Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Original Article

Development of high performance granite fine fly dust particle reinforced epoxy composites: structure, thermal, mechanical, surface and high voltage breakdown strength properties

Hariharan Arumugam [a], *Mohamed Iqbal M* [b], *Cheol-Hee Ahn* [c], *Sarawut Rimdusit* [a,*], *Alagar Muthukaruppan* [d,**]

[a] *Research Unit in Polymeric Materials for Medical Practice Devices, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok-10330, Thailand*

[b] *Department of Electrical and Electronics Engineering, PSG Institute of Technology and Applied Research, Neelambur, Coimbatore- 641062, India*

[c] *Research Institute of Advanced Materials (RIAM), Department of Materials Science and Engineering, Seoul National University, Seoul 08826, Republic of Korea*

[d] *Polymer Engineering Laboratory, PSG Institute of Technology and Applied Research, Neelambur, Coimbatore - 641 062, India*

ARTICLE INFO

Article history:
Received 8 February 2023
Accepted 27 March 2023
Available online 31 March 2023

Keywords:
Granite fly dust
Epoxy composites
Thermal behaviour
Electrical resistivity
Breakdown voltage
Dielectric strength
High voltage insulator

ABSTRACT

The granite waste generated from the granite cutting and polishing industries contributes to lot of environmental contamination and health hazards. In the present work, an attempt has been made to assess the method to minimise environmental problems associated with granite dust pollution to the possible extent by converting the granite dust waste into value added high voltage electrical insulator products. Two types of epoxy matrices comprising bisphenol-A diglycidyl ether-phenalkamine (ER-1) and bisphenol-A diglycidyl ether-methyl hexahydrophthalic anhydride (ER-2) separately reinforced with varying weight percentages of (20, 40, 60, 80 and 100 wt%) of granite dust. The matrices and composites obtained were characterized for their structural, morphology, hydrophobic properties, thermal stability, mechanical strength, thermal conductivity, thermal resistivity, electrical resistivity, breakdown voltage and dielectric strength behaviour using appropriate analytical testing methods. Data resulted from different studies, it was inferred that the composites prepared using ER-2 possess better properties than those of ER-1. The composites with 100 wt % of cutting waste granite fly dust reinforced ER-2 possesses the higher values of electrical surface resistivity (5.22×10^{12} Ω), and electrical volume resistivity (5.60×10^{13} Ω) than those of neat ER-2 matrix (surface resistivity 4.82×10^{9} Ω and volume resistivity 2.48×10^{13} Ω). The breakdown voltage and dielectric strength of ER-2 matrix were increased from 28 ±1 kV and 14 ± 0.5 kV/mm to 34 ±1 kV and 17 ± 0.5 kV/mm respectively, when reinforced with

* Corresponding author.
** Corresponding author.
E-mail addresses: sarawut.r@chula.ac.th (S. Rimdusit), muthukaruppanalagar@gmail.com (A. Muthukaruppan).

https://doi.org/10.1016/j.jmrt.2023.03.199

2238-7854/© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

100 wt % granite dust. The value of breakdown voltage was increased by 22% for 100 wt% granite dust reinforced composites when compared to that of neat epoxy matrix.
© 2023 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

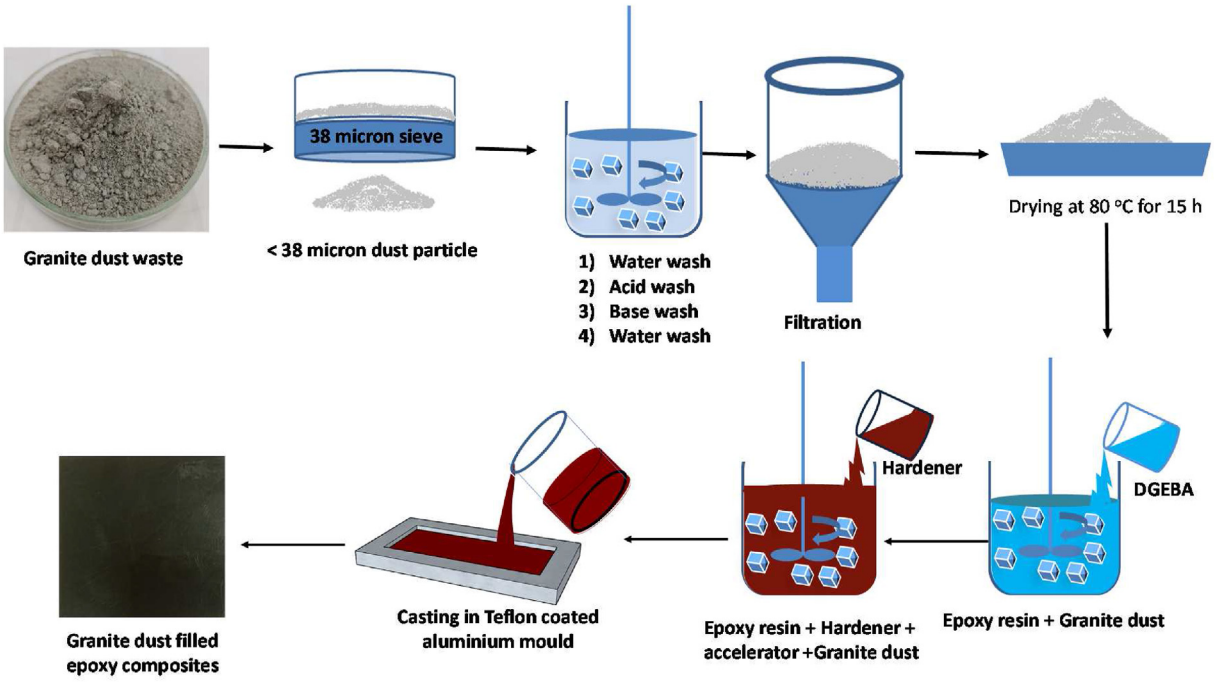
Granite is a type of closely packed natural stone, which is widely used in the field of civil engineering sector such as wall covering panels, floors, shelves, sinks, basins, fireplace mantle, table tops and monuments. An advancement of granite cutting and polishing processing industries generate massive wastes. It is well known that the millions of tons of granite waste generated from the granite cutting and polishing industries around the world. These granite waste causes lot of environmental problems by contaminating land, water and air, which in-turn contribute to health hazards [1]. The effective method of utilization of granite fly dust particulates for the development of new industrial products will mitigate the environmental problem to certain extent.

Ceramic materials were utilized widely in medium and high voltage electrical insulation applications. The ceramic materials possess better electrical resistance and have long lifetime. However, heavy weight, high energy required for material production and less performance in prolusion contaminated environments are the limitation with the ceramic materials. Polymer insulator is a counter part of ceramic insulator. Light weight, easy processes, economic design, and hydrophobic nature are main advantages of polymer insulator. Usually, silicone rubber, ethylene propylene diene monomer, epoxy resin and ethylene vinyl acetate, polytetrafluoroethylene, polyolefin elastomer and high-density polyethylene, polyurethane are used for low voltage and high voltage insulation applications. These polymeric materials contribute to an excellent hydrophobicity, good mechanical strength, excellent breakdown strength and higher volume resistivity. The polymer insulator systems are developed in the form of hybrid composites. Usually, metal oxides and non-metal oxides are used as a reinforcing material for high-voltage insulation materials such as silica, alumina, titanium oxide, zinc oxide, magnesium oxide, boron nitride, aluminium nitride, silicon nitride and silicon carbide. Previously our research group have been developed bio-silica hybrid benzoxazine composites for high voltage insulation application [2].

It is well known that the different epoxy based composites were utilised for various applications such as, coatings [3], friction materials [4–6], adhesives [7], military [8], building materials [9], electronic circuit boards [10], electrical insulation, etc. Majorly, the silica reinforced epoxy composites have been used for high voltage insulation application [11]. In this work two type of composite systems were prepared for different environment. The ER-1 is considered as a tough polymer system, which was derived from DGEBA and phenalkamine [12]. The phenalkamine is a cardanol based hardener [13] which contains a long aliphatic chain in *meta* position of phenol and triethylenetetraamine placed at *ortho* position of cardanol [14]. The ER-1 is a room temperature curable system. The ER-2 is considered as a brittle nature polymer system, which is derived from DGEBA and methyl hexahydrophthalic anhydride [15]. The ER-2 is considered as high temperature curable system, which will cures at about 100 °C [16]. The ER-2 is most widely used polymer system for high voltage insulation application [17].

The use granite fly dust is expected to replace the many of the traditional fillers [18–20], clay [21], and other conventional materials in the field of composite manufacturing sectors [22]. The granite is a silica rich stone, also contains of some metal oxides such as aluminium oxide, iron oxide, calcium oxide, magnesium oxide and trace of sodium and potassium oxides [23]. The silica rich granite dust material is a counter part of commercial silica fillers. Silica fillers are extensively used in the manufacture of polymer composites [24], in order to improve mechanical strength, hydrophobic nature, electrical resistivity, thermal stability and resistance to chemicals. In the recent past researchers and scientist around the world are concentrating towards converting waste materials to wealth and to eliminate the environmental problems associated with granite dust pollution [25–31]. Previously, granite dust was utilised in the field of ceramic, polymer composites for building materials, coating material and brake pads material applications. Gupta et al. reported on impact on mechanical properties of cement sand mortar containing waste granite powder [32]. Chen et al. inferred that the incorporation of granite polishing waste to reduce sand and cement contents and to improve the performance of resulting mortar [33]. Sadek et al. studied the reusing of marble and granite powders for making self-compacting concrete [25]. Lopes et al. studied on optimization of variation of particle size and pH of granite dust in paints [1]. Sugozu et al. developed granite dust based brake pad materials. Even though some of the earlier studies reported the utilization of granite dust for different industrial applications, still lot of new avenues to be developed in order to utilize granite dust more efficiently and economically to produce composite materials to widen the area of applications.

