

## Research Article

# Thermal and Electrical Conductivity of Unsaturated Polyester Resin Filled with Copper Filler Composites

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Thermal and electrical conductivity of unsaturated polyester resin with copper filler composite material are investigated both theoretically and experimentally. In the experiments, polyester matrix is combined with dendrite-shape copper to determine the effects of both filler size and content on thermal and electrical conductivity, respectively. It is observed that the increase in the concentration causes the thermal and electrical conductivity of composite mixture to grow up. It has also been observed that the both thermal and electrical conductivity increase with increasing filler particle size.

## 1. Introduction

Nowadays in many applications, thermal and electrically conductive polymer-based composites can replace metals. This technology is widely used because it introduces a new material that includes the thermal, insulation, and electrical properties of polymer materials. The advantages of polymers over metals are low density, corrosion and oxidation resistance, lightness, electromagnetic interference (EMI) protection, higher chemical resistance, and higher producibility. These superior features can be easily adjusted to different and widely applications [1, 2].

Too many studies in the literature are investigating the addition of nonpolymeric fillers to improve the physical properties of polymer. The addition of fillers with high thermal and electrical properties increases the thermal and electrical conductivity beyond the neat resin of the composite but cannot reach the level of pure filler material. The main motivation in this study is the theoretical and experimental investigation of the effects of particle size and concentration of dendritically shaped copper particles used as filler materials on thermal and electrical conductivity. Some of the existing studies examined in this subject are summarized as follows.

In a similar study, Choi et al. [1] investigate the thermal conductivity of polyacrylate matrix aluminum and

multiwalled carbon nanotube filled composites. For the fixed filler concentration, the composite loaded with 13  $\mu\text{m}$  aluminum dust had a higher thermal conductivity than the 3  $\mu\text{m}$  powder, and the composite filled with the two powder mixtures showed a synergistic effect on the thermal conductivity. The thermal conductivity of the composites strongly depended on the size and content of fillers. Moreira et al. [3] used unsaturated polyester resin (UPR) as binder and alumina and tenorite (copper oxide) as conductive particles in nanosize. The results showed that the thermal conductivity increases with particle concentration, as expected.

Agrawal and Satapathy [4] have proposed a new theoretical method to calculate the one-dimensional heat conduction, and thermal conductivity of typical particulate filled polymer composite systems. In their experimental work, epoxy binder was applied with aluminum nitrite filler material. The thermal conductivity of the composite increases with the addition of filler particle and the rate of increase of thermal conductivity is rapid for high volume fraction, that is, above 35% as compared with low volume fraction. In another study in which both thermal and electrical conductivities were examined together, Zhou et al. [5] reported that the thermal and electrical conductivity are related to the particulate shape and size as well as the added particle concentration. At higher filler loads, the thermal conductivity

has increased dramatically. Heat-conductive aluminum particles encapsulated by a polymer matrix could not contact each other at a low filler loading, resulting in the low thermal conductivity. This result is due to the high interfacial thermal contact resistance between the filler powder and the polymer matrix. The thermal and electrical conductivities of PVDF with flaky Al mixture composite is higher than spherical shape filler one. The thermal conductivity of the composite was found to be four times higher than the neat matrix for nickel-HDPE matrix composite [6].

The measurement of some parameters of the materials, such as thermal diffusivity, thermal conductivity, and thermal expansion coefficient, is very important for applications used especially in the manufacturing of devices. The thermal diffusivity given in Section 3.1,  $\alpha$  ( $\text{m}^2\text{s}^{-1}$ ), is an important thermophysical parameter that measures how effectively the phonons carry heat from the sample. However, the measurement of heat exchange or thermal impedance for a given material's heat exchange is essentially determined by the thermal effusivity,  $e$  ( $\text{Ws}^{1/2}\text{m}^{-2}\text{K}^{-1}$ ). The  $e$  is another important thermophysical parameter for quenching operations as much as for surface heating or cooling processes. These quantities are defined by  $\alpha = \lambda/\rho c$  and  $e = \sqrt{\lambda\rho c}$ , where  $\lambda$  is the thermal conductivity,  $c$  is the specific heat capacity, and  $\rho$  is the bulk density. The known thermal conductivity of  $\alpha$  and  $e$  can be obtained from  $\lambda = e\sqrt{\alpha}$  [7]. The variation of these parameters with respect to filler content will be given in Section 3.1 in more detail.

Considering the theoretical background of thermal conductivity, some predictive models of thermal conductivity emerge. The Maxwell Theoretical Model is the main focal point for most of these models. This model uses potential theory to obtain a precise solution for the conductivity of a system with spherical, noninteracting particles in a continuous matrix state [3–5, 8–10].

$$\lambda_c = \lambda_m \left[ \frac{\lambda_f + 2\lambda_m + 2\Phi_f(\lambda_f - \lambda_m)}{\lambda_f + 2\lambda_m - \Phi_f(\lambda_f - \lambda_m)} \right], \quad (1)$$

where  $\lambda_c$ ,  $\lambda_m$ , and  $\lambda_f$  are the thermal conductivities of the composite, matrix, and filler respectively, and  $\Phi_f$  is the volume fraction of filler. The Hashin-Shtrikman model is described as one of the best ways to estimate the lower limit when no information is available about the particle distribution in the matrix [6]. This lower limit can be expressed by the following equation:

$$\lambda_c = \lambda_m + \frac{\Phi_f}{1/(\lambda_f - \lambda_m) + (1 - \Phi_f)/3\lambda_m}, \quad (2)$$

where  $\lambda_c$ ,  $\lambda_m$ , and  $\lambda_f$  are the thermal conductivities of the composite, matrix, and filler, respectively, and  $\Phi_f$  is the volume fraction of filler.

