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RESEARCH PAPER

Investigation of Mechanical and Thermal Properties of Copper-Reinforced Epoxy Composites under Corrosive Chemical Environments

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ABSTRACT

The paper examines the synthesis and analysis of epoxy matrix composites with copper (Cu) particles as reinforcement for weight fractions of 2%, 4%, 6%, and 8%. The synthesis was performed using the hand lay-up method. The paper assesses the hardness, thermal conductivity, and chemical resistance of the composites at room temperature and after submerging for a period of 15 days in a 0.2N concentration of Hydrochloric acid (HCl) and Sodium Hydroxide (NaOH). The experiment showed the impact of copper percentage in raising hardness and thermal conductivity from 81.1 to 82.3 and from 31.8×10^{-2} to 31.9×10^{-2} W/m. °C, respectively, for a composition with a weight fraction of 8%. Conversely, analysis after submerging the composites showed a reduction in both hardness and thermal conductivity, with a higher reduction in hardness compared to thermal conductivity. The composites absorbed more solution with increasing immersion time and copper content. Copper reinforcement increases the initial properties; however, the durability of the composite is strongly influenced by the environmental condition.

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INTRODUCTION

There has been a paradigm shift in the field of materials science because of the ever-growing requirement for high-performance materials in aerospace and electronic sectors. Among the popular classes of materials, polymer matrix composites (PMCs) have gained widespread use because of their remarkable strength-weight ratio and resistance to corrosion [1]. Within the category of thermoses, the most widely used classes of resins are the epoxies, which are known for their remarkable mechanical performance and high-temperature resistance [2,3]. Nevertheless, the material is prone to brittleness and has low thermal conductivity, which restricts its use under heat-dissipating conditions [4]. Hence, the subject of interest for researchers is the development of a combination of the malleability of polymers and the beneficial properties of metals in epoxies reinforced with metallic-containing materials [5]. Cu particle addition to the epoxy matrix is a deliberate attempt to improve physical performance. Copper has, among other metals, been considered an excellent thermal conductor. Composites with copper micro-particles show increased hardness and enhanced heat dissipation. This study realizes the behavior of such materials under severe chemical attack. It is expected that

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acids and bases cause material degradation and loss of integrity in most industrial applications. Therefore, the determination of the durability of epoxy/copper composites in both acidic, such as HCl, and alkaline, such as NaOH, media will always remain vital to the prediction of useful service life. Various literature reports the use of metallic fillers in reinforcing polymers. Zhao and Lu, 2019, reported that the concentration of filler is critical in controlling thermal transport mechanisms [6]. Martinez et al., 2020, also outlined that micro sized copper particles will offer a robust skeletal framework that improves resistance to deformation [7]. Recent works conducted by Garcia & Patel (2022) indicated the effect of metallic particles on the cross-linking density of the epoxy, which influences stability [8]. The literature also covered the field of chemical aging. The research indicated the presence of a nucleus at the interface between the polymer and the filler material, which drives the de-bonding process [9,10]. Despite the progress, a research void still prevails on the relative kinetic analysis of diffusion for both acidic and basic conditions in copper-filled epoxy. Certain authors indicated the differences for basic hydrolysis conditions compared to the acidic conditions during certain experiments [11]. Although many manufacturing procedures have been developed, the Hand Lay-Up process still gains popularity owing to its economy and ease of manufacturing the different weight fractions [12]. This technique is very beneficial for particulate composites, as settling problems need to be controlled using a precise curing [13] process. The main aim of this research work is to prepare epoxy/copper composites with weight ratios of (2%, 4%, 6%, and 8%) based on their performance and behavior in normal and corrosive environments. This research is applicable for surface hardness and thermal conductivity test analysis of composites. This research helps to interpret a wide set of key factors for a complete understanding of a 15-day immersion test of an epoxy/copper composite and adds beneficial references to material research for a chemical processing plant.

MATERIALS AND METHODS

Specimen Preparation and Mold Design

The composite samples were made by casting a precision-made glass mold. The base part of the mold was made of a high-quality glass sheet measured at 300 x 300 mm^2 with a thickness of 4 mm. In order to determine the boundaries between which the casting would take place; the mold was accompanied by adjustable glass stripes measuring 300x50x4 mm^3. The method involved meticulous procedures for preparing the samples. The glass parts being cleaned with soap solution, water, and ethanol. This ensured any contaminants on the glasses' surface were eliminated. A non-stick polymer release film was applied to the base glass sheet to prevent adhesion between the epoxy composite and the mold surface during curing. This ensured the polymer didn't stick to the glass sheet. The glass stripes were coated with a layer of Fablon paper. They were fixed on the base glass sheet through a high-strength adhesive. The object was left to set for a period of 30 minutes. The glass mold was set on a flat surface. This ensured equal thickness was measured on the sheets being cast. The thickness of the composite sheets was controlled using calibrated glass spacers during mold assembly to ensure uniform thickness across all samples. After curing, specimen thickness was measured using a digital micrometer with an accuracy of ±0.01 mm. The average thickness was maintained at 4 mm with a dimensional tolerance of ±0.05 mm. Surface finishing was carried out using progressively finer silicon carbide abrasive papers to obtain smooth and uniform surfaces prior to testing. This procedure ensured proper contact during hardness and thermal conductivity measurements and minimized surface-related measurement errors.