With this in view, an attempt has been made in the present work to produce high voltage electrical insulation granite fly dust waste and different epoxy systems. The two types of composites were prepared using varied weight percentages of granite fly dust with bisphenol-A diglycidyl ether-phenalkamine (ER-1) and bisphenol-A diglycidyl ether-methyl hexahydrophthalic anhydride (ER-2) matrices. The composites developed were studied for their structural morphology, thermal stability, mechanical behaviour, thermal conductivity, electrical resistivity and break down voltage using appropriate analytical test methods. Data obtained from different studies are discussed and reported.



Scheme 1 – Process of granite fly fine dust reinforced epoxy composites.

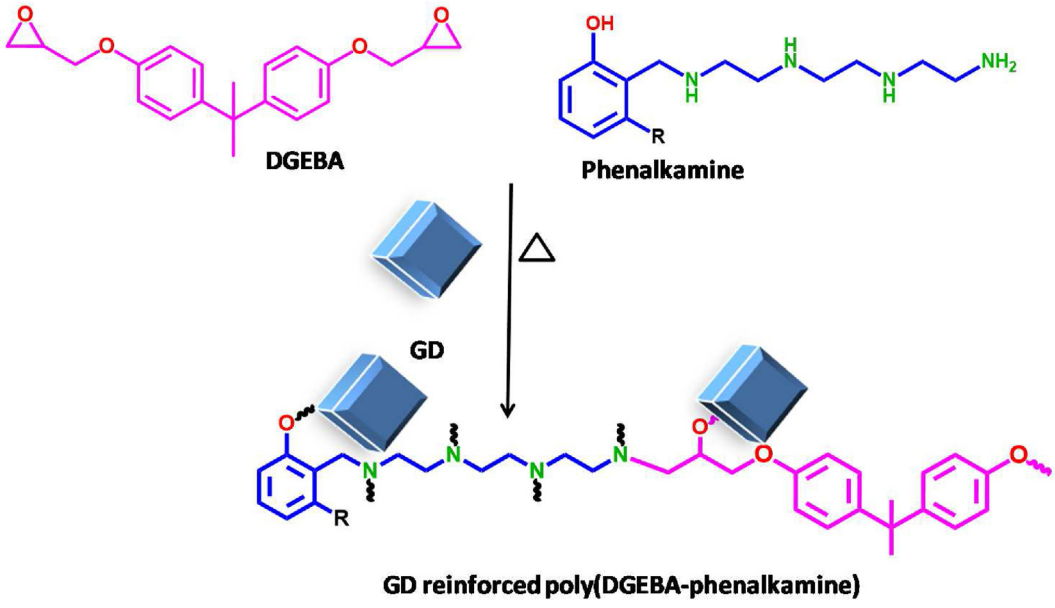
2. Experimental section

2.1. *Materials*

Cutting waste granite fly fine dust was received from A Blue Hill Granites India Private Limited, Coimbatore, India. Bisphenol-A diglycidyl ether (DGEBA - epoxy resin)) and phenalkamine (phk) epoxy hardener were obtained from Roto polymers ltd, Chennai, India. Methyl hexahydrophthalic anhydride (mhhpa) was received from Hindustan speciality chemicals India ltd. Gujarat, India.

2.2. *Preparation of granite fly dust filled epoxy composites*

The collected granite fly fine dust were sieved with 38 μm mesh to remove the bulk particle and other dust materials. Further, it was washed with distilled water and treated with 0.1 N hydrochloric acid to reduce the conductive metal oxide.



Scheme 2 – Preparation of granite fly dust filled ER-1 (poly(DGEBA-phk)) composites.

Further, washed with 0.1 N sodium hydroxide solution for surface activation and subsequently washed with water, until reach the neutral pH. Further, the washed granite fly dust was dried at 80 °C for overnight (Scheme 1). The 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of granite fly dust was homogenously mixed separately with DGEBA epoxy resin and phenalkamine system (1:0.5) and are cured at room temperature. The neat epoxy matrix and homogeneously granite dust reinforced system were separately poured into the mould with required dimensions. Further the curing system was post cured at 60 °C for 2 h (Scheme 2).

Similarly, the 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of granite fly dust was homogenously mixed separately with DGEBA epoxy resin and methyl hexahydrophthalic anhydride (mhhpa) system (1:1). Then, the curing process of ER-2 system was accelerated by adding 2 g of N,N-dimethyl aniline (Scheme 3). The granite fly dust reinforced epoxy resin system was poured into the required size of the Teflon coated aluminium mould and cured at 100 °C for 3 h. Then, the completely cured samples were separated from mould and placed for characterisation.

2.3. *Measurements*

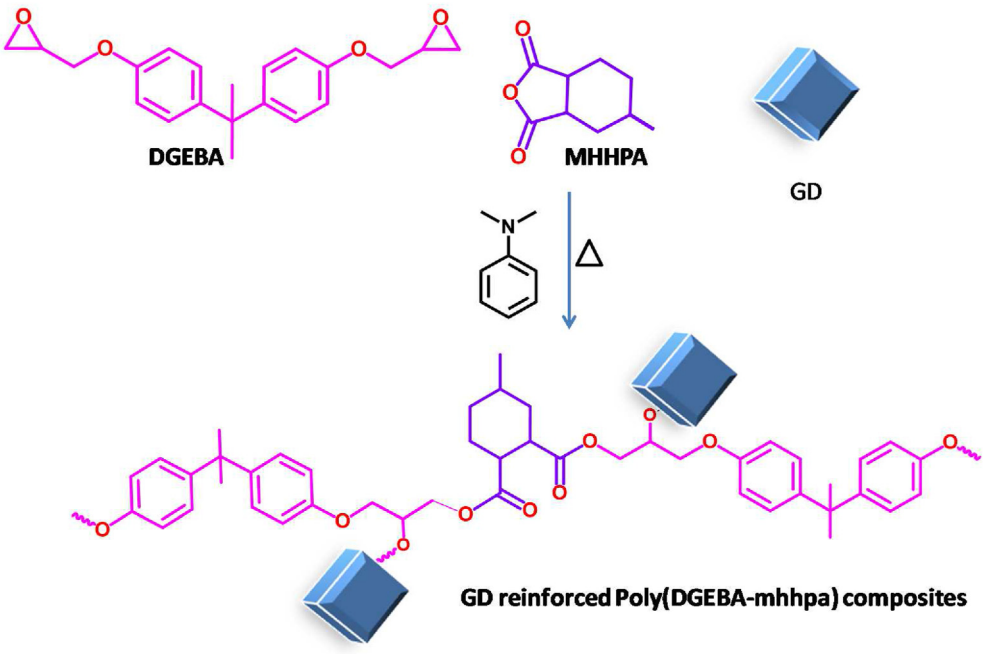
The functional group of materials were studied by FTIR spectral technique (SHIMADZU FTIR Spectrophotometer). The thermal degradation behaviour of the granite flay dust filled epoxy composites was analysed by Thermogravimetric technique (HITACHI STA 700 series). Tensile strength and flexural strength of neat epoxy matrix and granite dust reinforced epoxy composites were determined through INSTRON 8801 instrument as per ASTM-D638 and ASTM-D790 standards respectively. The thermal conductivity and thermal resistivity of neat epoxy matrix and granite dust reinforced epoxy composites were analysed by heat flow meter (HFM). Surface resistivity and volume resistivity behaviour were studied using Fischer Elektronik TE50, Germany. Water contact angle of granite dust reinforced epoxy composites was analysed by goniometer. The breakdown voltage (BDV) of composites was measured by 100 kV high voltage transformer setup. The dielectric strength of granite dust reinforced epoxy composites was calculated from the values of breakdown voltage (BDV).

3. Results and discussion

The granite fly dust reinforced polymer composites were subjected to different analysis such as molecular structure, morphology, thermal stability, mechanical behaviour, thermal conductivity, hydrophobic behaviour and electrical resistivity, and high voltage insulation behaviour and the data obtained are discussed and reported.

3.1. *FTIR analysis*

The structural behavior of neat and granite fly dust reinforced epoxy composite materials were analyzed by FTIR and SEM-EDX spectral techniques. The functional groups of the neat epoxy matrix and granite fly dust reinforced epoxy composite materials were analyzed by FTIR spectroscopy and are presented in Fig. 1. The peaks observed at 2933 cm^{-1} and 2861 cm^{-1} were confirm the symmetric and asymmetric stretching vibration of the $-CH_2-$ (methylene) groups respectively. The peak noticed at 1725 cm^{-1} represents the stretching vibrations of carbonyl (–CO–) and 1178 cm^{-1} infers the presents of -C-O- link of the ester groups respectively. The stretching vibration of –C-N- and ether (–C-O-) linkages were observed at 1233 cm^{-1} and 1034 cm^{-1}, respectively. The stretching vibration bands appeared at 1077 cm^{-1} and



Scheme 3 – Preparation of granite fly dust (GD) filled ER-2 (poly(DGEBA-mhhpa)) composites.