Budiansky has provided a consistent way called “self-consistent” to calculate  $\lambda_c$  for composites. This model can be related to the calculation of a similar electrostatic problem. The model allows us to determine the thermal conductivities of the N-component system, which knows only the thermal

conductivities of pure materials ( $\lambda_i$ ) and volume parts ( $\Phi_i$ ) with respect to (4) [11]:

$$\sum_{i=1}^N \Phi_i \left[ \frac{2}{3} + \frac{1}{3} \left( \frac{\lambda_i}{\lambda_c} \right) \right]^{-1} = 1. \quad (3)$$

For a seconder system consisting of matrix and filler, (2) can be rewritten to the form given by (3)–(6):

$$\lambda_c = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (4)$$

$$a = 2 \quad (5)$$

$$b = \lambda_f - 2\lambda_m - 3(\lambda_f - \lambda_m)\Phi_f \quad (6)$$

$$c = -\lambda_f\lambda_m. \quad (7)$$

The Lewis–Nielsen model is defined by (8) and (9) for various shapes of fillers, as shown as follows [3, 4, 8, 11–13]:

$$\lambda_c = \lambda_m \frac{1 + AB\Phi_f}{1 - B\psi\Phi_f}, \quad (8)$$

where

$$\psi = 1 + \frac{(1 - \Phi_{\max})\Phi_f}{\Phi_{\max}^2} \quad (9)$$

$$B = \frac{\lambda_f/\lambda_m - 1}{\lambda_f/\lambda_m + A}.$$

$A$  is a variable which depends on the shape of the particles and  $\Phi_{\max}$  is the maximum insertion fraction. Various values  $A$  and  $\Phi_{\max}$  have been reported in the literature in different forms and different packing geometries (e.g., hexagonal, face and body centered cubic, simple cubic, and random). It is difficult to select correct values for  $A$  and  $\Phi_{\max}$  in order to calculate the thermal conductivities with respect to the filler content.

In the study of Krupa, the Lewis–Nielsen theoretical model reveals experimental data significantly. The above parameters obtained by adaptation of experimental data have the following values:  $A = 5.5 \pm 0.7$  and  $\Phi_{\max} = 0.6$  ( $R^2 = 0.982$ ) [6]. According to the Tavman [14],  $A$  and  $\Phi_{\max}$  are taken as 3 and 0.64, respectively. The Budiansky and the Maxwell model give the closest tendency with our experimental data for the lower concentrations. The comparison results will be given in Section 3.

## 2. Experimental Study

Dendrite-shape copper powder with 75  $\mu\text{m}$  average particle size is used as conductive filler material. The copper powder is sieved into 15–25  $\mu\text{m}$ , 25–32  $\mu\text{m}$ , 32–45  $\mu\text{m}$ , 45–53  $\mu\text{m}$ , 53–63  $\mu\text{m}$ , 63–75  $\mu\text{m}$ , 75–90  $\mu\text{m}$ , 90–106  $\mu\text{m}$ , 106–120  $\mu\text{m}$ , 120–150  $\mu\text{m}$ , and 150–180  $\mu\text{m}$  fractional size groups (See in Figure 2) in order to test the effect of particle size on thermal and electrical conductivity. The SEM image of dendritic-shaped copper particle is shown in Figure 1. As can be seen

TABLE 1: Properties of UPR given by the manufacturer.

Physical properties		Pure UPR properties		Mechanical properties	
		Hardening characteristics			
Viscosity	600–700 cps	Gelling time	$7 \pm 2$ min	Microhardness	18.62 HV
Monomer	Styrene (35%)	Peak temp.	$150 \pm 5^\circ\text{C}$	Elong. at break	20%
Acid number	$28 \pm 2$ mg/KOH/g	Peak temp. dur. time	12 min	Tensile stress	45.26 MPa
Density	$1.2 \pm 0.01$ g/cm <sup>3</sup>	Tot. peak temp. reach time	20 min	Tensile modulus	1.177 GPa

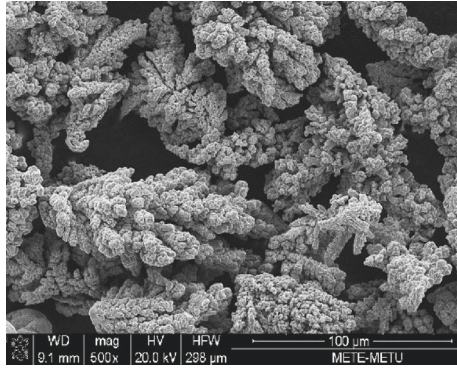
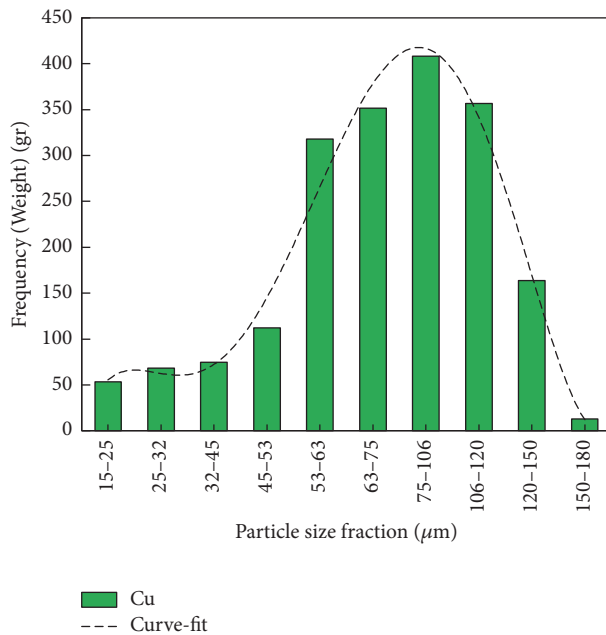
FIGURE 1: Dendrite-shape copper particle ( $\times 500$ ).

FIGURE 2: Copper powder particle size distribution.

in SEM image, the dendritic-shaped particle structure has much more contact surface area than the spherical and flake structures.

Unsaturated polyester (orthophthalic type UPR), including  $35\% \pm 2$  styrene as reactive diluent, with a brand name of CE 92-N8 was obtained from Cam Elyaf A.Ş. (Istanbul, Turkey). Methyl ethyl ketone peroxide used as initiator and cobalt naphthenate used as an accelerator were obtained from

TABLE 2: Component physical properties of composite (matrix and filler) materials.

