the hybrid epoxy systems described in this paper may be useful candidates for structural applications that need both stiffness and a reasonable tolerance to impact loading.

Keywords: Epoxy nanocomposites, Ferrite, Graphene oxide, Mechanical properties, Hybrid nanocomposites

1. INTRODUCTION

Polymer-matrix composites are now widely used in engineering. The reasons are well known: they are light, easy to shape, and their final properties can be tuned by choosing the reinforcing phase (Soupionis et al., 2020). Within this family, epoxy resins are among the most common matrix candidates, since they combine acceptable mechanical strength with strong adhesion to a variety of substrates and high chemical resistance (J. Tang et al., 2014). The cured resin, by contrast, is brittle; it absorbs little energy on impact and shows limited resistance to crack growth, which restricts its direct use in load-bearing parts under dynamic loading (Lodh & Gadhave, 2024; Sukanto et al., 2021). With the rapid development of nanotechnology, polymer properties can be markedly improved by introducing nanoscale fillers that combine a high specific surface area with specific physicochemical characteristics (Buzea et al., 2007). In this group, ferrite (Fe_2O_3) nanoparticles have received particular attention: they are magnetic, thermally stable, and they raise stiffness and structural integrity when added to a polymer matrix (Sun et al., 2020). Carbon-based fillers, namely graphene and its oxidised form graphene oxide (GO), have been investigated almost as intensively, mainly because of their very high in-plane strength, their two-dimensional surface area and their ability to carry load from the matrix (Rashid Khasheet &

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Abdullah, 2025; J. Tang et al., 2014). GO, in particular, carries oxygen-containing groups (hydroxyl, epoxy, carboxyl) on its surface; these groups improve both dispersion and compatibility with the polymer at the interface, so GO often outperforms pristine graphene in the same composite formulation (Abdullah & Ansari, 2015; Rafiee et al., 2009). Single-filler systems, although promising on paper, do not always translate into reproducible composites. Agglomeration and uneven dispersion within the matrix remain the main practical problems; both reduce load-transfer efficiency at the filler–matrix interface and create local stress concentrators that weaken the bulk material. A common way to address this difficulty is to use two complementary fillers in the same matrix—a hybrid system—in which the two phases co-operate rather than compete (Dhuha Muhammad Abdul Nabi Salman & Fadhel Essa, 2025; Manobalan et al., 2024). Combining a magnetic oxide such as ferrite with a carbon nanofiller (graphene or GO) in the same matrix has already been reported to improve the mechanical response of several polymer systems (Li et al., 2018). The two phases play different but complementary roles: ferrite mainly contributes stiffness and structural integrity, whereas graphene-type sheets increase tensile strength and act as efficient pathways for load transfer along the interface (Sun et al., 2020; L. C. Tang et al., 2013). GO brings an extra benefit: thanks to its oxygenated surface groups it disperses more easily inside the resin, and its mechanical bond to the matrix is stronger — both factors raise the overall performance of the composite (Abdullah & Ansari, 2015). Despite this growing interest, reports combining ferrite with graphene or GO in an epoxy matrix remain relatively scarce. Fewer still follow how different filler loadings of such hybrid systems alter the mechanical behaviour of the cured resin (El-Masry et al., 2020; Wilczewski et al., 2025). This work was motivated by this gap. Two hybrid epoxy systems were prepared, Fe_2O_3/graphene and Fe_2O_3/GO, each at four loading levels, and their mechanical performance was followed through tensile, impact, and hardness measurements. Special attention is paid to how dispersion quality, interfacial adhesion and agglomeration shape the final response of the cured material.

Previous studies have shown considerable interest in reinforcing epoxy with ferrite, graphene, or graphene oxide individually. However, information on the effect of Fe_2O_3/Graphene and Fe_2O_3/GO hybrid systems on mechanical properties remains limited, particularly when

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examining different loading ratios and directly comparing the two hybrid systems. This study aims to fill this gap and evaluate the behavior of these composites through tensile, hardness, and impact tests.