Composition and Mixing Ratio

The epoxy resin and its corresponding hardener were of American origin and used as supplied by the manufacturer. The copper (Cu) powder was obtained from Merck (Germany) with a stated purity of 99%. According to the supplier's specifications, the copper powder possessed a controlled particle size distribution (D10 = XX µm, D50 = XX µm, and D90 = XX µm). Optical examination indicated that the particles exhibited predominantly irregular morphology. The copper powder was used as received without any additional surface treatment. The particle surfaces were metallic and uncoated, with no chemical modification prior to composite fabrication. The composites were prepared by adding copper (Cu) micro-particulates to the epoxy (EP) matrix in different weight fractions. The details of the compositions for this work are listed in Table 1. The copper particles were gradually

added to the epoxy resin and mechanically mixed using a laboratory mechanical stirrer at a speed of 500 rpm for 10 minutes to ensure homogeneous dispersion. To enhance particle distribution and minimize agglomeration, mixing was performed in a circular motion while maintaining constant speed. After mixing, the hardener was added according to the manufacturer's recommended ratio and stirred for an additional 3 minutes. The mixture was then subjected to manual degassing for approximately 5 minutes to remove entrapped air bubbles prior to casting. To reduce particle settling during curing, the mixture was cast immediately after preparation, and the mold was kept on a leveled surface under static conditions at room temperature until full solidification.

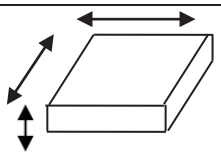
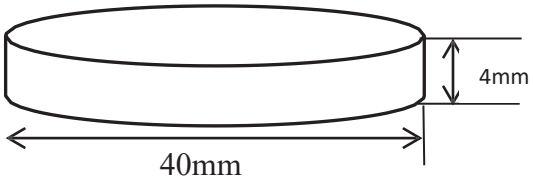
Post-Processing and Sample Dimensioning

After full solidification, the composite sheets were extracted from the mold. Precision machining involved the use of a high-speed stationary electric saw, which has fine teeth. The surfaces were further smoothened using sandpaper, which enabled the required dimensions to be met. All the samples were manufactured in accordance with the ASTM standards, as has been noted in Table 2, and Fig. 1 indicates the shapes. After casting, the composite samples were allowed to cure at

Table 1. Composition and weight fractions of EP/Cu composites.

Sample no	Weight fraction%	Composite materials
1	2	EP%98+Cu%2
2	4	EP%96+Cu%4
3	6	EP%94+Cu%6
4	8	EP%92+Cu%8

Table 2. Standardized dimensions for the experimental tests.

SI	Standard demotion of sample	Test
ASTM -D2240	10 mm 10 mm 4mm 	Hardness & Diffusivity Test
Lee's Disk		Thermal Conductivity Test

room temperature (25 ± 2°C) for 24 hours under laboratory conditions. Relative humidity during curing was maintained at approximately 50 ± 5%. To ensure complete cross-linking and enhance mechanical stability, a post-curing process was performed at 60°C for 2 hours in a laboratory oven. After post-curing, the samples were allowed to cool gradually to room temperature before machining and testing.

Thermal conductivity measurements were carried out using the Lee's Disk apparatus under steady-state conditions. Prior to testing, the apparatus was calibrated using a reference material of known thermal conductivity to ensure measurement accuracy. During the experiment, the system was allowed to reach thermal equilibrium before temperature readings were recorded. Steady-state was confirmed when the temperature variation was less than ±0.5 °C over a 5-minute interval. The thermal conductivity (k) was calculated using the standard Lee's Disk equation:

$$\frac{d}{t}\cdot\frac{mc(T_2 - T_1)}{A(T_1 - T_2)} = k$$

Where: k= thermal conductivity (W/m·K), m = mass of the brass disk, c = specific heat capacity, A = cross-sectional area of the specimen, d = specimen thickness, T_2, T_1, T_0 = measured temperatures, t = time. To minimize thermal contact resistance between the specimen and the brass disks, the contact surfaces were carefully polished and a thin layer of thermal paste was applied to ensure proper thermal contact during testing.

Characterization Techniques

Various analyzing tools were also used to determine the physical and mechanical properties of the composites. The Shore D hardness method is practical, as the method is designed for hard polymer composites. The analysis involved multiple indentations. The chemical absorption rate measurements were carried out using a highly accurate weighing scale (Sartorius) for the measurement of mass gain (ΔM) after immersion in chemicals. For the immersion tests, each specimen was placed in a separate container containing 250 mL of test solution to ensure a constant solution-to-specimen volume ratio and avoid concentration changes due to absorption. The solutions (0.2N HCl and 0.2N NaOH) were maintained at room temperature (25 ± 2°C) throughout the immersion period. No mechanical agitation was applied during immersion to simulate static exposure conditions. The test solutions were refreshed every 5 days to maintain consistent chemical concentration. The pH of the solutions was periodically monitored using a calibrated digital pH meter to ensure stability of the corrosive environment during the 15-day exposure period. The measurement of the thermal conductivity