Physical properties	UPR resin (CE 92-N8)	Copper filler
Average particle size ( $d$ , $\mu\text{m}$ )	-	75
Density ( $\rho$ , g/cm <sup>3</sup> )	1.20	8.92
Melting temperature ( $T_m$ , $^\circ\text{C}$ )	280	1084.62
Thermal conductivity ( $\lambda$ , $\text{Wm}^{-1}\text{K}^{-1}$ )	0.22	385

Akzo-Nobel (USA). In Table 1 pure UPR properties are given by the manufacturer.

The total volume of UPR and the filler,  $30\text{ cm}^3$ , is mixed after 1.5 g of the accelerator catalyst is added at the calculated ratios using a small mechanical mixer for about 15 minutes (at 40–60 rpm). Then, the mixture is stirred for 5 minutes after adding 5 g of hardener. The composite mixture in a viscous form is cast into a mold and left for 15 minutes for initial curing. In total, the hardened sample is obtained in about 35 minutes. The specimens are cured in a furnace for 4 hours at  $150^\circ\text{C}$  [12]. The cured specimens are machined to disc shape with 20 mm diameter and 8 mm thickness. The thermal conductivity is measured using a thermal conductivity analyzer (C-Therm TCi) by modified transient plane source technique in characterizing the thermal conductivity and effusivity of tested materials. The measurements are carried out at  $24 \pm 1^\circ\text{C}$  with a 17 mm diameter flat probe. The thermal stability of the samples is measured by thermogravimetric analysis (TGA) using a HITACHI TG/DTA 6300 thermogravimetric analyzer. The TGA analysis was performed under flowing nitrogen. Mass loss was traced as samples were heated at a rate of  $10^\circ\text{C min}^{-1}$  from room temperature to  $700^\circ\text{C}$ . The morphology of the inner state of composites was examined by scanning electron microscopy. The physical properties of component of the composite materials are given in Table 2.

After the preparation of 15 mm in diameter and 2 mm in thickness disc shaped samples the electrical resistance was measured by the two-point contact (pin) method [13, 15] using a KEITHLEY-619 direct current electrometer which has the measuring range of 0.1– $2.0\text{E}13$  ohm.

### 3. Results and Discussion

This section consists of three subsections; thermal conductivity, mechanical properties, and electrical conductivity. The results of experimental work in each section are presented.

TABLE 3: Thermal conductivity, effusivity, and diffusivity change with filler content.

$\Phi_f$ %	P/C, $\lambda$ [ $\text{Wm}^{-1}\text{K}^{-1}$ ]	P/C effusivity [ $\text{Ws}^{1/2}\text{m}^{-2}\text{K}^{-1}$ ]	P/C diffus. [ $\text{m}^2\text{s}^{-1}$ ]
16	1.577	1759.90	$8.0E-07$
23	1.837	1904.51	$9.3E-07$
30	2.193	2096.59	$1.1E-06$
37	2.536	2275.42	$1.2E-06$
43	2.827	2422.27	$1.4E-06$
47	3.363	2682.83	$1.6E-06$
50	3.475	2735.61	$1.6E-06$
52	3.682	2831.80	$1.7E-06$
55	3.898	2930.33	$1.8E-06$
57	4.722	3290.23	$2.1E-06$

**3.1. Thermal Conductivity.** Thermal conductivity measurements of the polyester-copper (P/C) composites with various filler loadings are displayed and comparison of the theoretical models is given in this section. The Hashin-Strikman and the Lewis-Nielsen models give the closest tendency with the experimental data. The overall trend for all composites is that  $\lambda$  increases with higher filler content. These results were expected and were consistent with other studies [1, 3–11, 14]. Thermal conductivity and effusivity results are tabulated in Table 3. The conductivity and effusivity of composite materials increase with increasing copper filler content. The thermal conductivity probe measures the effusivity of a material (Figure 3), which is

$$\text{Effusivity } (E) = \sqrt{\lambda \rho c_p}, \quad (10)$$

$$\text{Diffusivity } (D) = \frac{\lambda}{\rho c_p} \quad (11)$$

$$D = \left( \frac{\lambda}{E} \right)^2, \quad (12)$$

where  $\lambda$  is the thermal conductivity ( $\text{W/m K}$ ),  $\rho$  is the density ( $\text{g/cm}^3$  or  $\text{kg/m}^3$ ), and  $c_p$  is the heat capacity ( $\text{J/kg K}$ ). Diffusivity can be derived (12).

The thermal effusivity defined (10) is an important thermophysical property, which characterizes the thermal impedance of matter [7, 16]. Figure 3 compares the effusivity and calculated diffusivity of composite mixtures with copper filler volumetric content. The effusivity values of P/C composites are increasing with volume filler fraction.

Comparing the measured values of  $\lambda$  for P/C composites, it can be observed that P/C system was more effective than proposed theoretical models (Figure 4) as in literature [3, 5, 17]. This result could be attributed to the more suitable packing of copper particulates. The fillers would be able to bridge gaps among them and create a more extensive three-dimensional thermal conductivity network throughout the UPR matrix. The P/C composites do not obey the given theoretical models at higher concentrations.

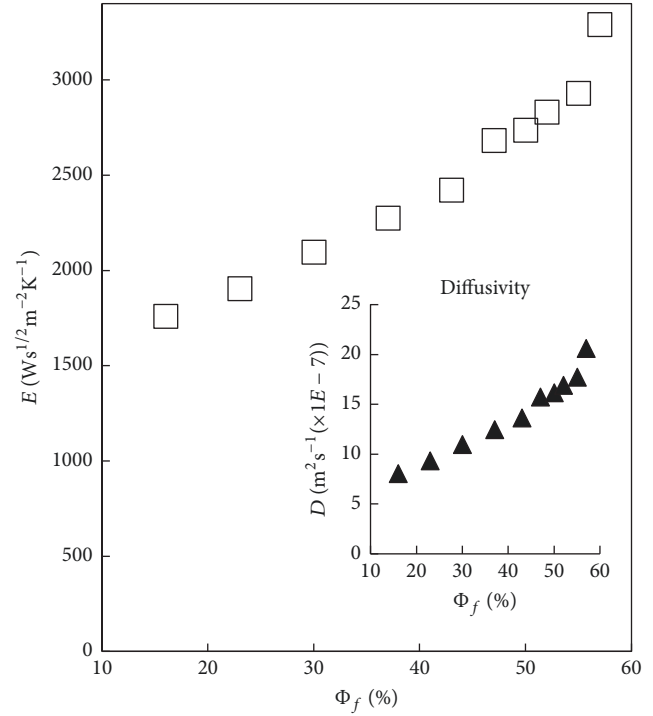


FIGURE 3: Measured effusivity and calculated diffusivity of P/C versus copper filler content.