2. MATERIALS AND METHODS

A two-component Chinese-origin epoxy resin was selected as the base material and mixed with its hardener in a 2:1 weight ratio. Three filler nanomaterials were used: γ-Fe_2O_3 nanoparticles (γ-Fe_2O_3) prepared by SkySpring Nanomaterials, Inc., USA, with a purity of 99% and particle sizes ranging from 20 to 40 nm, as the magnetic phase; graphene prepared by SkySpring Nanomaterials, Inc., USA, with a purity of approximately 99.5%; and graphene oxide prepared by Platonic Nanotech Private Limited, USA, with a purity of at least 98%, as the carbon phase. All three powders have a high specific surface area, allowing them to interact with the resin at the interface and modify its mechanical response. The manual casting process was used to prepare the compounds with four levels of filler materials (1, 3, 5, and 7% by weight).

3. RESULTS AND DISCUSSION

Tensile measurements were carried out on a universal testing machine (UTM) manufactured by Jinan Hensgrand Instrument Co., Ltd., China. From each stress–strain curve we extracted Young's modulus, the tensile strength and the elongation at fracture. The impact response under dynamic loading was measured using a calibrated pendulum hammer, and the surface hardness was obtained from Shore D readings. The same data were then compared across the four filler levels of both hybrid systems. The interpretation of the trends is given in terms of dispersion quality, the strength of the filler–matrix interface, the influence of agglomeration on stress transfer, and the overall effect of the filler loading.

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Figure 1: Tensile test specimens of epoxy nanocomposites.

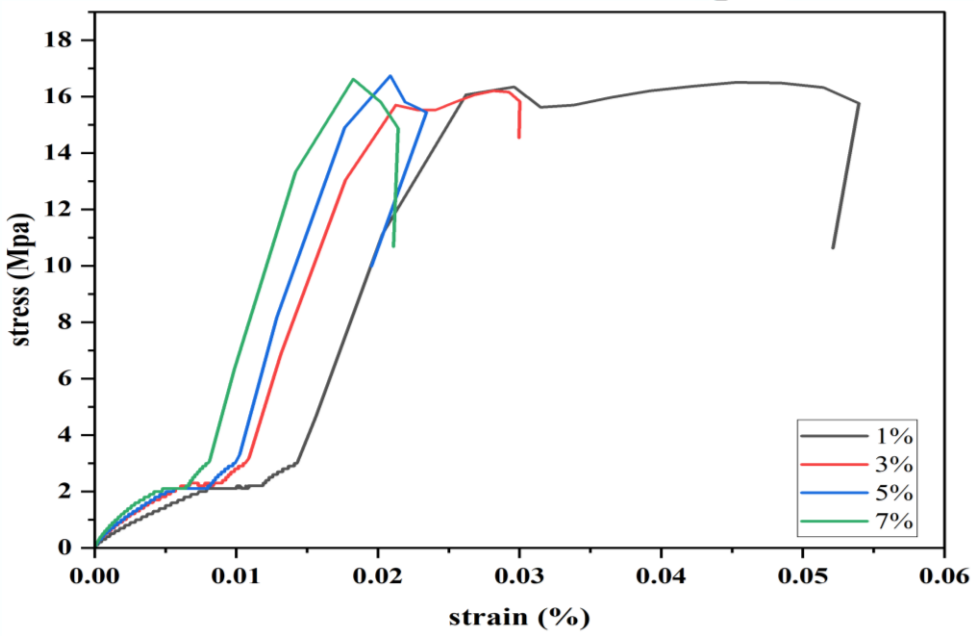

Figure 2: Stress–strain curves of hybrid epoxy nanocomposites reinforced with graphene and Fe_2O_3 at different weight fractions.