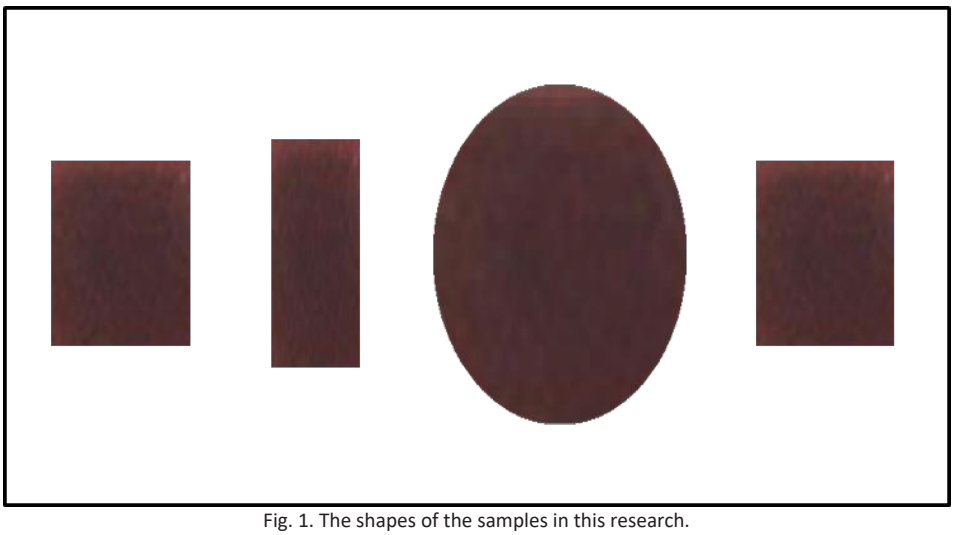


Fig. 1. The shapes of the samples in this research.

of the materials was carried out using the Lee's Disk apparatus, which is designed for materials displaying lower values of thermal conduction. The morphology at the interface, as well as the surfaces, of the specimens after immersion were determined. The morphology at the interface and specimen surfaces after immersion was examined using an optical light microscope at magnifications of 100× and 400× to observe particle distribution, interfacial features, and surface degradation characteristics, which is designed to provide information on the distribution of the copper particles on the surfaces. Four different composite formulations (2%, 4%, 6%, and 8% Cu) were investigated. One specimen per formulation was tested under each experimental condition. All measurements were conducted under controlled laboratory conditions with calibrated instruments to minimize experimental uncertainty. Future studies will include multiple replicates to enable statistical validation.

RESULTS AND DISCUSSION

Hardness Analysis and Discussion

The experimental results, shown in Table 3 and Table 4, indicate a good correlation between filler concentration and surface hardness of the resulting composites at day 0. Under natural conditions (N.C.), Shore D hardness values were found to increase steadily in correspondence with the increased concentration of wt. Cu fillers from 81.1 for 2% wt. Cu filler composite to a maximum of 82.3 for 8% wt. Cu filler composite. The improved hardness is due to its relatively high stiffness value compared with that of the polymer matrix of the respective epoxide matrix. The incorporation of Cu fillers effectively closes any interstitial voids, thus decreasing the volume of free epoxide in

Table 3. Shore D hardness values of EP/Cu composites under ambient conditions and after immersion in an acidic medium (0.2N HCl).

Sample Number	Sample Composition	Hardness					
		N.C	Immersion Time(day)				
		0	1	3	5	10	15
1	EP%98+Cu%2	81.1	80.5	80	79.4	79	78.5
2	EP%96+Cu%4	81.5	80	79.5	79	78.5	78.1
3	EP%94+Cu%6	81.8	79.4	79	78.5	78.1	77.6
4	EP%92+Cu%8	82.3	78.9	78.5	78	77.6	77

Table 4. Shore D hardness values of EP/Cu composites under ambient conditions and after immersion in an alkaline medium (0.2 N NaOH).

Sample Number	Sample Composite	Hardness					
		N.C	Immersion Time(day)				
		0	1	3	5	10	15
1	EP%98+Cu%2	81.1	80.9	80.6	80.2	79.6	79.4
2	EP%96+Cu%4	81.5	80.6	80.2	79.7	79.3	79
3	EP%94+Cu%6	81.8	80.3	79.8	79.3	78.9	78.6
4	EP%92+Cu%8	82.3	80	79.4	78.9	78.4	78.2

the matrix. The result is a more intimately locked micro-structure in which chain mobility of epoxide is remarkably reduced. Similar results were found by Hassan et al. (2022) [14], who noted that metal filler reinforcement impedes micro-deformation around metal centers of plastic flow. Moreover, Zheng et al., (2021) [15] succeeded in proving that raising the packing density using metallic fillers increases the resistance of the composite surface to indentation, matching the results of the present study. On immersion in the acidic (HCl) and basal (NaOH) environments, a gradual decrease in hardness was measured in each of the samples. The decrease in hardness is largely due to the entry of H+, Cl-, Na+, and OH- ions into the epoxy matrix. The ions effectively assist in disrupting the cross-linked network through hydrolysis, resulting in plasticization and swelling. The entry of these ions was verified by Al-Amri and Al-Zahrani (2023) [16], who confirmed that in polymer composites, chemical plasticization resulted in a substantial decrease in the Shore D hardness value due to the relaxed network resulting from ionic enter into the matrix The Role of Filler Interface: Notably, in the 8%wt. Cu-filled sample, there was a considerable decrease in hardness compared to the lower concentrations after 15 days. This can be attributed to the higher interfacial area, which serves as a preferential diffusion path. According to Williams & Lee (2024) [9], "the interface between the filler and matrix represents the weakest point in corrosion media, where interfacial deboning takes place, resulting in accelerated loss of mechanical properties in highly filled materials. "Comparative Analysis (HCl vs. NaOH). It was observed that the rate of degradation was higher in the acidic environment (HCl) compared to alkaline medium (NaOH). For the 8% wt. composite, a reduction to 77.0 was recorded in HCl, compared to 78.2 in NaOH. This is in line with the findings of Sivakumar et al., (2022) [17], which validates that acidic mediums are more aggressive compared to alkaline mediums to accelerate copper corrosion at the interface of copper-filled polymers, which in turn results in accelerated surface softening compared to alkaline mediums.