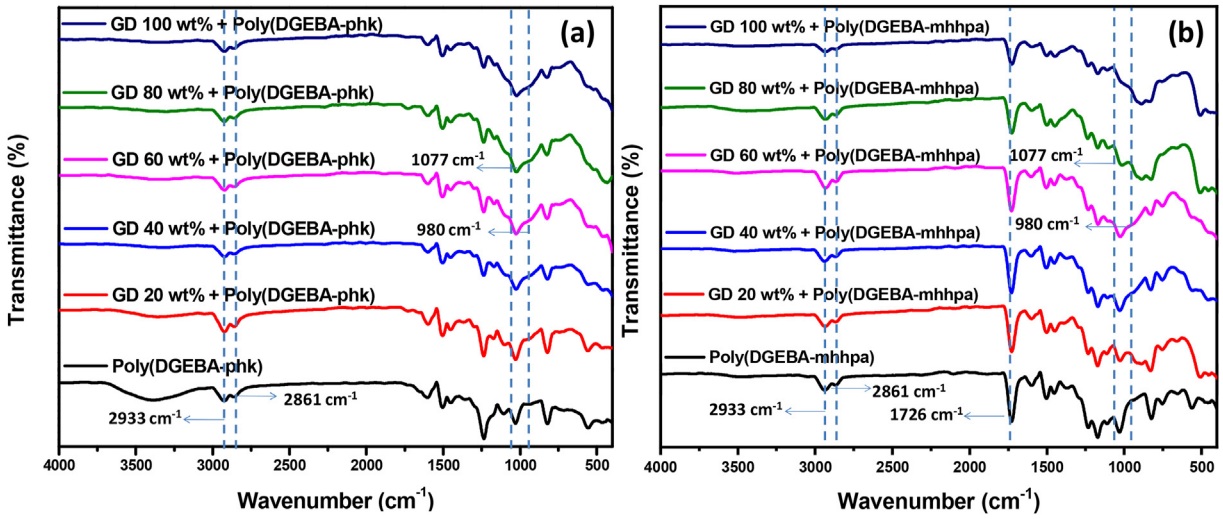


Fig. 1 – FT IR spectra of neat epoxy matrix and granite fly dust (GD) reinforced epoxy composites of (a) ER-1 (poly(DGEBA-phk)) and (b) ER-2 (poly(DGEBA-mhhpa)).

980 cm^{-1} were confirm the presence of Si–O–Si (siloxane) and -Si-OH (silanol) linkages in the composites.

3.2. *Microscopy analysis*

Further, the homogeneous dispersion of granite fly dust reinforced epoxy composites were studied using scanning electron microscopy (SEM) and transmission electron microscope (TEM) techniques. The raw granite dust, neat epoxy matrix and 100 wt% granite fly dust reinforced ER-1 and 100 wt % granite fly dust reinforced ER-2 composites were taken as a representative sample for the morphological analysis through SEM and TEM analysis. The SEM and TEM images of raw granite dust and the fractured surface of neat polymer matrix and 100 wt% granite fly dust reinforced ER-1 and 100 wt% granite fly dust reinforced ER-2 composites are shown in Figs. 2 and 3 respectively. From the SEM and TEM images, it was observed that the raw granite fine dust particles are obtained as spherical and amorphous particles. As seen from SEM image of the granite fly fine dust reinforced epoxy composites, the dust particles show uniform distribution and compact interface structures, which are no obvious clusters or voids in the composites. The compact interface and homogeneous distribution could be explained by the intra-molecular interaction between granite dust particle and epoxy resin matrix. The interface between granite dust particle and epoxy matrix looks more indistinct, which is attributed to the occurrence of covalent bonding interaction and contribute to the strong and efficient compatibility.

In addition, the elemental analysis of granite dust, neat epoxy matrix, 100 wt% granite fly dust reinforced ER-1 and 100 wt% granite fly dust reinforced ER-2 were analysed by EDX spectral technique (Fig. 5) and elemental mapping (Fig. 4), and the results obtained are presented in Figs. 4 and 5. From the EDX spectrum and elemental mapping (Figs. 4 and 5a), granite fly dust waste contains major element of SiO_2 and trace of other oxides viz. Al, Ti, Fe, Cu, Cr and Ca. Fig. 2c, d and 5b ascertain that the smooth neat epoxy matrix possesses only carbon, oxygen and nitrogen atoms. The homogeneous dispersion of granite flay dust present in ER-1 and ER-2 composites were noticed from Fig. 5c and d. From Fig. 5c and d, it is noticed that the elements above mentioned are obtained in composite materials.

3.3. *XPS analysis*

XPS analysis is employed to study of the functional groups and are shown in Fig. 6. For the case of Si, the peaks appeared at around 98 eV and 162 eV were conform the Si 2p, Si 2s. The peaks noticed at around 125 eV and 75 eV were ascertain the Al 2s and Al 2p, respectively. The spectra of C1s noticed at 286 eV, corresponds to C–Si, C–C, C–O, C–N and C=O, respectively. In the case of N element, a peak appeared in the rage of 395 eV infers the N 2s of N–C group. The peak noticed at 455 eV represents the Ti 2p. A peak obtained at 533 eV indicates the O 1s of O–C, O–Si, O=C, O–N and Oxides of metals (O-M). The peak observed at 592 eV confirms the Cr 2p. For the Fe element, a peak appeared at around 705 eV ascertains the Fe 2p. The peak obtained at around 945 eV represents the Cu 2p.

3.4. *Thermal behaviour*

The thermal behaviour of granite fly dust reinforced epoxy composites namely thermal stability, thermal conductivity and thermal resistivity nature obtained are discussed below.

3.5. *Thermal stability*

The thermal stability of neat epoxy matrix and granite dust reinforced ER-1 and ER-2 composites were studied by thermogravimetric analysis (TGA) under N_2 environment with the order of increment of 20 °C/min. The recorded TGA data of neat epoxy matrix and granite fly dust reinforced ER-1 and ER-

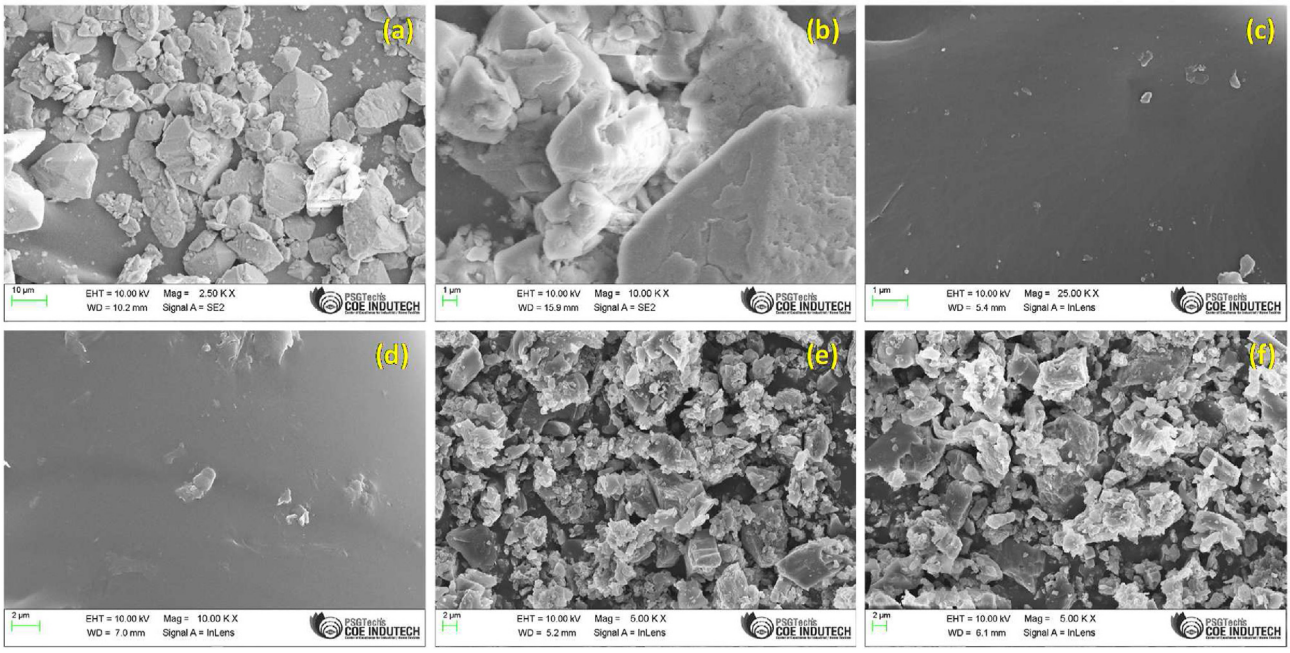


Fig. 2 – FESEM micrograph of (a), (b) granite fly dust particle, (c) neat ER-1, (d) neat ER-2, (e) 100 wt% GD reinforced ER-1 and (f) 100 wt% granite fly dust reinforced ER-2 composites.