Figures 2 and 3 present the tensile stress–strain curves of the two hybrid epoxy systems Fe_2O_3/graphene and Fe_2O_3/GO at the four loading levels (1, 3, 5 and 7 wt%). Adding the hybrid filler to the resin clearly alters the curve shape, and the effect depends on both the filler type and amount.

In the Fe_2O_3/G case, Table 1 shows that the highest tensile strength (UTS) was 16.74 MPa at 5 wt% reinforcement, followed by 16.62 MPa at 7 wt%,

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then 16.34 MPa at 1 wt%, while the lowest value was 16.20 MPa at 3 wt%. This indicates that the 5 wt% reinforcement ratio provided the best stress transfer efficiency between the nanofillers and the epoxy matrix.

Young's modulus increased steadily with increasing reinforcement ratio, rising from 1377.25 MPa at 1 wt% to 1633.13 MPa at 3 wt%, then to 1867.34 MPa at 5 wt%, reaching a maximum value of 1873.56 MPa at 7 wt%. This is attributed to the increased rigidity of the composite, as graphene and iron oxide nanoparticles restrict the movement of epoxy chains.

In the Fe_2O_3/GO system, Table 1 shows that tensile strength rose steadily with filler content up to an optimum: the highest value, 20.9 MPa, was recorded at 5 wt%, consistent with efficient load transfer between the resin and the hybrid filler. Adding more filler did not help; strength dropped slightly to 20.16 MPa at 7 wt%, likely the first sign of agglomeration at higher loadings.

Young’s modulus, on the other hand, kept rising throughout the loading range, from 1586.45 MPa at 1 wt% to 1977.83 MPa at 7 wt%. This continuous gain in stiffness is consistent with the well-known restriction of polymer-chain mobility caused by rigid fillers. The high specific surface area of GO and its strong adhesion to the epoxy at the interface both contribute to this effect.

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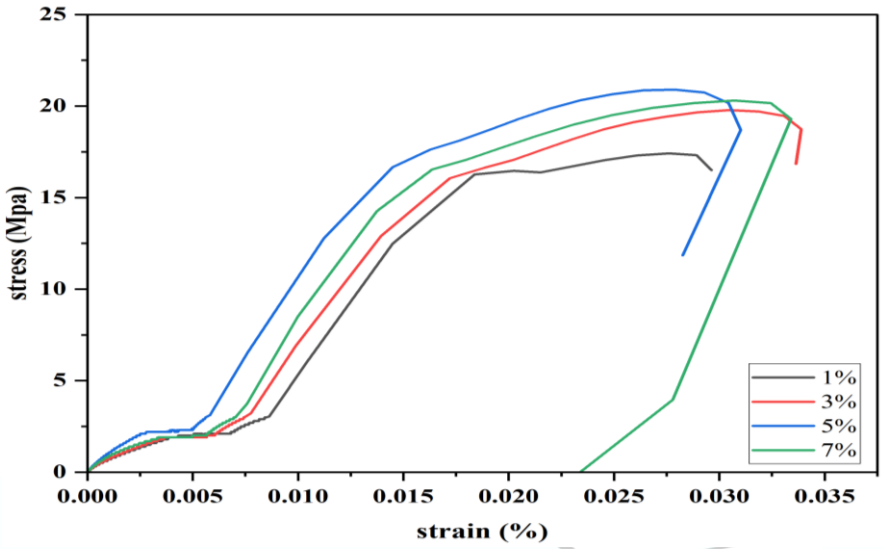

Figure 3: Stress–strain curves of hybrid epoxy nanocomposites reinforced with graphene oxide (GO) and Fe_2O_3 at different weight fractions.

Table 1: Young's modulus (E), coefficient of determination (R^2), and tensile test results of hybrid epoxy nanocomposites reinforced with Fe_2O_3/GO and Fe_2O_3/graphene at different weight fractions.