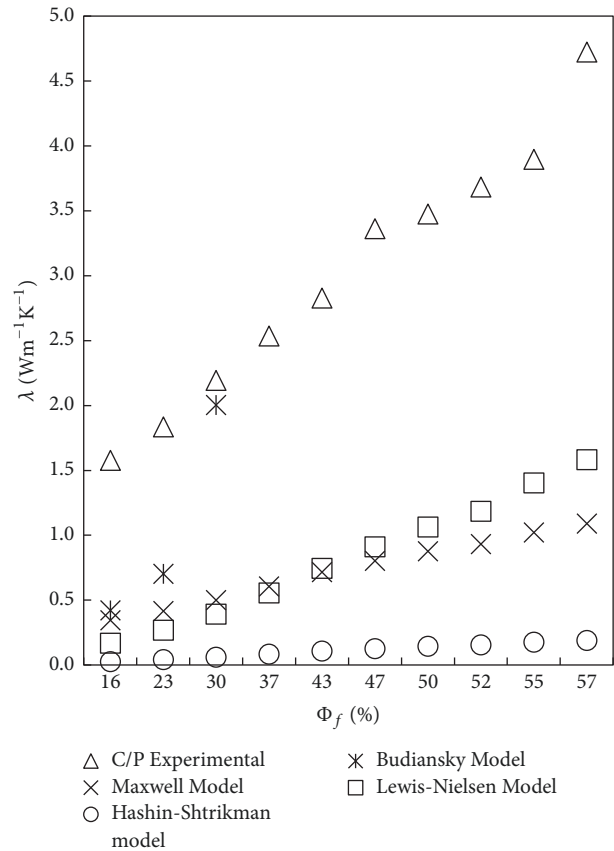


FIGURE 4: Variation of thermal conductivity of composite versus volume content of filler and comparison of the theoretical models.

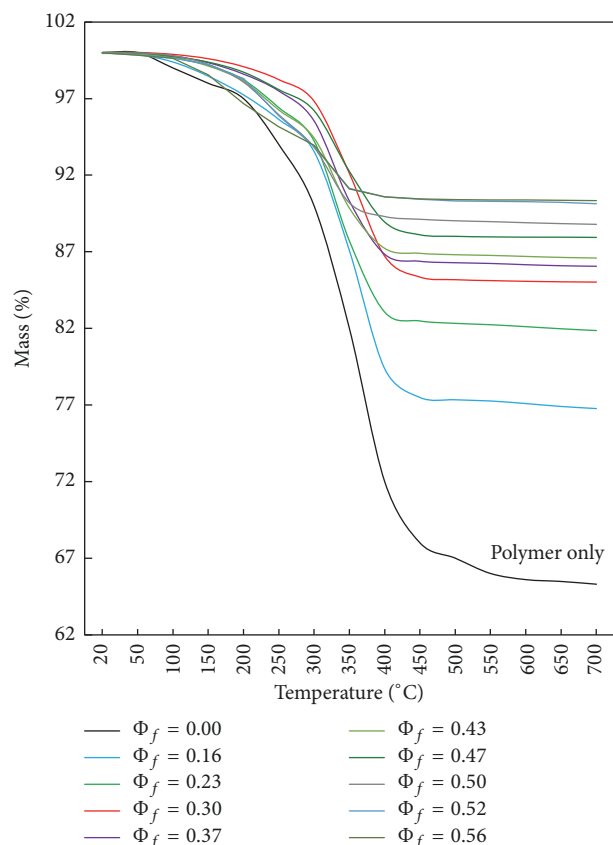


FIGURE 5: TGA curves of P/C powder composite specimens for different weight percentage of copper filler.

However, Maxwell and Budiansky models give closer results below 37% filler content. As can be seen from the result, the addition of copper into the UPR matrix increased the thermal conductivity over 21 times that of neat UPR. The composite mixture saturates at a volumetric concentration of about 55–60% when copper is added. The TGA curves of P/C composites are given in Figure 5. There is a significant increase in the thermal stability of the UPR with increasing Cu% content. This can be explained by the higher heat capacity and thermal conductivity of the copper, which causes heat absorption. This causes the UPR chains to start to decompose at higher temperatures [18, 19].

In the TGA curve of UPR, initial weight loss occurs at a temperature of 250°C approximately. In almost all samples, the complete degradation of the polymer (weight loss) is completed about 420°C. The major degradation temperature of UPR was found to be improved from 230 to 400°C incorporating the P/C. The P/C composites have shown better thermal stability compared to neat resin. The dynamic DTA curves of the decomposition of UPR and composites with different copper filler concentrations are plotted in Figure 6. The maximum weight loss occurs at the temperature interval of 400–440°C. This analysis reveals that the thermal stability of composites increases with increasing of the copper content [20].