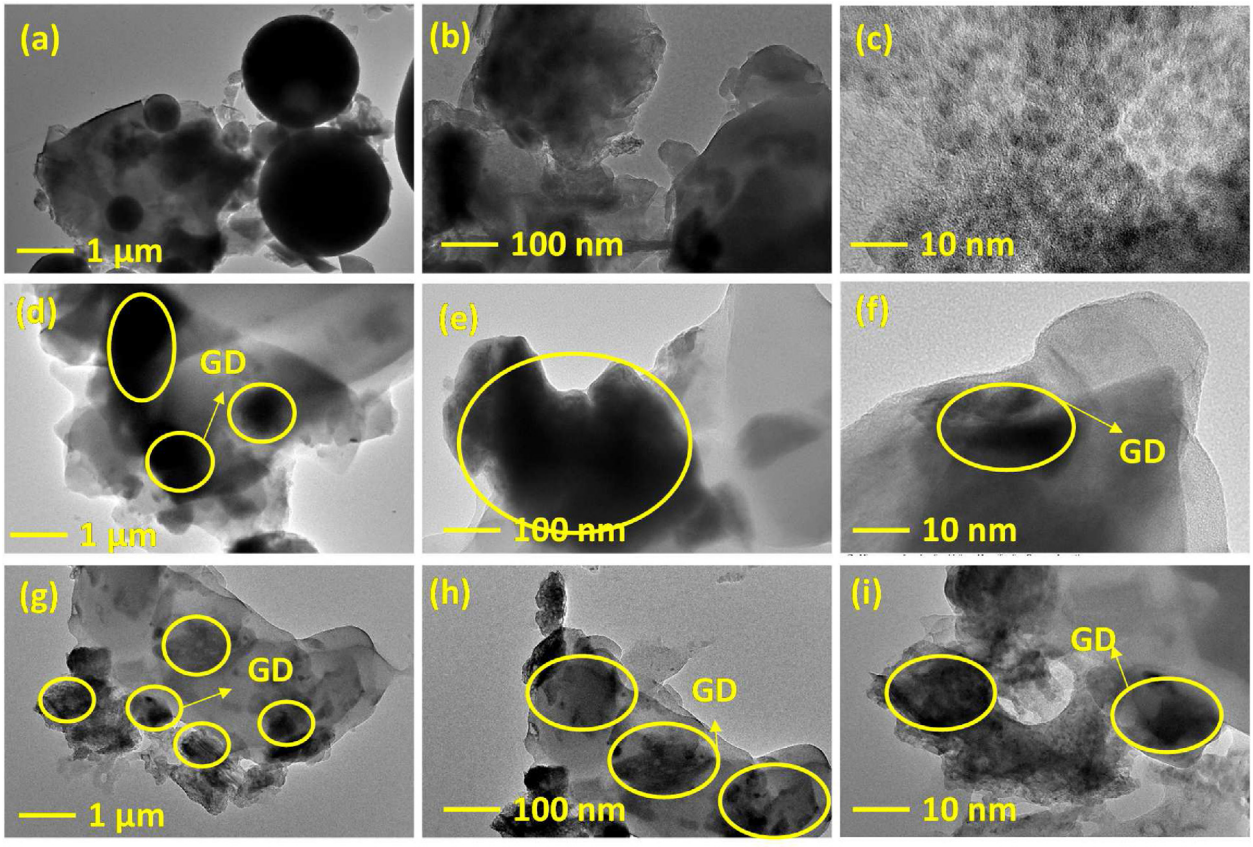


Fig. 3 – TEM micrograph of (a–c) granite fly dust particle (d–f) 100 wt% GD reinforced ER-1 and (g–i) 100 wt% granite fly dust reinforced ER-2 composites.

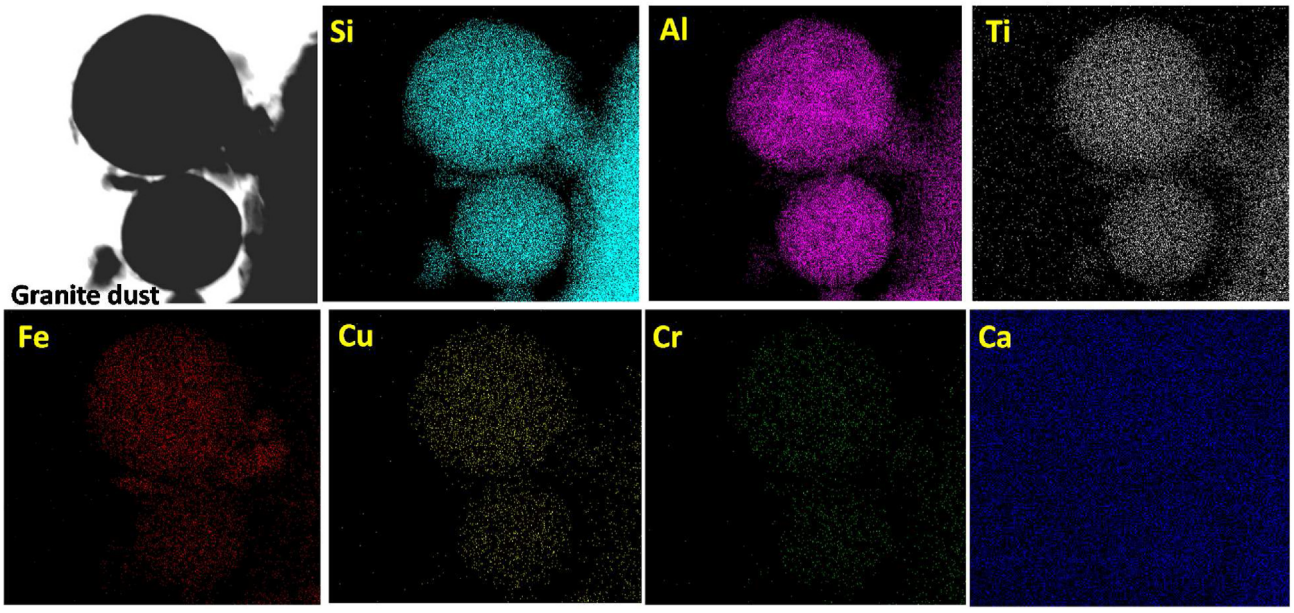


Fig. 4 – Elemental mapping of a granite fly dust particle.

2 are presented in Fig. 7 and Table 1. Thermal stability of polymer composites is an important parameter for the device fabrication, to predicts, its service temperature. The behaviour of stability was measured using the weight loss at every moment observed for ER-1 composites is presented in Fig. 7a. The 5% weight loss ($T_{5\%}$) of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of ER-1 composites were noticed at around 309 °C and that there was no significant changes noticed. The 10% weight loss ($T_{10\%}$) of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of ER-1 composites were noticed at 325 °C, 326 °C, 327 °C, 329 °C, °C, 329 °C and 331 °C, respectively. The maximum degradation temperature (T_{max}) of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of ER-1 composites were observed at 364 °C, 369 °C, 370 °C, 372 °C,

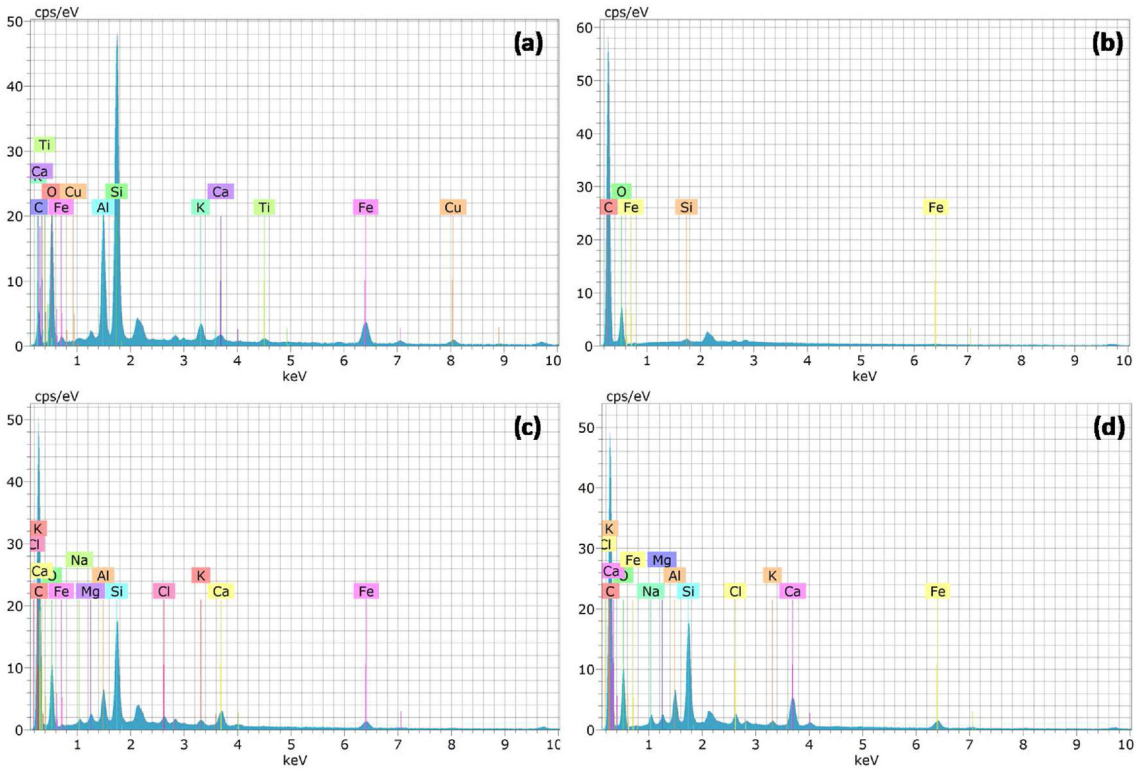


Fig. 5 – EDX spectra of (a) granite fly dust, (b) neat epoxy matrix (c) 100 wt% granite fly dust reinforced ER-1. and (d) 100 wt% granite fly dust reinforced ER-2 composites.