Sample	E (MPa)	R^2	UTM
Epoxy	1761	0.982	15.2
Ep + GO +Fe_2O_3 1%	1586.45	1	17.42
Ep + GO +Fe_2O_3 3%	1554.83	0.998	19.78
Ep + GO +Fe_2O_3 5%	1774.54	1	20.9
Ep + GO +Fe_2O_3 7%	1977.83	1	20.16
Ep + G +Fe_2O_3 1%	1377.25	1	16.34
Ep + G +Fe_2O_3 3%	1633.13	1	16.2
Ep + G +Fe_2O_3 5%	1867.34	1	16.74
Ep + G +Fe_2O_3 7%	1873.56	1	16.62

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Table 1 shows the Young's modulus (E), the modulus of determination (R^2), and the tensile test results for hybrid epoxy nanocomposites reinforced with Fe_2O_3/GO and Fe_2O_3/graphene at different weight ratios. In the Fe_2O_3/graphene system, the tensile strength varied within a narrow band of 16.2–16.74 MPa, while the modulus moved from 1377.25 MPa up to 1873.56 MPa. These values are higher than those of the neat resin, but the gain is clearly smaller than that obtained with GO. Comparing the two systems side by side, Fe_2O_3/GO outperforms Fe_2O_3/graphene at every loading. The reason is the same one that justifies using GO in many polymer composites: the oxygenated surface groups on GO improve its dispersion in the resin and create a stronger chemical–mechanical bond with the matrix at the interface (Bindu Sharmila et al., 2016; Eqra et al., 2021). Stress transfer is therefore more efficient, and fewer local defects are formed during curing. From these tensile measurements, the best compromise depends on which property is targeted: 5 wt% gives the highest strength, whereas 7 wt% gives the highest stiffness. These results are consistent with Abdullah et al. (2012). In both cases, the underlying physics reflects the same balance between filler dispersion, interfacial adhesion, and the onset of agglomeration.

The impact-energy data for the two hybrid systems at all four loadings are detailed in Table 2. The hybrid filler has a clear, although moderate, effect on the energy that the composite can absorb on impact.

Table 2. Impact energy values of neat epoxy and reinforced epoxy composites under hammer loading conditions.

sample	Hammer weight	Air resistance	Sample and Air Strength
Ep pure	25	0.09	0.4
Ep + GO +Fe_2O_3 1%	25	0.1	0.25
Ep + GO +Fe_2O_3 3%	25	0.1	0.24
Ep + GO +Fe_2O_3 5%	25	0.1	0.26

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Ep + GO +Fe_2O_3 7%	25	0.1	0.25
Ep + G +Fe_2O_3 1%	25	0.1	0.25
Ep + G +Fe_2O_3 3%	25	0.1	0.22
Ep + G +Fe_2O_3 5%	25	0.1	0.24
Ep + G +Fe_2O_3 7%	25	0.1	0.24

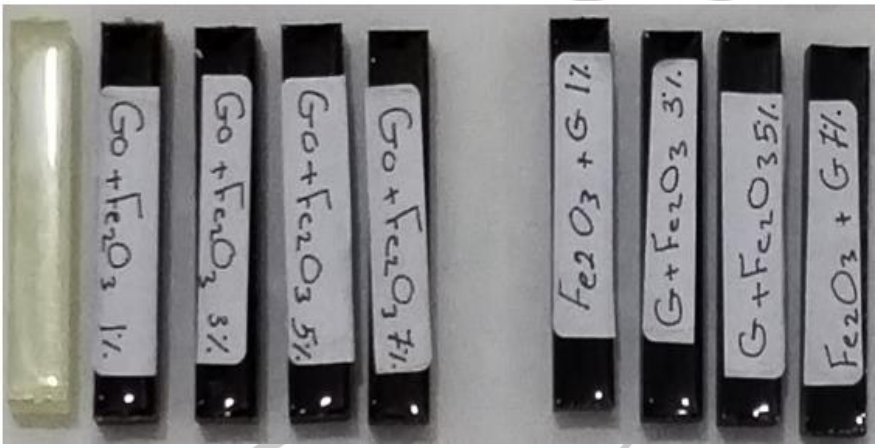

Figure 4: Charpy impact test specimens of epoxy nanocomposites reinforced with Fe_2O_3 nanoparticles, graphene (G), and graphene oxide (GO) at different weight fractions.