The perfection of the crystalline domains of pure UPR is degraded by the interaction between the pure UPR and

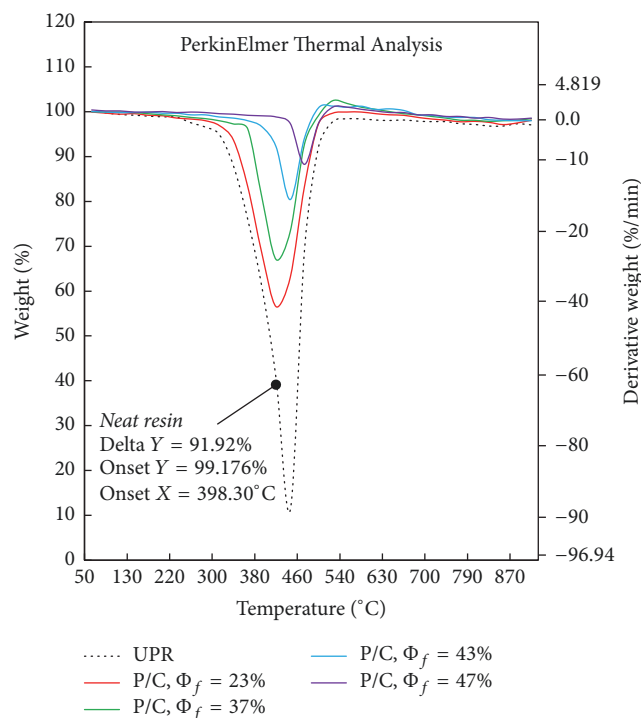


FIGURE 6: DTA curves of P/C composites as various amounts of Cu content.

the Cu filler, and the filler particles could cause a more pronounced effect on crystallinity as the filler concentration is increased [19, 21].

In the experiments of filler particle size effect, the average copper filler (25–32 μm, 32–45 μm, 45–53 μm, 53–63 μm, 63–75 μm, 75–90 μm, 90–106 μm, 106–120 μm, and 120–150 μm) fractional particle size specimen groups having 43%  $\Phi_f$  (median value) are tested. Thermal conductivity-particle size relationship is given in Figure 7.

The thermal conductivity increases slightly with particle size. In other words, larger filler particles should result in a lower thermal barrier (thermal resistivity). Figure 7 shows the thermal conductivity of copper filled UPR composites for different particle size distributions. In the study of Biswas et al., the same results were achieved for Cu/UPR composite system. They reported that the addition of Cu filler to the UPR increased the thermal and electrical conductivity. According to this result, the electrical conductivity obeys the same trends as thermal conductivity [21].

**3.2. Mechanical Properties.** The addition of Cu into the polyester matrix material has a significant effect on the mechanical characters of the composite due to its dendritic shape and excellent mechanical strength. The stress-strain curves representing the neat UPR and its composites in various filler loadings are shown in Figure 8. The mechanical properties of the compound mixture have been found to be significantly increased compared to pure UPR [14, 17, 19–21]. The slope of the curves increases with increasing Cu content. Based on the slope of the elastic zone, the tensile modulus



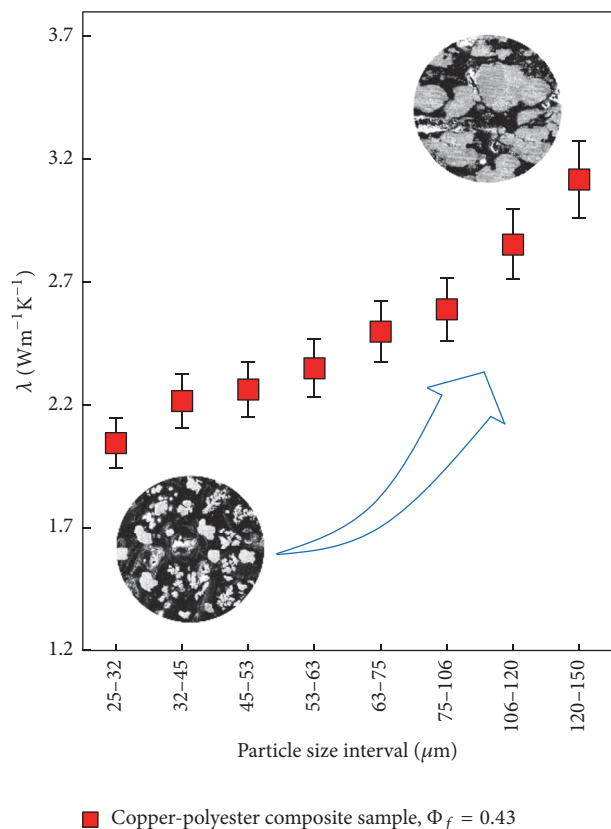


FIGURE 7: The copper filler particle size effect on thermal conductivity.

values are calculated and their variations through  $\Phi_f\%$  are shown in Figure 9.

Tensile properties were tested according to ASTM Standard D-638 (Standard Test Method for Tensile Properties of Plastics). The tests were carried out at a temperature of 23°C and 2 [mm/min] tensile speed using a microcontrolled universal testing machine (model WDW 50 E). The tensile strength and percentage of elongation of P/C composites are shown in Figure 9.

The elongation at break value for neat UPR given by the manufacturer is at about 20%. The neat resin samples prepared in this study are baked at 150°C for 4 hours. The postcure resultant internal structure becomes more brittle and elongation at break falls to 8–12%.

The average tensile strength for pure UPR resin is 45.26 [MPa]. The tensile strength values were found to increase with increasing Cu loading up to 16%. After this value, the copper content tends to decrease gradually as the copper content increases.

The P/C composite structure has reached the highest tensile stress value with a volume load of 16% Cu. The maximum tensile strength value is 82.23 [MPa], which corresponds to an improvement of about 129% (maximum tensile stress, 63.78 [MPa]) when compared to neat resin. This increased tensile property can be attributed to the good dispersion of the filler in the polymer matrix. The maximum elongation was approximately 0.8 mm (8%) at break for neat UPR.