The durability of the EP/Cu Composites was assessed based on immersion in 0.2N Hydrochloric Acid (HCl) environment for 1, 3, 5, 10, and 15 days, which showed a corresponding decrease in Shore-D hardness values based on the immersion time and the amount of copper used, as shown in Table 3 and Fig. 2, which can be attributed to the nature of the environment, where HCl diffuses into the matrix of the composite material in a diffusion-controlled process to break the hydrolysis of the

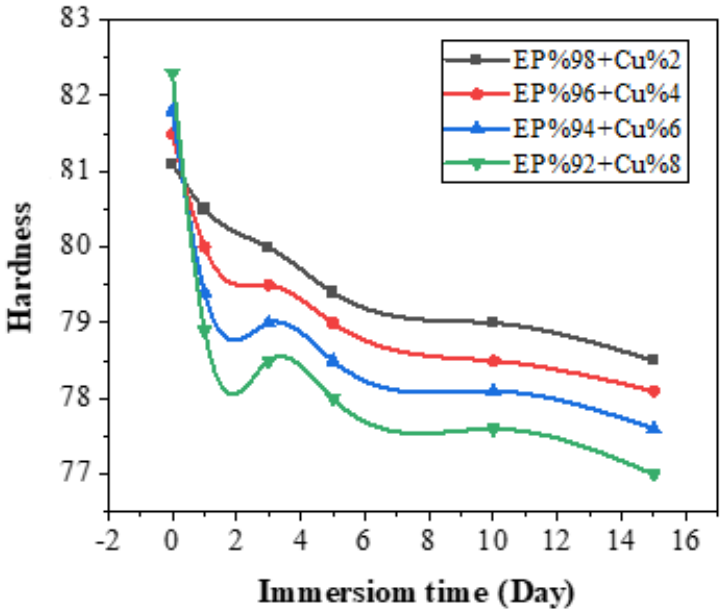


Fig. 2. Shore D hardness of EP/Cu composites as a function of immersion time in 0.2N Hydrochloric acid (HCl).

cross-links of the epoxy, thereby forming micro voids/bubbles, thus increasing the porosity of the material to eventually act as secondary conduits to further accelerate the breakdown of the composite material's interface of the copper to the matrix. Therefore, the reduced adhesion force between the interfaces makes it difficult to transfer the force, leading to greater matrix plasticity and reduced resistance to the indentation, known as "Chemical Plasticization" proposed by Williams and Lee (2024) [9]. These results show an extremely good level of consistency with the results proposed by Al-Amri and Al-Zahrani (2023) [16], which discussed how the acidic ion, especially the Cl-, helps in the leaching of the metal ion at the interface, which makes the integrity of the composite's surface fail drastically. Also, the drastic decrease in the hardness value of the 8% wt. Cu samples shows consistency with the results proposed by Hassan et al., (2022) [14] regarding the increase in the interface density, which unintentionally provides more pathways for the diffusion of corrosive materials.

As shown in Fig. 3, a notable difference is noticed between the values of the dry (initial) specimens and those that underwent immersion for a period of 15 days under the action of 0.2 N HCl. This reduces with all composition ratios; yet, the rate at which softening occurs escalates with increasing concentrations of the copper filler material. The basic cause for such a deterioration, therefore, is the penetration of acidic molecules, owing to micro-cracks present in the epoxy matrix, a phenomenon that has been supported by Clark et al., (2018) [18], attributing accelerated ion transport to micro-structural features in thermosetting polymers. Once the interface is reached, the acidic environment causes a separation between the polymer material and the copper, a condition denoted as interfacial deboning. This chemical attack efficiently induces interfacial debonding between the resin and the copper surfaces, resulting in a significant increase in matrix expansion and swelling. According to the study of Al-Amri and Al-Zahrani (2023) [16], this phenomenon can be seen in the metallic-filled composites, whereby the authors stated that the leaching of the metallic ions due to the increase in the acidity of the environment results in a considerable reduction in the bond of the interfacial interface. As the concentration of the copper increased, the overall interfacial area increased as well. This results in more diffusion routes of the acid and a consequent reduction in the overall value of the Shore D hardness. This phenomenon can support the study conducted by Hassan et al., (2022) [14], which found that as the concentration of the filler increased, the overall