In the Fe_2O_3/GO system the readings stay in a narrow band of 0.24–0.26 J, the highest value (0.26 J) being recorded at 5 wt%. This modest improvement is consistent with a better interface in this system: GO sheets help deflect propagating cracks and dissipate some impact energy through this deflection mechanism. For Fe_2O_3/graphene the impact values are slightly lower, between 0.22 and 0.25 J, and the minimum (0.22 J) is reached at 3 wt%. Pristine graphene improves several mechanical properties, but its surface is poorly functionalised compared with GO, and this limits its ability

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to deflect cracks and absorb impact energy. These results are consistent with Abdullah et al. (2012).

Overall, the impact response is not strongly sensitive to filler content; the hybrid filler gives a modest gain in toughness across the range. The occasional drops seen at some loadings are most easily explained by localised agglomeration of the powder: such regions act as stress concentrators and can become preferred sites for crack initiation. Comparing the two systems, Fe_2O_3/GO is marginally better than Fe_2O_3/graphene under impact loading. This is yet another reminder that fracture resistance in epoxy nanocomposites depends as much on the quality of the filler–matrix interface and the homogeneity of dispersion as on the chemical identity of the filler.

The Shore D readings for the two hybrid systems at the four loadings are listed in Table 3. Adding the hybrid filler increases the resin's surface hardness in every case, and the effect is more pronounced in the GO-based system.

Table 3. Hardness values of neat epoxy and reinforced epoxy composites at different filler loadings.

Ratio	Sample code	Hardness values
Pure	Ep	68
1%	Ep + GO +Fe_2O_3	66.5
3%	Ep + GO +Fe_2O_3	69
5%	Ep + GO +Fe_2O_3	73.5
7%	Ep + GO +Fe_2O_3	77.5
1%	Ep + G +Fe_2O_3	67.5
3%	Ep + G +Fe_2O_3	70
5%	Ep + G +Fe_2O_3	69.5
7%	Ep + G +Fe_2O_3	69

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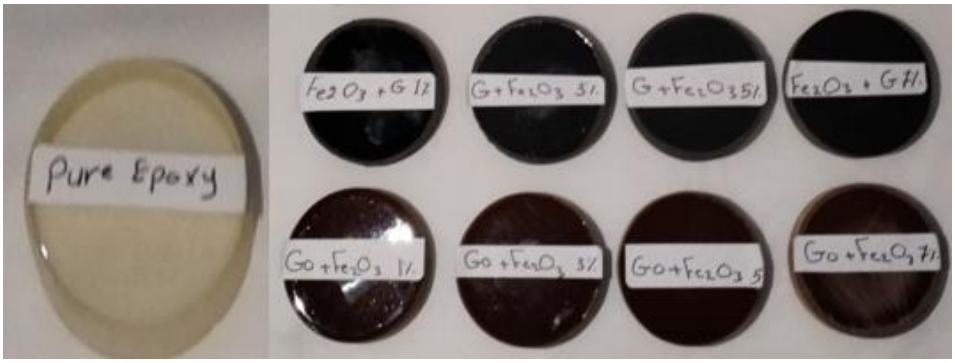

Figure 5: Shore D hardness test specimens of epoxy-based nanocomposites.

In the Fe_2O_3/GO system, the values climb monotonically with filler content, from 66.5 at 1 wt% up to 77.5 at 7 wt%. This progressive increase is consistent with gradual restriction of polymer-chain mobility by the rigid nanoparticles, aided by strong interfacial adhesion between the resin and GO. The maximum value (77.5) at the highest loading suggests that GO still acts as an efficient reinforcement at 7 wt% and that the cured composite structure becomes more rigid and compact.