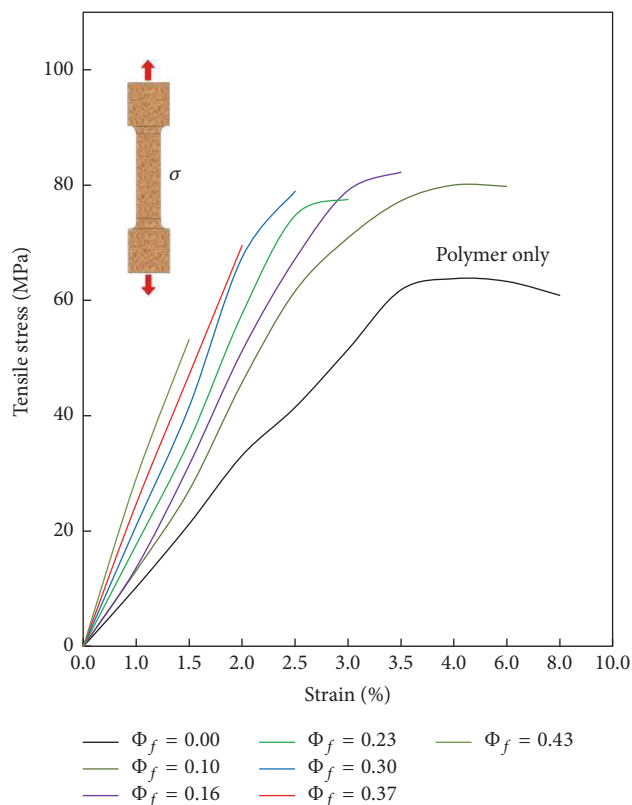


FIGURE 8: Stress-strain curves of the composites with various Cu loadings.

On the other hand, a gradual decrease in the elongation at break of the composites was observed with increasing Cu content. The fracture elongation for  $\Phi_f = 43\%$  Cu loading decreased from 79.88% to 20.83% for pure polymer. The metal particles dispersed in the matrix restrict the movement of the polymer chains, which tend to move due to temperature changes or mechanical forces. Similar evaluations can be found in the literature [2, 14, 17, 22].

Hardness is another indication of the ability of a material to resist deformation [22]. Addition of Cu fillers increased significantly the hardness of neat UPR as shown in Figure 10.

The bar chart shows experimental microhardness (HV) of composites as a function of Cu. As Cu content increases, microhardness of composites increases with respect to pure UPR matrix. Namely, the filler material incorporated into the UPR increases the microhardness of the resin around 18 HV by about ten times (180 HV).

In literature, the studies of Goyal et al. [22], Pargi et al. [23], and Teh et al. [24] reported the same result that the hardness and strength of composite mixture increase with increasing copper filler.

**3.3. Electrical Conductivity.** The easiest way to produce conductive polymer composites is to fill an insulating polymer having good mechanical properties with highly conductive particles, that is, metal powders. Electrical conductivity of metal filled polymers has evidenced the known classical

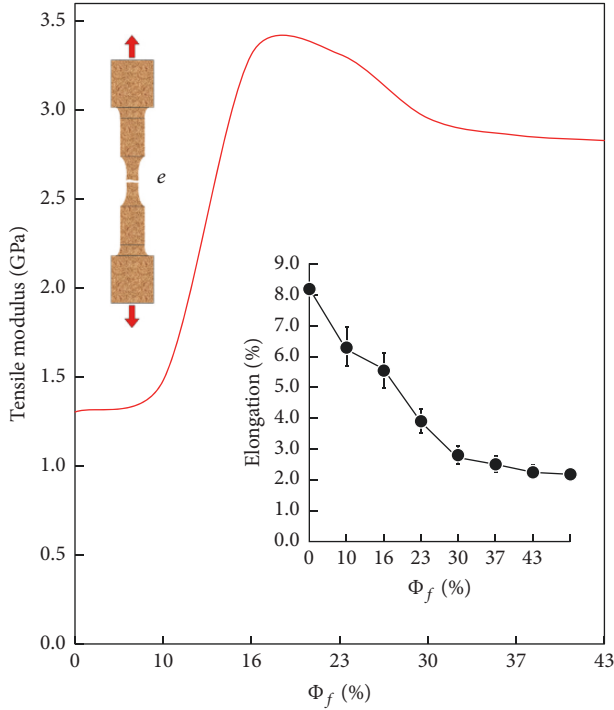


FIGURE 9: Tensile modulus and elongation for  $\Phi_f$  % curves of the composites mixture.

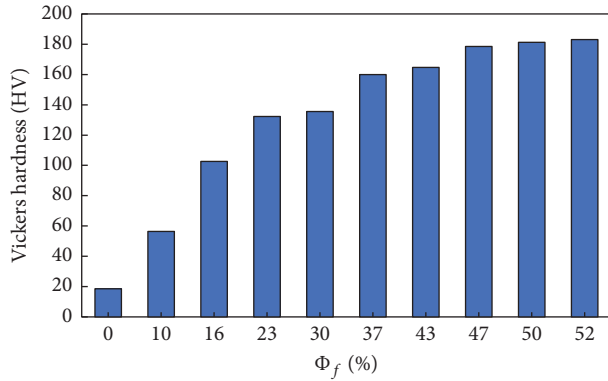


FIGURE 10: Hardness as a function of vol.% of Cu in UPR matrix.

Insulating to Conducting Transition (ICT). The behavior of this property depends strongly on the filler concentration. It increases when the concentration of metal increases and the transition occurs at a fixed fraction called threshold of percolation. In percolation theory, the relationship between the electrical conductivity of the mixture and the volume fraction of the conductive filler is given by (1) [25]:

$$\sigma = \sigma_f (\Phi_f - \Phi_c)^t. \quad (13)$$

Conductivity of the composite mixture depends primarily on the concentration of conducting elements. In expression

(10)  $\Phi_c$  is the critical volumetric content (percolation threshold) meaning a minimal volume fraction of conducting filler at which a continuous conducting network of macroscopic length appears in the system, so the equation is applied only above the percolation threshold,  $\Phi_f$  is the volume portion of the filler,  $\sigma_f$  is the conductivity of the conducting component or conductivity of conducting phase, and  $t$  is a parameter determining the power of the conductivity increase above  $\Phi_c$  [25]. Roldughin and Vysotskii [26] obtained higher  $\sigma$  for mixture of nickel powder (8  $\mu\text{m}$  average filler size) with ED-20 epoxy resin hardened at 100°C temperature. They reported that  $\sigma$  increases with increasing nickel content  $\Phi_f$  and particle radius. Furthermore, it is claimed that lower viscosity of matrix material has a positive effect on the formation of conductive chains during curing.