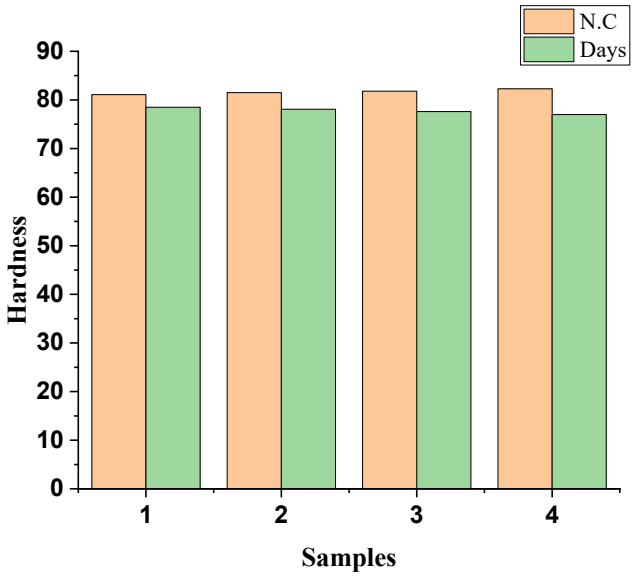


Fig. 3. Comparative analysis of Shore D hardness for EP/Cu composites in ambient (N.C.) state and after 15 days of immersion in 0.2 N HCl.

interfacial network increased and the material's susceptibility to the "chemical plasticization effect" increased accordingly. Furthermore, the positive correlation between the increase in expansion and the reduction in hardness in this study can support the Thomas et al. (2025) [10] finding that the interfacial failure is the main factor in determining the corresponding reduction in the mechanical properties of the epoxy-based reinforced material aged under a considerable corrosive process.

The specimens were then immersed in an alkaline solution of 0.2N Sodium Hydroxide (NaOH) for periodic intervals of 1, 3, 5, 10, and 15 days. The experimental data, as seen in Table 4 and graphically illustrated in Figs. 4 and 5, show that there is a progressive loss of Shore D hardness with an increase in immersion time and copper powder concentration. This time-dependent softening phenomenon agrees with the finding of Sivakumar et al. (2022) [17], which reports that an epoxy-based system gradually loses its cross-linking density with long-term exposure to alkalinity. The noted deterioration primarily results from the shrinkage and incomplete wetting of the epoxy-copper interface during the specimen fabrication process. According to Hassan et al. (2022) [14], such micro-structural defects provide an impetus to initiate hairline fractures and micro-voids, which act as conduits for the access and permeation of the alkaline solution into the composite through capillary action. With increased spreading of the NaOH solution, hydrolytic degradation of the polymer chains dramatically enhanced matrix plasticity. Alkaline-induced swelling followed by matrix relaxation was further corroborated by Kaur and Singh's findings of 2021 [11], where hydrolysis was established as the major cause for mechanical weakening of thermosetting resins. Conversely, the addition of higher percentages of copper weight fractions ironically accelerates this process. This process can be explained by the total expansion of interfacial area, which causes a higher degree of interfacial deboning, especially when subjected to alkaline stress. According to a discussion by Williams and Lee (2024) [9], a greater concentration of metallic fillers increases the number of 'paths of preferential diffusion' along the interface of the filler and matrix. The distance between the copper reinforcement and copper fillers disrupts stress distribution, thereby reducing its resistance to surface indentation. It can be noted that this study confirms the predictions by Thomas et al. (2025) [10] on particulate composites, which suggest that a high sensitivity to interfacial surface area extensively affects the rate of degradation

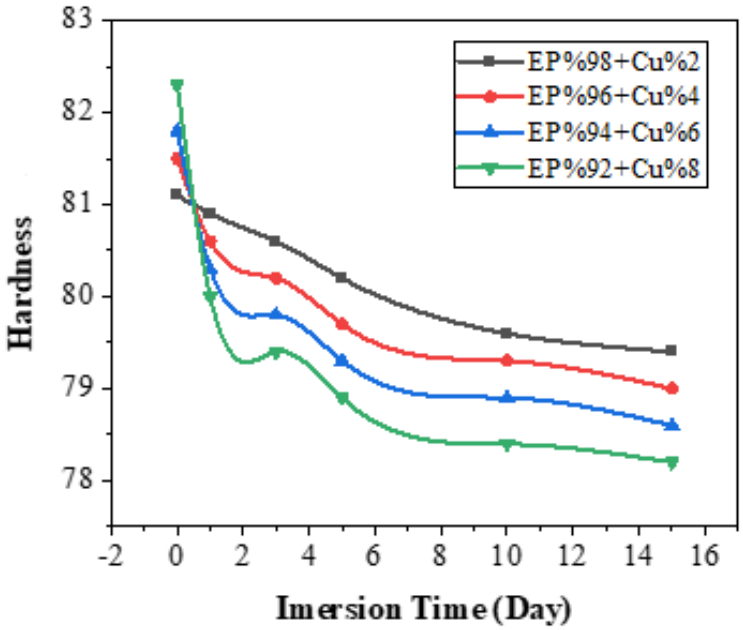


Fig. 4. Shore D hardness profiles of EP/Cu composites as a function of immersion time in a 0.2 N alkaline medium (NaOH).

of particulate composites. Moreover, this study's internal stress propagation along the cracks relates to the 'alkaline-aging process' explained by Al-Amri & Al-Zahrani (2023) [16].