The Fe_2O_3/graphene system follows a different pattern. Hardness first rises from 67.5 (1 wt%) to 70 (3 wt%), then falls slightly to 69.5 at 5 wt% and 69 at 7 wt%. The most likely reason is that graphene sheets begin to agglomerate at higher concentrations; once they do, the dispersion becomes uneven and the reinforcing efficiency drops. These results are consistent with (Kaadhm et al., 2021). GO's better performance than graphene is again related to its oxygen-containing surface groups. These groups make GO more chemically compatible with the resin, promote finer dispersion of the

sheets within the matrix, and result in a stronger filler–matrix bond—all of which help distribute the local load more evenly. Taken together, the hardness measurements indicate that the Fe_2O_3/GO formulation gives the largest gain, and that this gain is still increasing at the highest filler content tested. For the other measurements, the underlying parameters are the same: dispersion quality, interface strength, and the degree of filler aggregation. Based on the results obtained, it can be said that the use of hybrid fillers, particularly the Fe_2O_3/GO system, is an effective way to improve the mechanical properties of epoxy composites, due to the synergy between the nanofillers and the improved interconnection within the polymer matrix.

4. CONCLUSION

The results showed that the mechanical properties of epoxy composites reinforced with the Fe_2O_3/Graphene and Fe_2O_3/GO hybrid systems are significantly affected by the filler type and weight percentage. The Fe_2O_3/GO system achieved the best mechanical performance compared to the Fe_2O_3/Graphene system, recording the highest values for tensile strength, Young's modulus, hardness, and impact resistance. The results also indicated that moderate filler percentages, particularly 5% by weight, provided the best balance between strength and toughness, while higher percentages contributed to increased hardness and modulus of elasticity. This improvement is attributed to good dispersion of graphene oxide within the epoxy matrix and strong interfacial bonding between the nanofillers and the substrate. Therefore, the Fe_2O_3/GO hybrid system is a promising material for engineering applications requiring a combination of strength, toughness, and durability

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REFERENCES

1. Abdullah, S. I., & Ansari, M. N. M. (2015). Mechanical properties of graphene oxide (GO)/epoxy composites. *HBRC Journal*, *11*(2), 151–156. https://doi.org/10.1016/j.hbrcj.2014.06.001
2. Abdullah, S. I., Ansari, M. N. M., Fei, L. W., & Huang, N. M. (2012). *Mechanical Properties of Graphene oxide/Epoxy Composite*.
3. Bindu Sharmila, T. K., Antony, J. V., Jayakrishnan, M. P., Sabura Beegum, P. M., & Thachil, E. T. (2016). Mechanical, thermal and dielectric properties of hybrid composites of epoxy and reduced graphene oxide/iron oxide. *Materials and Design*, *90*, 66–75. https://doi.org/10.1016/j.matdes.2015.10.055
4. Buzea, C., Pacheco, I. I., & Robbie, K. (2007). Nanomaterials and nanoparticles: Sources and toxicity. *Biointerphases*, *2*(4), MR17–MR71. https://doi.org/10.1116/1.2815690
5. Dhuha Muhammad Abdul Nabi Salman, B., & Fadhel Essa, A. (2025). *Study of Mechanical properties and electrical conductivity of graphene-silicon-silver hybrid/polymer Nanocomposites* (Master's thesis). Wasit University. Iraq.
6. El-Masry, M. M., Ramadan, R., & Ahmed, M. K. (2020). The effect of adding cobalt ferrite nanoparticles on the mechanical properties of epoxy resin. *Results in Materials*, *8*. https://doi.org/10.1016/j.rinma.2020.100160
7. Eqra, R., Moghim, M. H., & Eqra, N. (2021). A study on the mechanical properties of graphene oxide/epoxy nanocomposites. *Polymers and Polymer Composites*, *29*(9_suppl), S556–S564. https://doi.org/10.1177/09673911211011150
8. Kaadhm, E., Salman, K., & Raja, A. (2021). Investigating The Effect of Magnetite (Fe3O4) Nanoparticles on Mechanical Properties of Epoxy Resin. *Engineering and Technology Journal*, *39*(6), 986–995. https://doi.org/10.30684/etj.v39i6.2063
9. Li, B., Weng, X., Sun, X., Zhang, Y., Lv, X., & Gu, G. (2018). Facile synthesis of Fe3O4/reduced graphene oxide/polyvinyl pyrrolidone ternary composites and their enhanced microwave absorbing