In El-Tantawy et al.'s work [27], the relationship between the electrical conductivity and carbon black content under precure and postcure conditions was investigated. In experiments, epoxy resin and 20  $\mu\text{m}$  average size filler powder were mixed at different ratios and cured for 3 hours and 1 week at 80°C. They found that conductivity increased with volumetric filler rate of graphite. The dielectric properties of the low-density polyethylene- (LDPE-) matrix composites with the different conducting fillers (carbon fiber (CF), copper (Cu), and nickel (Ni) powders) were studied by Dang et al. [28] over a broad range of frequency and volume fraction of fillers. The electrical conductivity increases with an increase in frequency and the amount of fillers. Wu et al. showed the filler size effect on percolation threshold of isotopically conductive adhesive (ICA). Ag particles with 50 nm average diameter were used as filler. The results show that the percolation threshold of ICAs depends strongly on the filler sizes, which reaches 63% wt. Results obtained by theoretical calculation are in good agreement with the experimental results [29].

In our study, logarithmic  $\sigma$  of the copper filled electrodes increases with increasing copper concentration  $\Phi_f$ . In the P/C composite mixture, the conductivity chain is established at about 20% copper  $\Phi_f$  value which is percolation threshold of C/P composite system. As can be also seen from Figure 11, the solution reaches saturation at about 55% volume fraction.

In the experiments of filler particle size effect, the average filler fractional particle size specimen groups having 46%  $\Phi_f$  are tested. It is observed that the electrical conductivity increases with increasing particle size exponentially [12]. In other words, larger filler particles should result in a lower composite resistivity. Figure 12 shows the conductivity of C/P composites for different particle size distributions.

The scanning electron micrograph (SEM) photographs of 86% wt copper-polyester composite with  $\times 1000$  magnification are given in Figures 13(a)–13(b). The microphotographs of composites are also shown in Figures 13(d)–13(f) as 60% wt, 70% wt, and 90% wt-Cu, respectively.

In the SEM images, the formation of agglomerates of the copper filler in the resin can be observed. As can be seen from Figure 13, the addition of higher volumetric rate of filler material brings the particles closer to one another and even provides contact. The samples obtained by mixing copper filler with UPR give very high electrical conductivity values compared to the matrix material alone. Because of this

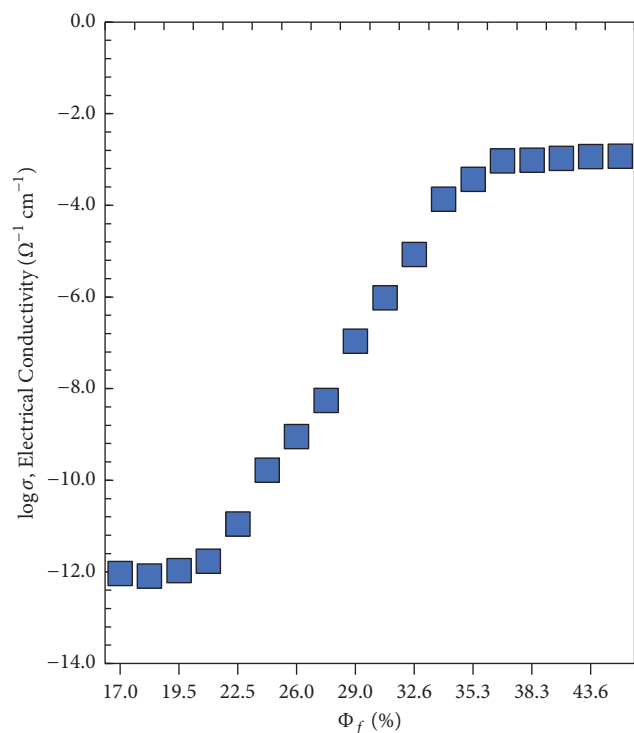


FIGURE 11: Variation of electrical conductivity of composite specimens versus filler rate.

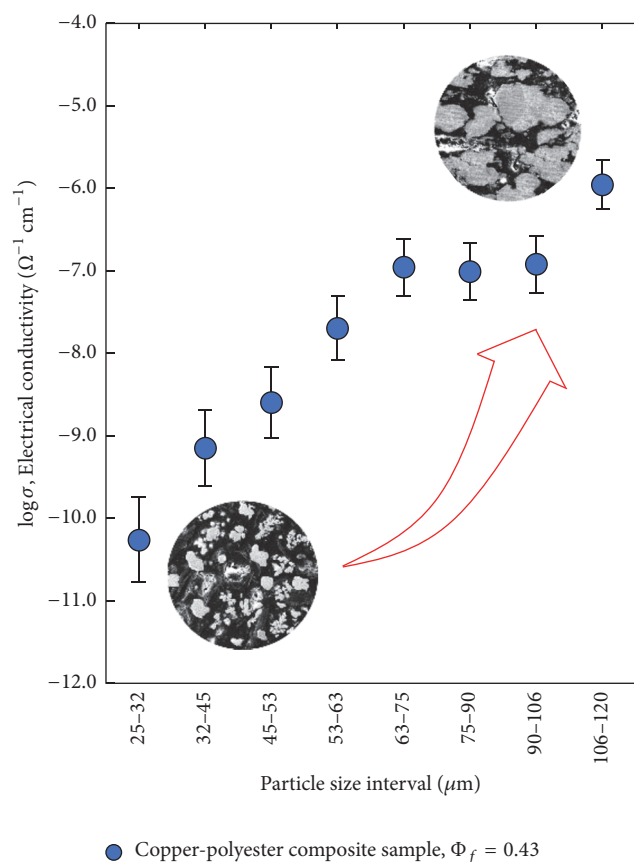


FIGURE 12: The copper filler particle size effect on electrical conductivity.

high level of electrical conductivity, Yaman and Çoğun used this composite material as electrodes for machining SAE1040 steel material by a die-sinker electrical discharge machine successfully.

Figure 14 shows the machined metallic material and used electrode images. They compared the electrical conductivity of their novel electrode with respect to the copper filler content. They found out that the electrical conductivity of composite electrodes increases with increasing the copper filler content [12].