Fig. 6 compares a relative test of the corrosive effect of the acidic environment of HCl and alkaline environment of NaOH on EP/Cu. After a 15-day immersion, from the results, specimens immersed in 0.2N alkaline environment showed higher Shore D hardness values compared to those immersed

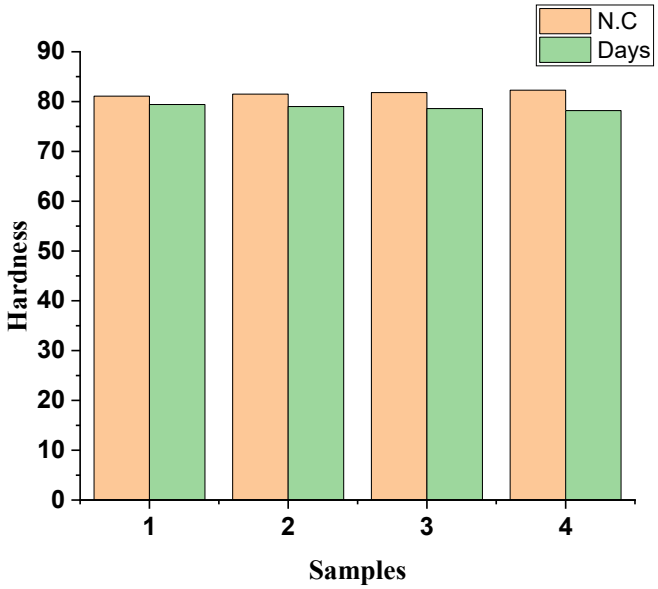


Fig. 5. Comparative evaluation of Shore D hardness for EP/Cu composites at ambient (N.C.) state and following 15 days of immersion in 0.2 N NaOH.

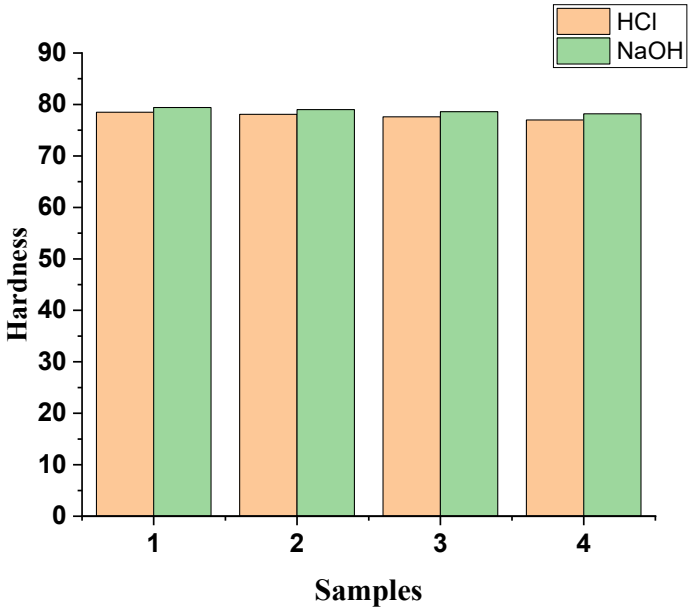


Fig. 6. Comparative analysis of Shore D hardness for EP/Cu composites after 15 days of exposure to acidic (0.2N HCl) and alkaline (0.2N NaOH) environments.

in acidic HCl of similar normality. This variation shows that HCl has a stronger corrosive effect on the EP/Cu than NaOH environment. The sensitivity of EP/Cu to HCl corrosion can be explained

Table 5. Thermal conductivity (k) values of EP/Cu composites in ambient (N.C.) state and at various immersion intervals in 0.2 N HCl.

Sample Number	Sample Composition	Thermal Conductivity(W/m.C°)					
		N.C	Immersion Time (Day)				
		0	1	3	5	10	15
1	EP%98 +Cu%2	0.318551	0.318551	0.31844	0.31834	0.318252	0.318052
2	EP%96 +Cu%4	0.318654	0.318491	0.318351	0.318234	0.318134	0.317981
3	EP%94 +Cu%6	0.318781	0.318262	0.318241	0.318152	0.318051	0.317885
4	EP%92 +Cu%8	0.319011	0.318150	0.318001	0.317991	0.317851	0.317711

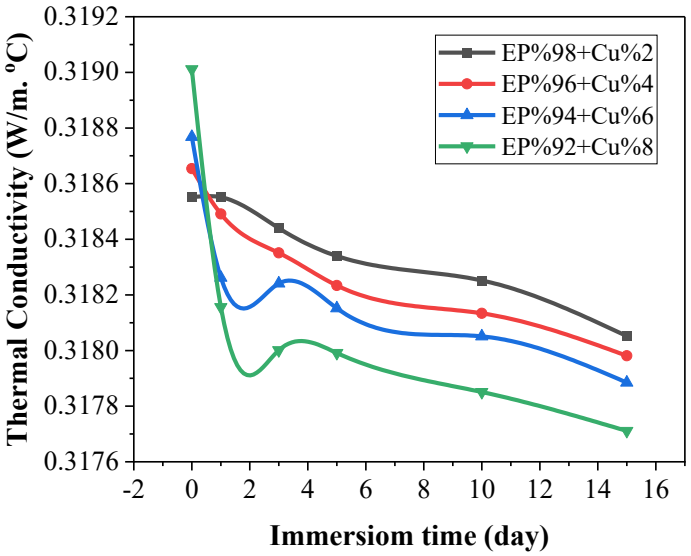


Fig. 7. Temporal variation of thermal conductivity (k) for EP/Cu composites as a function of immersion duration in 0.2 N Hydrochloric acid (HCl).