properties. *Journal of Saudi Chemical Society*, *22*(8), 979–984. https://doi.org/10.1016/j.jscs.2018.02.006

10. Lodh, F. P., & Gadhave, R. V. I. (2024). Reinforcing Effect of Graphene in Epoxy Adhesives: Review. *Open Journal of Composite Materials*, *14*(01), 60–70. https://doi.org/10.4236/ojcm.2024.141005
11. Manobalan, S., Bose, S., & Sumangala, T. P. (2024). Effect of cobalt ferrite concentration on the EMI shielding effectiveness of cobalt ferrite/graphene-based epoxy composites. *Polymer Composites*, *45*(17), 15804–15819. https://doi.org/10.1002/pc.28871
12. Rafiee, M. A., Rafiee, J., Wang, Z., Song, H., Yu, Z. Z., & Koratkar, N. (2009). Enhanced mechanical properties of nanocomposites at low graphene content. *ACS Nano*, *3*(12), 3884–3890. https://doi.org/10.1021/nn9010472
13. Rashid Khasheet, M., & Abdullah, E. T. (2025). Characterization of Graphene/Epoxy Nanocomposites. *Iraqi Journal of Physics*, *23*(1), 78–84. https://doi.org/10.30723/ijp.v23i1.1298
14. Soupionis, G., Georgiou, P., & Zoumpoulakis, L. (2020). Polymer composite materials fiber-reinforced for the reinforcement/repair of concrete structures. *Polymers*, *12*(9). https://doi.org/10.3390/POLYM12092058
15. Sukanto, H., Raharjo, W. W., Ariawan, D., Triyono, J., & Kaavesina, M. (2021). Epoxy resins thermosetting for mechanical engineering. *Open Engineering*, *11*(1), 797–814. https://doi.org/10.1515/eng-2021-0078
16. Sun, T., Wang, Y., Yang, Y., Fan, H., Liu, M., & Wu, Z. (2020). A novel Fe2O3@APFS/epoxy composite with enhanced mechanical and thermal properties. *Composites Science and Technology*, *193*, 108146. https://doi.org/10.1016/j.compscitech.2020.108146
17. Tang, J., Zhou, H., Liang, Y., Shi, X., Yang, X., & Zhang, J. (2014). Properties of graphene oxide/epoxy resin composites. *Journal of Nanomaterials*, *2014*. https://doi.org/10.1155/2014/696859
18. Tang, L. C., Wan, Y. J., Yan, D., Pei, Y. B., Zhao, L., Li, Y. B., Wu, L. Bin, Jiang, J. X., & Lai, G. Q. (2013). The effect of graphene

dispersion on the mechanical properties of graphene/epoxy composites. *Carbon*, *60*, 16–27. https://doi.org/10.1016/j.carbon.2013.03.050

19. Wilczewski, S., Nowak, Z., Maj, M., Osial, M., Minikayev, R., & Giersig, M. (2025). Enhancing Epoxy Composites with Graphene and Graphene Oxide: Thermal and Mechanical Insights. *ChemNanoMat*, *11*(2). https://doi.org/10.1002/cnma.202400488