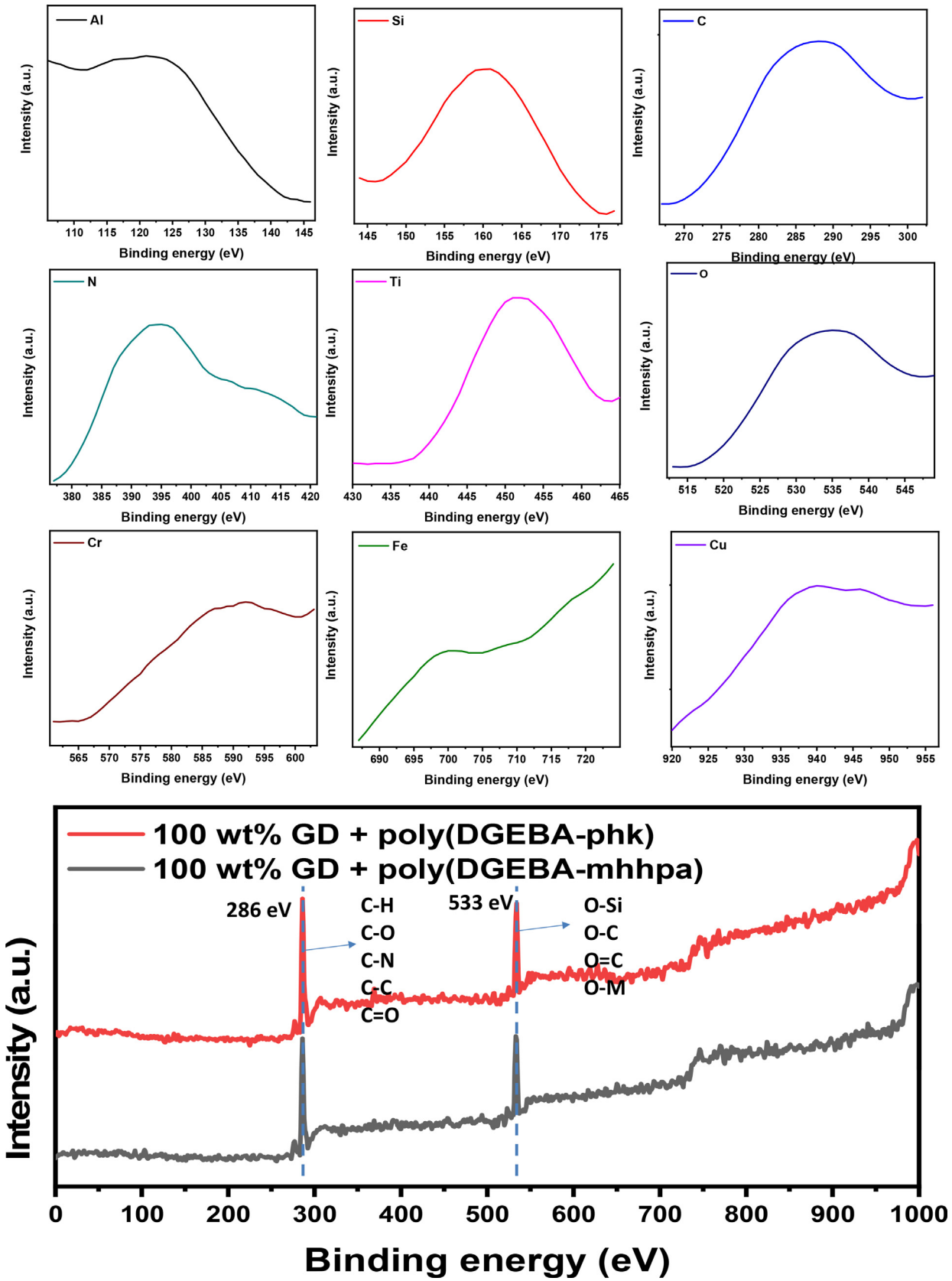


Fig. 6 – XPS spectra of granite dust (GD) reinforced epoxy composites.

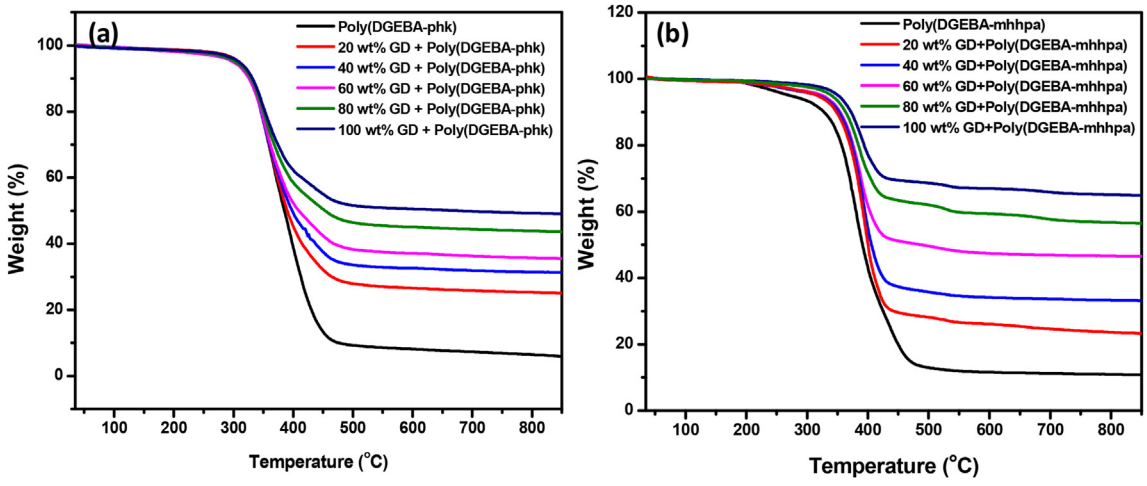


Fig. 7 – TGA thermogram of neat epoxy matrix and granite fly dust (GD) reinforced epoxy composites of (a) ER-1 and (b) ER-2.

374 °C and 375 °C, respectively and that of char yield (residual) percentage at 850 °C was noticed at 6%, 24%, 31%, 36%, 43% and 49%, respectively.

In the case of ER-2 composites (Fig. 7b and Table 1), the 5% weight loss of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of ER-2composites were observed at 270 °C, 314 °C, 319 °C, 326 °C, 338 °C and 350 °C, respectively. The maximum degradation temperature noticed at 371 °C, 383 °C, 385 °C, 387 °C, 389 °C, and 391 °C, respectively. The char yield was obtained at 10%, 23%, 33%, 46%, 55% and 64%, respectively. Thermal stability of both granite fly dust reinforced ER1 and ER-2 composites was increased with increasing concentration of granite fly fine dust particle. The ER-2 composites possess higher stability in thermal environment than that of ER-1 composites, because of the presence of thermally stable skeletons of methylhexahydro phthalic anhydride curative. Among the composites, 100 wt% of granite fly dust reinforced with ER-2 matrix have better stability under thermal environment than that of other composites, due to the higher weight percentage of silica rich granite fine fly dust. The higher thermal stability displays the higher degradation temperatures of the material, which enhance the operational temperature limits in the electrical insulation applications.

Table 1 – TGA traces of granite fly dust (GD) reinforced epoxy composites.

Sample	Thermal stability				
	$T_{5\%}$ (°C)	$T_{10\%}$ (°C)	T_{max} (°C)	Char yield (%) at 850 °C	Limiting Oxygen Index
GD reinforced ER-1 composites					
ER-1	303	325	364	6	19.9
GD 20 wt% + ER-1	306	326	369	24	27.1
GD 40 wt% + ER-1	306	327	370	31	29.9
GD 60 wt% + ER-1	306	329	372	36	31.9
GD 80 wt% + ER-1	309	329	374	43	34.7
GD 100 wt% + ER-1	309	331	375	49	37.1
GD reinforced ER-2 composites					
ER-2	270	328	371	10	21.5
GD 20 wt% + ER-2	314	345	383	23	26.7
GD 40 wt% + ER-2	319	350	385	33	30.7
GD 60 wt% + ER-2	326	352	387	46	35.9
GD 80 wt% + ER-2	338	361	389	55	39.5
GD 100 wt% + ER-2	350	373	391	64	43.1

3.6. *Limiting oxygen index (LOI)*

The fire resistant property of material [34] is an important factor for electrical insulation to withstand prevailing thermal conditions during service [35]. The fire-resistant nature is expressed in the name of flame retardant, which can be estimated by the residual char yield (θ) obtained from the thermogravimetric analysis at 850 °C. The flame retardant property of prepared composites can be observed by LOI, which is calculated using van Krevelen equation [36] (Table 1). The granite dust reinforced epoxy composites possess better flame retardant behaviour than that of neat epoxy matrix. Among the composites developed, ER-2 possess better flame retardant behaviour than that of ER-1 composites (Table 1).

3.7. *Thermal conductivity and thermal resistivity behaviour*

The thermal conductivity and thermal resistivity [37,38] of neat epoxy matrix and granite dust reinforced epoxy composites were studied by heat flow meter (HFM) in mean temperature of 40 °C. The 300x300 × 10 mm neat epoxy matrix and composite panels were prepared and used for the analysis [39]. The both neat ER-1 and ER-2 matrices possess lower value of thermal conductivity than that of granite dust reinforced epoxy composites. The thermal conductivity of composite panels was increased with increasing weight percentage of the granite dust in epoxy matrix. This may be explained due to the fact that the granite dust particles are closely packed as denser material. The values of observed thermal conductivity of granite dust reinforced epoxy composites are presented in Table 2 and Fig. 8. Among the composites, 100 wt% of granite fly dust reinforced ER-1 and ER-2 composites possess maximum thermal conductivity than that of other composites (Table 2).

Table 2 – Thermal resistivity behaviour and water contact angle of granite dust (GD) reinforced epoxy composites.

Sample name	Thermal conductivity behaviour		Water contact angle (°)
	Thermal conductivity (W/m.k)	Thermal resistivity (M^2 k/w)	
GD reinforced ER-1 composites			
ER-1	0.0401	0.1282	88
GD 20 wt% + ER-1	0.0410	0.1221	90
GD 40 wt% + ER-1	0.0516	0.0969	90
GD 60 wt% + ER-1	0.0627	0.0797	92
GD 80 wt% + ER-1	0.0697	0.0779	93
GD 100 wt% + ER-1	0.0703	0.0712	95
GD reinforced ER-2 composites			
ER-2	0.0620	0.1198	86
GD 20 wt% + ER-2	0.0626	0.1113	87
GD 40 wt% + ER-2	0.0649	0.1077	89
GD 60 wt% + ER-2	0.0659	0.1058	92
GD 80 wt% + ER-2	0.0683	0.1024	92
GD 100 wt% + ER-2	0.0749	0.0998	93

The higher value of thermal conductivity of granite fly dust reinforced epoxy composites makes them suitable for electrical insulation applications. The lower thermal conductivity materials display the higher electrical conductivity and higher the electric field stress in the range of conductor. In addition, the lower thermal conductivity is an important parameter to reduce the power rating of the electrical component. Furthermore, the similar pattern value of thermal conductivity was compared with that of reported results. Kochetov et al. and Xie et al. stated that an increased thermal conductivity of epoxy composites with increasing weight percentage of filler materials (silica, aluminium oxide, titanium oxide, magnesium oxide, boron nitride and aluminium nitride) [30].