by its high ion mobility and reactivity, which easily penetrate deeper to undertake hydrolytic reactions on the cross-links of the epoxy matrix of EP/Cu, according to Al-Amri & Al-Zahrani, 2023 [16]. Though NaOH causes surface-level hydrolysis and matrix swelling, the acidic environment has a better ability to penetrate at the interface between the filler and matrix, resulting in a drastic failure of interfacial adhesion. This result strongly agrees with the research conducted by Sivakumar et al. (2022) [17], which demonstrated that the presence of acidic ions can cause more pronounced degradation of the secondary bonds within the thermosetting resin. This results in a drastic decrement in the mechanical strength. Moreover, the findings by Williams and Lee (2024) [9] indicate the importance of reduced hardness when metallic-filled polymer composites are subjected to acidic mediums due to enhanced electrochemical properties at the interface. This correlates with our results on reduced hardness on treatment with HCl. The reduced hardness observed due to both media can be emphasized by the aging models described by Thomas et al. (2025) [10].

The thermal conductivity of EP/Cu composites has been measured prior and after immersing in 0.2 N Hydrochloric Acid solution for 1, 3, 5, 10, and 15 days. From experiments, based on Table 5, Figs. 7 and 8, a dual behavior has been identified based on specimen status (under ambient condition & aged condition). Under ambient condition, there is a proportional increase in thermal conductivity based on increasing Copper Weight Fractions. This is due to the high thermal conductivity value of Copper Metal. As higher fillers of Copper are introduced, higher percentages of Copper particles fill the air gaps in between in EP/Epoxy matrix, thus decreasing volumes of insulating medium and increasing heat-conductive pathways. This is in agreement with the findings of Zhao & Lu (2019) [6], who found that joining high-conductivity micro-metallic particles decreases thermal distance due to continuous paths of high-conductivity. Conversely, for data after immersion, there is a systematic decrease in thermal distance based on increasing durations and filler concentration. The diffusion of HCl molecules through inherent micro-cracks and spherical porosities induces a derivative effect on the polymeric bonds. This chemical attack leads to a reduction in the interfacial bonding forces, which paradoxically increases the local material expansion as the immersion time progresses. The primary mechanism for the reduction in k is the arrival of acid molecules at the filler-matrix interface, leading to interfacial swelling and deboning. This separation creates a “thermal barrier” that significantly scatters phonons—the primary heat carriers in non-metallic and

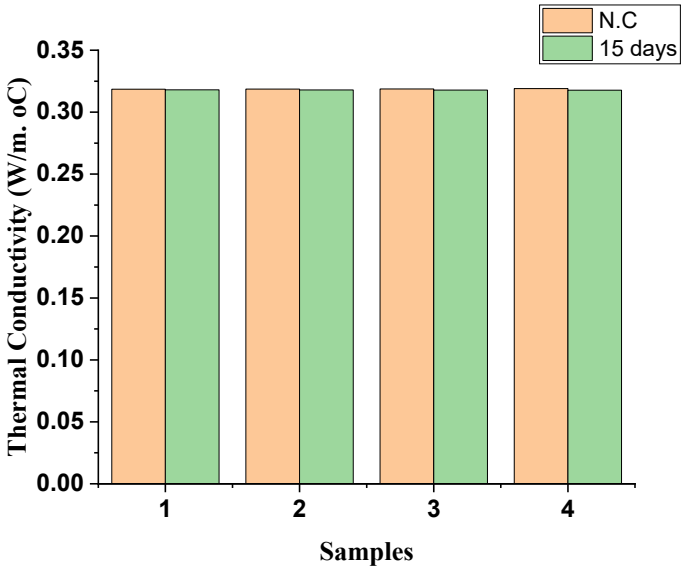


Fig. 8. Comparative analysis of thermal conductivity for EP/Cu composites: A baseline evaluation (N.C.) versus 15-day acidic immersion in 0.2 N HCl.

composite systems. As noted by Miller and Davis (2024) [19], any disruption in the filler-matrix continuity, such as that caused by chemical aging, hinders phonon transport, thereby drastically reducing the effective thermal conductivity. Fig.10 provides a comparative visualization of the thermal conductivity values between baseline samples and those aged for 15 days in the acidic medium.

Table 6. Thermal conductivity (k) values of EP/Cu composites in ambient (N.C.) state and at various immersion intervals in 0.2N Sodium Hydroxide (NaOH).

Sample Number	Sample Composition	Thermal Conductivity(W/m.°C)					
		N.C	Immersion Time (day)				
		0	1	3	5	10	15
1	EP%98 +Cu%2	0.318554	0.318591	0.318491	0.318351	0.318291	0.318191
2	EP%96 +Cu%4	0.318654	0.318434	0.318301	0.318261	0.318134	0.318081
3	EP%94 +Cu%6	0.318784	0.318304	0.318234	0.318134	0.318034	0.317925
4	EP%92 +Cu%8	0.319144	0.318232	0.318152	0.31805	0.317904	0.317828