As a consequence, studies in the literature show that both thermal and electrical conductivity increase with increasing filler content and size [1–13, 15–31]. It is also understood that the filling material particle shape is another important factor [30, 31]. Similar to the results obtained by Wang et al., this study suggests that dendrite shaped particles are a significant contributor to the thermal and electrical conductivity of the composite structure. At any filler concentration, particles with large dimensions (aspect ratio) may form better conductive paths towards heat and electrical flow. This causes significant increases in the thermal and electrical conductivity of the composite structure.

## 4. Conclusions

This paper presents theoretical and experimental investigation on thermal and electrical conductivity in a polymeric composite composed of UPR matrix with dendrite shaped copper particles as fillers. The thermal conductivity was found to increase along with filler content. P/C was found to be more effective in promoting both the thermal and electrical conductivity of the material when compared to theoretical systems. Thermogravimetric analysis (TGA) and differential thermogravimetric analysis (DTA) also showed an increment in thermal stability after the addition of filler in UPR. The maximum thermal conductivity value of composite sample is obtained as  $4.72 \text{ [Wm}^{-1} \text{ K}^{-1}]$  experimentally so the addition of copper into the matrix increased the thermal conductivity over 21 times that of neat UPR. The Hashin-Strikmann and the Lewis-Nielsen models give the similar tendency with the experimental data. However, particularly for lower (below 37% volumetric) filler content, Maxwell and Budiansky models exhibit convergence to the experimental results.

The next portion of the study focused on the effect of particle size of filler on conductivity. The results show that the larger particle size causes relatively higher thermal conductivity. The electrical conductivity results obey the same trends as thermal conductivity. The electrical conductivity increases with increasing filler content exponentially. It is also observed that the electrical conductivity increases with increasing particle size.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.



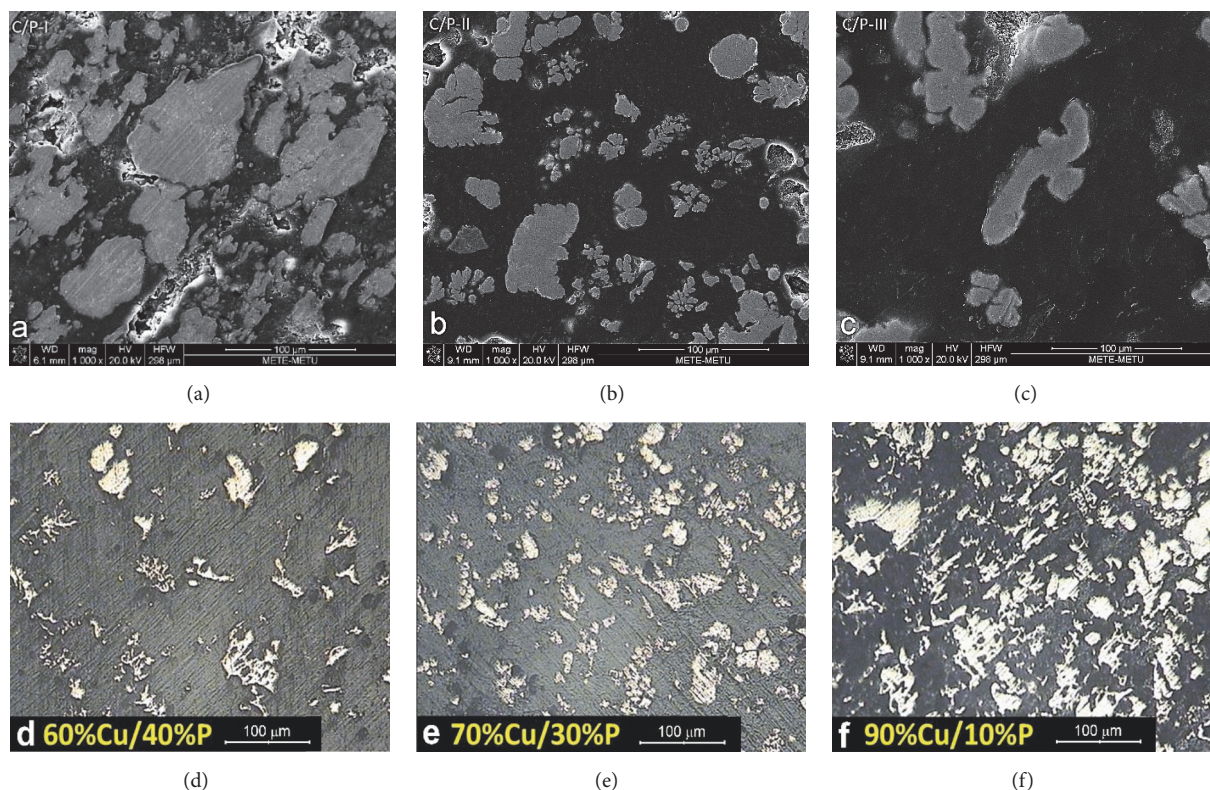


FIGURE 13: SEM ( $\times 1000$ )/Micro ( $\times 100$ ) images of (a) Cu 86% wt, (b) Cu 75% wt, (c) Cu 60% wt, (d) Cu 60% wt, (e) Cu 70% wt, and (f) Cu 90% wt-polyester composite mixture.

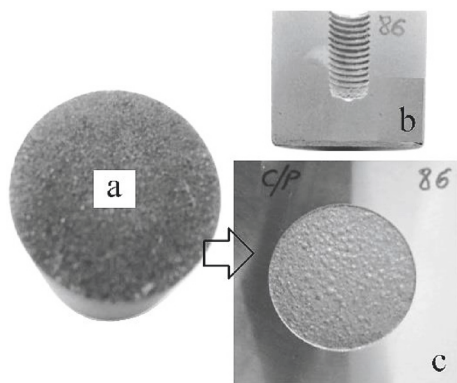


FIGURE 14: Electrode and machined workpiece produced from a P/C composite material with a copper content of 86% wt: (a) machine surface of electrode, (b) electrode cross section, and (c) machined SAE 1040 steel material.

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