The value of thermal resistivity of granite fly dust reinforced ER1 and ER-2 composites are shown in Table 2 and Fig. 9. The thermal resistance is in reverse to the thermal conductivity. The value of thermal resistance of granite dust reinforced ER1 and ER-2 composites was studied and the values observed are lower than that of neat epoxy matrix. The increasing weight percentage concentration of granite dust in epoxy composites, the value of thermal resistance was also increased. The granite dust reinforced ER-2 composites exhibit higher value of thermal resistivity than that of granite dust reinforced ER-1 composites. Among the composites, 100 wt% of granite dust reinforced ER-2 and 100 wt% of granite fly dust reinforced ER-1 composites possess lower thermal resistivity and higher value of thermal conductivity than those of neat epoxy matrix and other composites.

3.8. *Hydrophobic behaviour*

The hydrophobicity behaviour of granite fly dust reinforced epoxy composites was studied by water repulsive nature. The water repulsive nature was assessed from the value of water contact angle (WCA) and are presented in Fig. 10 and Table 2. The values of WCA of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of fly fine dust reinforced ER-1 composites were observed at 88, 90, 90, 92, 93 and 95 ±1°, respectively. Similarly, the values of WCA of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of granite fly fine dust reinforced ER-2 composites were observed at 86, 87, 89, 90, 92 and 93 ±1°, respectively. From the values of WCA, it was inferred that the water resistive behaviour was enhanced from neat epoxy matrices to 100 wt% granite fly fine dust reinforced epoxy composites, due to the intrinsic hydrophobic behaviour of silica rich granite particle. In addition, the roughness of composites also helps to enhance the water contact angle. The higher hydrophobic nature contributes to increase the electrical surface resistivity.

3.9. *Mechanical behaviour*

3.9.1. *Tensile strength*

The tensile behaviour of granite fly fine dust reinforced polymer composites was studied as per standard and the values are presented in Fig. 11 and Table 3. The values of tensile strength (Fig. 11a) noticed for 0, 20, 40, 60, 80 and 100 wt% of

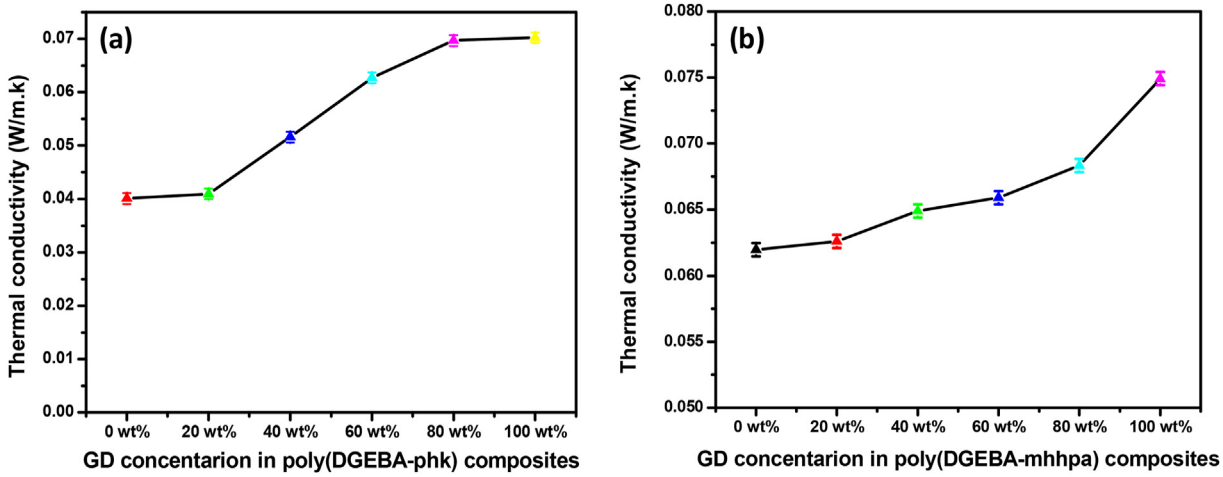


Fig. 8 – Thermal conductivity of (a) granite fly dust (GD) reinforced ER-1 (poly(DGEBA-phk)) and (b) ER-2 (poly(DGEBA-mhhpa)) composites.

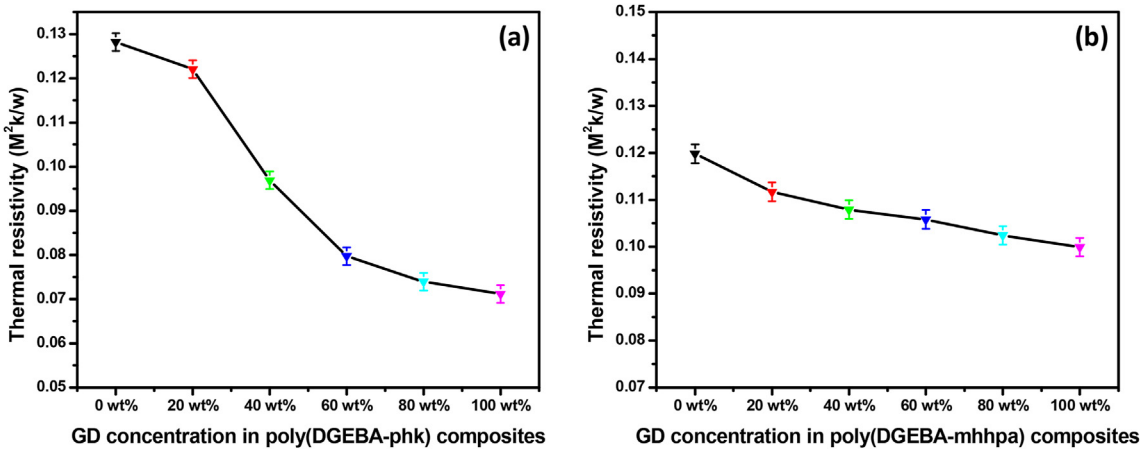


Fig. 9 – Thermal resistivity of (a) granite fly dust (GD) reinforced ER-1 and (b) GD reinforced ER-2 composites.

granite fly dust reinforced ER-1 composites are 47, 28, 24, 20, 18 and 17 MPa respectively. Similarly, the values of tensile strength (Fig. 11b) of 0, 20, 40, 60, 80 and 100 wt% of granite fly dust reinforced ER-2 composites observed are 52, 42, 31, 27, 25 and 25 MPa respectively. The tensile modulus of both granite fly dust reinforced composites was increased with increasing concentration of granite fly dust particle in the composites (Fig. 11).

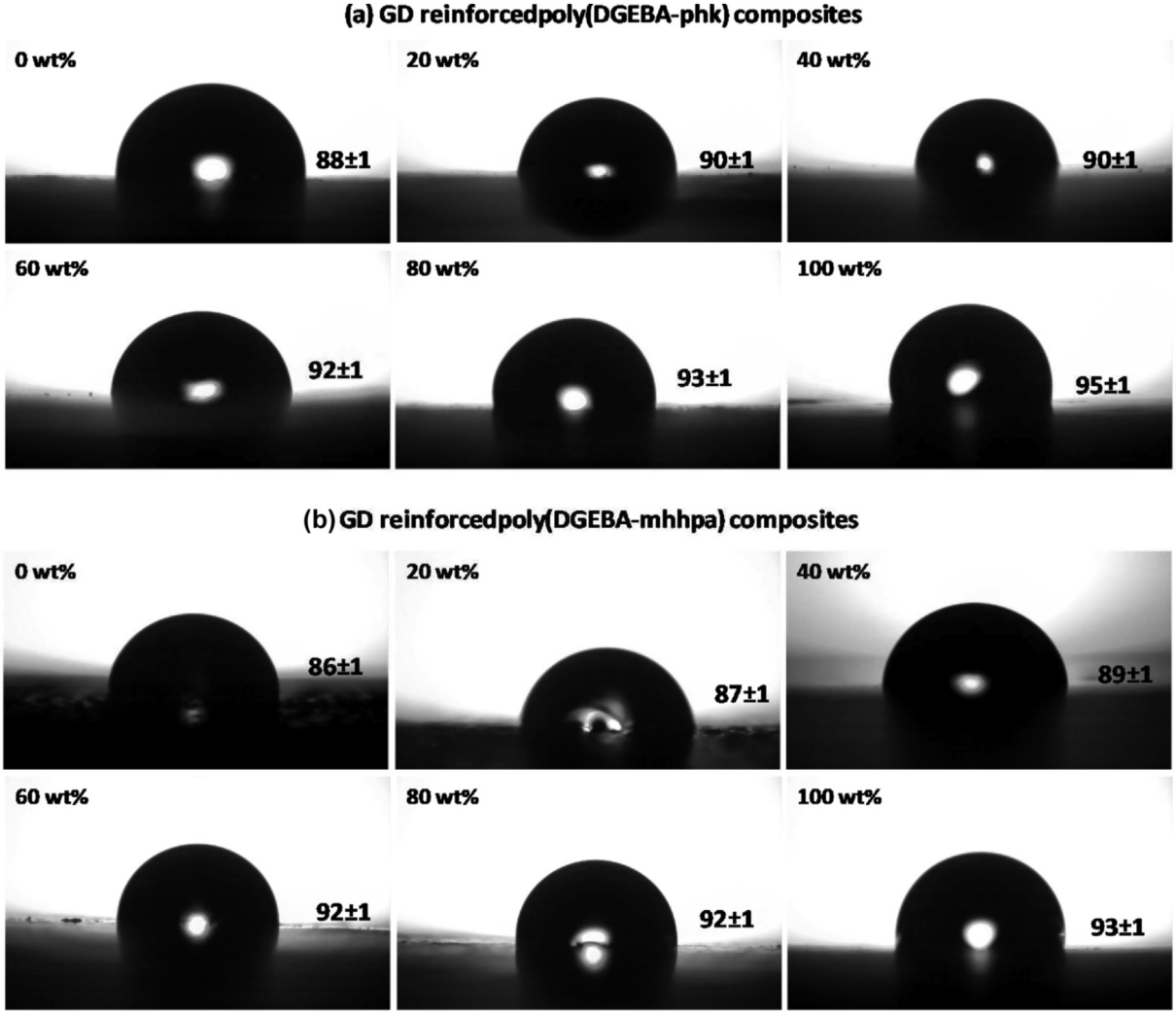


Fig. 10 – Water contact angle of (a) GD reinforced ER-1 and (b) GD reinforced ER-2 composites.