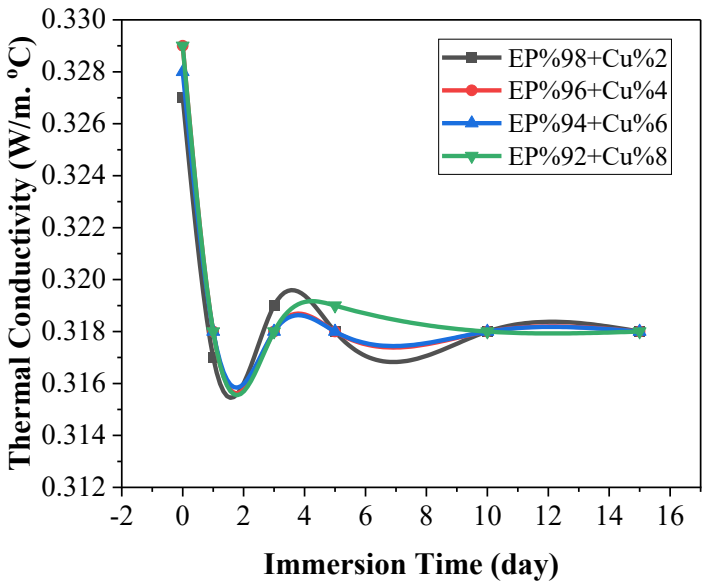


Fig. 9. Temporal variation in the thermal conductivity (k) of EP/Cu composites as a function of immersion duration in 0.2N Sodium Hydroxide (NaOH).

While the ambient samples show an upward trend with increasing copper concentration, the aged samples exhibit an inverse relationship. This behavior aligns with the research of Thomas et al. (2025) [10], who reported that higher filler loading (e.g., 8% wt. Cu) provides a greater interfacial surface area, which inadvertently creates more preferential pathways for corrosive diffusion, leading to a more pronounced drop in thermal performance compared to lower-filled samples. Furthermore, Nguyen and Tran (2023) [20] confirmed that solution-induced plasticization and swelling are the dominant factors in degrading the thermal transport efficiency of metallic-filled epoxies over prolonged exposure.

The thermal conductivity (k) behavior for the EP/Cu composites after dipping into the alkaline solution (0.2 N NaOH) is presented in Table 6 and Fig. 9. The results clearly show a reduction in the efficiency of thermal conduction with time and an increase in copper concentration. The trend of thermal conductivity with ambient conditions reveals a definite increase with copper weight fraction concentrations, which can be attributed to the increased metal-to-polymer interaction and the consequent development of a conducting metal framework. On the other hand, a definite reduction in the trend of k with the proposed model in an acidic matrix translates into a reduction with the exposure to the alkaline material (NaOH). The reduction in k can thus be mainly attributed to the increased hydroxyl ions (OH-) diffused into the microscopic porosities present in the composite material and the consequent hydrolysis of the epoxy matrix. The infiltration of the NaOH solution into the interface between the microscopic porosities and the copper material causes a reduction in the bonding between the matrix and the copper material. A reduction in bonding between the matrix and the copper material translates into an increase in phonon scatterings, which hinders the major mechanism of heat transfer. This is in agreement with Miller and Davis (2024) [19], who emphasized that the aging process at the filler-matrix interface plays a significant role in increasing the interfacial resistance to thermal flow. A major contrast in the thermal conductivity values for each sample after immersion for 15 days indicates that the k values in the alkaline medium (NaOH) are greater than in the sample aged in the acidic medium (HCl), which has a similar normality. This is clear evidence that the sample exposed to the acidic medium has been influenced to a greater extent in its effect on the bond strength at the interface. This is attributed to the capacity of HCl to deteriorate faster, which is due to the greater mobility and smaller ionic radius compared to OH- in the alkaline medium, which has relatively greater ionic radius. As quoted by Sivakumar et al., (2022) [17], in an acidic medium, the secondary cross-linking bonds in the epoxy are separated at a faster rate, hence causing a greater distance between the metallic filler and the matrix. This type of failure at the interface will adversely affect the ability of these phonons to move. This will be responsible for a reduction in thermal conductivity, as was observed in HCl samples. Thomas et al. (2025) [10] stated that a stronger process of “chemical plasticization” will occur in an acidic environment. This will correspond to larger losses of thermal functionality, which have been observed in our HCl experiments.

CONCLUSION

On the basis of the experimental research carried out on the mechanical and thermal properties of copper-filled epoxy (EP/Cu) composites during corrosive aging, the following conclusions can be made: The addition of copper (Cu) particles results in a considerable increase in both the surface hardness (Shore D) and the thermal conductivity (k) of the epoxy matrix at room temperature due to the high properties of copper. Exposure to acidic (HCl) and alkaline (NaOH) environments leads to a systematic degradation of all physical properties. This deterioration is time-dependent, where the maximum loss in performance was recorded after 15 days of immersion due to matrix plasticization and bond scission. The acidic medium (0.2 N HCl) showed a higher derivative effect compared with the alkaline medium (0.2 N NaOH). The reason for this may be attributed to the higher ionic radii and lower ion mobility of the Na+ ions compared with the Cl- ions. The main cause for the decrease in the thermal conductivity due to chemical aging is phonon scattering at the interfacial interfaces. The diffusion process of the chemical induces deboning, interfacial swelling, and formation of interfacial barriers to heat transfer. Higher copper content with higher weight percentages (e.g., 8%) may offer better starting properties; contrastingly, the composite is highly susceptible to chemical attack as the interfacial area is increased with higher copper content because of the increased

HCl NaOH diffusion path through the interfacial area, reflecting a higher percentage decrease in properties than the lower-filled composite.

From the results, it is confirmed that EP/Cu composites have a promising thermal management application; however, their durability in the environment is highly dependent on the pH value of the environment. Additionally, there is a need for surface protection when in an aggressive chemical environment.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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