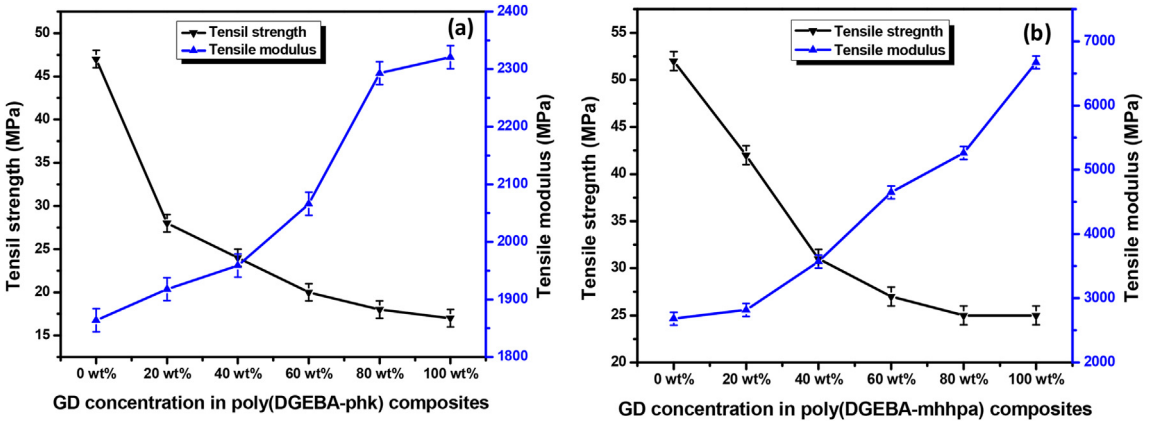


Fig. 11 – Tensile strength of (a) GD reinforced ER-1 and (b) GD reinforced ER-2 composites.

3.9.2. *Flexural strength*

The values of flexural strength obtained for 0, 20, 40, 60, 80 and 100 wt% of granite fly fine particle dust reinforced ER-1composites are 85, 43, 31, 26, 25, and 23 MPa respectively (Fig. 12a). Similarly, the value of flexural strength of ER-2 composites reinforced with 0, 20, 40, 60, 80 and 100 wt% granite fly dust (Fig. 12b) are 98, 90, 62, 57, 52 and 48 MPa, respectively. The values of flexural modulus of both granite fly dust reinforced composites were increased with increasing concentration of granite dust in the composites (Fig. 12). In addition, the similar pattern of results of epoxy composites were noticed and compared with granite fly dust reinforced epoxy composites. I. Ozsoy et al., B. Wetzel et al., H. Zhang et al. and Bakshi et al. reported that the tensile strength and flexural strength were decreased with increasing weight concentration of silica, aluminium oxide, titanium oxide and marble dust in epoxy composites [40]. It was also observed that the values of tensile modulus and flexural modulus were increased by increasing the weight concentration of fillers in epoxy composites [41].

3.10. *Hardness behaviour*

The hardness behaviour of granite dust reinforced ER-1 and ER-2 composites was measured by Shore D hardness tester and the results obtained are displayed in Table 3 and Fig. 13. The values of hardness of 0, 20, 40, 60, 80 and 100 wt% granite fly dust reinforced ER-1 composites are noticed at 77, 77, 79, 81, 81 and 82 HD units respectively. Similarly, the values of hardness of the 0, 20, 40, 60, 80 and 100 wt% granite fly dust filled ER-2 composites are observed at 86, 88, 88, 90, 91 and 91 HD units respectively. The hardness value of neat ER-1 is lower than that of ER-2. The increase in weight percentage of granite dust in the composites, increases the value of hardness according to its concentration. Comparably granite fly dust reinforced ER-2 composites have higher values of hardness than that of granite fly dust reinforced ER-2 (Table 3).

3.11. *Electrical behaviour*

The detailed electrical behaviour of granite fly dust reinforced composites was studied using the measurement of surface

Table 3 – Mechanical behaviour of GD reinforced epoxy composites.

Sample name	Tensile Strength (±1 MPa)	Tensile modulus (±10 MPa)	Flexural strength (±2 MPa)	Flexural modulus (±10 MPa)	Shore D Hardness (±2 HD)
GD reinforced ER-1 composites					
ER-1	47	1864	85	1312	77
GD 20 wt% + ER-1	28	1918	43	1559	79
GD 40 wt% + ER-1	24	1959	31	1644	79
GD 60 wt% + ER-1	20	2066	26	1831	81
GD 80 wt% + ER-1	18	2293	25	1854	81
GD 100 wt% + ER-1	17	2321	23	1915	82
GD reinforced ER-2 composites					
ER-2	52	2681	98	3645	86
GD 20 wt% + ER-2	42	2817	90	3920	88
GD 40 wt% + ER-2	31	3571	62	4743	88
GD 60 wt% + ER-2	27	4649	57	4789	90
GD 80 wt% + ER-2	25	5261	52	5105	91
GD 100 wt% + ER-2	25	6671	48	5811	91

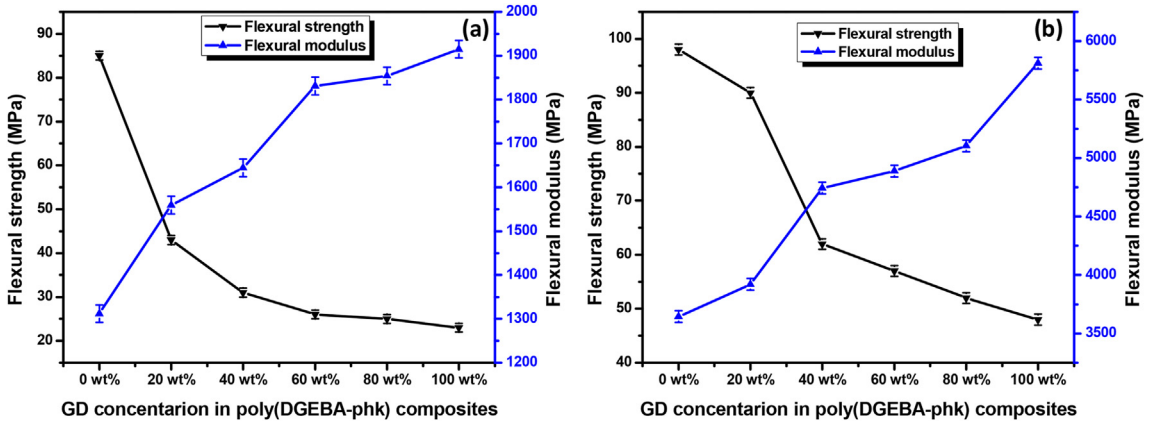


Fig. 12 – Flexural strength of (a) GD reinforced ER-1 and (b) GD reinforced ER-2 composites.

resistivity, volume resistivity, breakdown voltage (BDV), and dielectric strength. The 100x100 × 2 mm of neat epoxy matrix and granite dust reinforced composites sample specimens were prepared for electrical behaviour studies.

3.12. *Electrical surface resistivity*

The surface finish and surface cleanliness will contributes to resist the electrical leakage along the surface of material [42]. Hydrophobic surface, and smooth surface provides the higher electrical surface resistance. The surface resistivity of neat epoxy matrix and granite fly fine dust reinforced ER-1 and ER-2 composites are shown in Fig. 14 and Table 4. The value of surface resistivity of neat epoxy matrices reaches at 10^9 Ω, which exhibits antistatic behaviour. Among the granite dust reinforced composites, the 100 wt% granite dust reinforced ER-2 matrix possesses the better surface resistivity than that of other granite dust reinforced epoxy composites. The surface resistivity value of composites with more than 80 wt% of granite dust reinforced composites exhibits higher than 10^{12} Ω, which infers the insulating behaviour of composites.

The values of surface resistivity of 0, 20, 40, 60, 80 and 100 wt% of granite dust reinforced ER-1 and ER-2 composites are displayed in Fig. 14 and Table 4. The values of surface resistivity of ER-1 matrix and ER-2 matrix were observed at 10^9 Ω, which ascertained their antistatic behaviour. Among the composites, the 100 wt% granite dust reinforced ER-2 composites exhibits the better surface resistivity than that of other composites. The surface resistivity with above 80 wt% granite dust reinforced composites exhibits more than 10^{12} Ω, confirms their insulating behaviour.

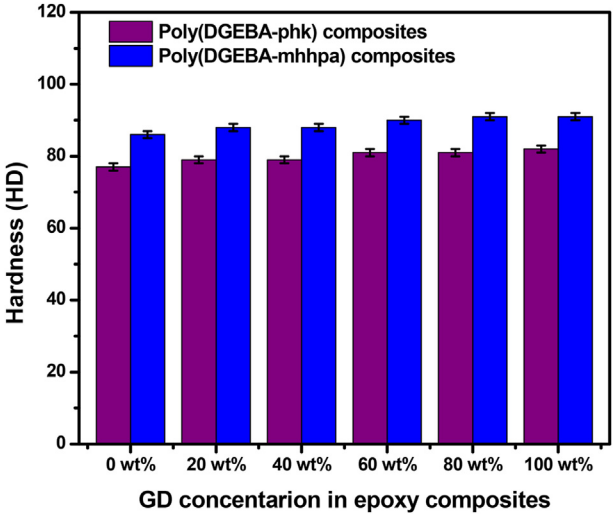


Fig. 13 – Hardness of granite fly dust (GD) reinforced ER-1 (poly(DGEBA-phk)). and ER-2 (poly(DGEBA-mhhpa)) composites.

3.13. *Volume resistivity*

Volume resistivity is the resistance to the flow of electricity through a body of material [39,43]. Generally, the electrical insulator materials should be above 10^{12} Ω. The volume resistivity of both neat epoxy matrix and granite dust reinforced epoxy composites possess more than 10^{13} Ω and are displayed in Fig. 15 and Table 4. The value of volume resistivity was increased with increasing concentration of granite dust in ER-1 and ER-2 composites. The apparent value of volume resistivity of 100 wt% granite fly dust reinforced ER-1 and ER-2 composites was observed at 4.43 × 10^{13} Ω and 5.60 × 10^{13} Ω respectively. Among the composites, 100 wt% granite dust reinforced epoxy composites exhibit better insulating behaviour. However, the volume resistivity was inferred that all the composites studied in the work exhibit excellent insulator character.

3.14. *High voltage breakdown strength*

The dielectric strength of composite materials was calculated from breakdown voltage [11,44]. The 100x100 × 2 mm sample specimens were prepared and placed at 100 kV high voltage transformer for breakdown voltage studies. The value of BDV of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of granite dust reinforced ER-1 composites obtained are 27 ± 1, 28 ± 1, 30 ± 1, 30 ± 1,31 ± 1 and 31 ±1 kV, respectively (Fig. 16a and Table 2). The values of calculated dielectric strength of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of granite dust reinforced ER-1 composites are13.5, 14.0, 15.0, 15.0,

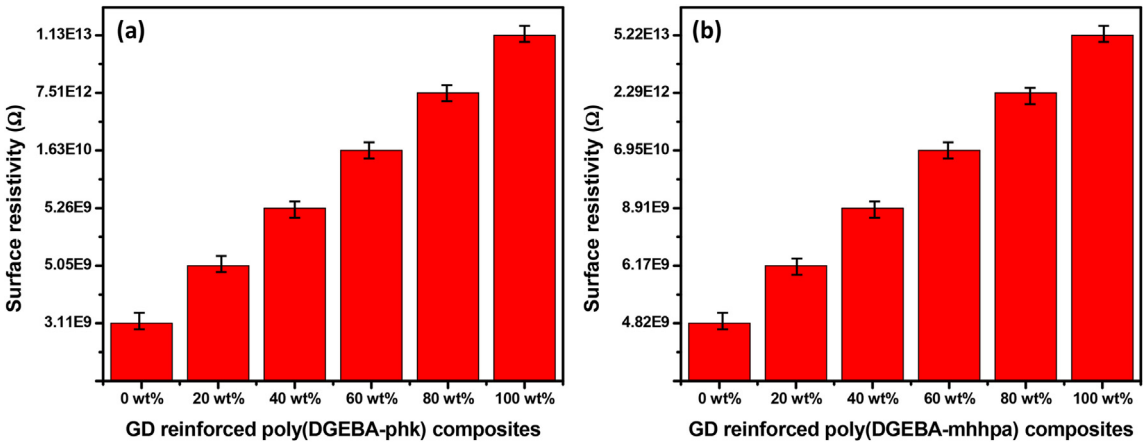


Fig. 14 – Electrical surface resistivity of granite fly fine dust (GD) reinforced (a) ER-1 (poly(DGEBA-phk)) and (b) ER-2 (poly(DGEBA-mhhpa)) composites.

Table 4 – Electrical behaviour of GD reinforced epoxy composites.

Sample	Surface resistivity in 100 V (±0.1Ω)	Volume resistivity in100 V ((±0.1Ω)	BDV (kV)	Dielectric Strength (kV/mm)
GD reinforced ER-1 composites				
ER-1	3.11×10^{9}	1.15×10^{13}	27 ± 1	13.5
GD 20 wt% + ER-1	5.05×10^{9}	1.16×10^{13}	28 ± 1	14.0
GD 40 wt% + ER-1	5.26×10^{9}	2.26×10^{13}	30 ± 1	15.0
GD 60 wt% + ER-1	1.63×10^{10}	3.55×10^{13}	30 ± 1	15.0
GD 80 wt% + ER-1	7.51×10^{12}	4.23×10^{13}	31 ± 1	15.5
GD 100 wt% + ER-1	1.13×10^{13}	4.43×10^{13}	31 ± 1	15.5
GD reinforced ER-2 composites				
ER-2	4.82×10^{9}	2.48×10^{13}	28 ± 1	14.0
GD 20 wt% + ER-2	6.17×10^{9}	3.02×10^{13}	29 ± 1	14.5
GD 40 wt% + ER-2	8.91×10^{9}	3.32×10^{13}	30 ± 1	15.0
GD 60 wt% + ER-2	6.95×10^{10}	4.70×10^{13}	32 ± 1	16.0
GD 80 wt% + ER-2	2.29×10^{12}	5.45×10^{13}	34 ± 1	17.0
GD 100 wt% + ER-2	5.22×10^{13}	5.60×10^{13}	34 ± 1	17.0

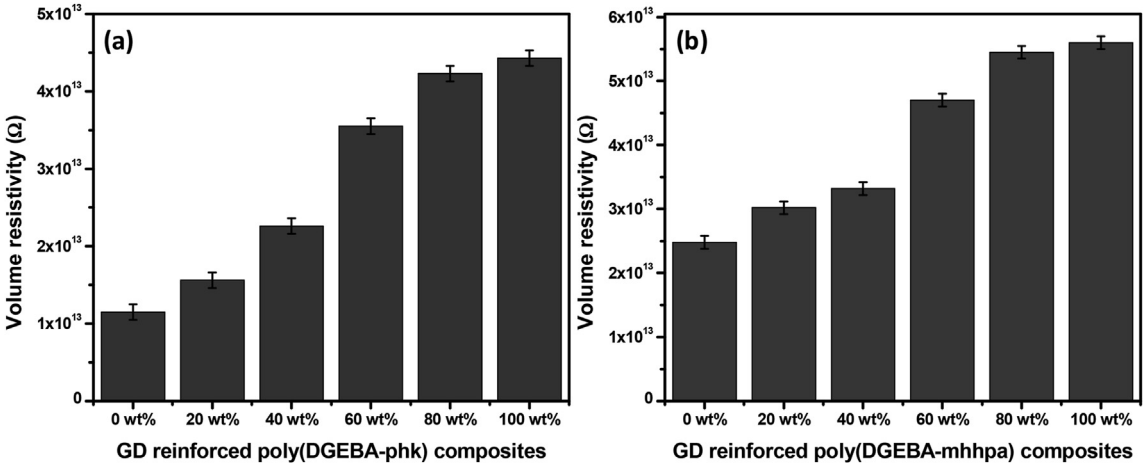


Fig. 15 – Electrical volume resistivity of granite fly dust (GD) reinforced (a) ER-1 (poly(DGEBA-phk)) and (b) ER-2 (poly(DGEBA-mhhpa)) composites.

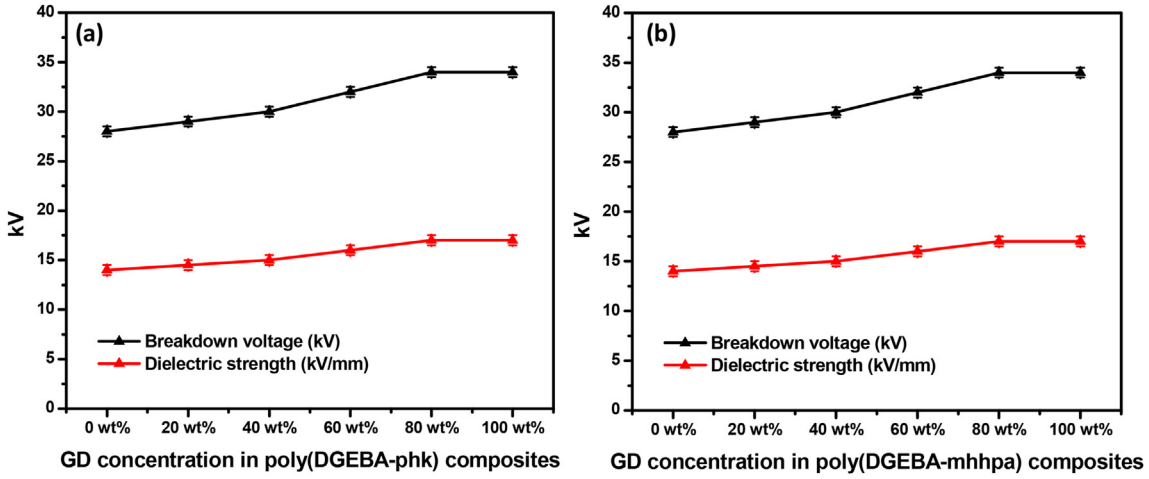


Fig. 16 – Breakdown voltage and dielectric strength of GD reinforced (a) ER-1 (poly(DGEBA-phk)) and (b) ER-2 (poly(DGEBA-mhhpa)) composites.

15.5and 15.5 ±5 kV/mm, respectively. The value of dielectric strength was increased according to weight percentage of granite dust (0–100 wt%) incorporated in ER-1 composites.

Similarly, the value of BDV of 0 wt%, 20 wt%, 40 wt%, 60 wt %, 80 wt% and 100 wt% of granite dust reinforced ER-2 composites obtained are 28 ± 1, 29 ± 1, 30 ± 1, 32 ± 1, 34 ± 1, 34 ±1 kV, respectively (Fig. 16b and Table 4). The value of breakdown voltage was increased by 22% for incorporation of 100 wt% granite dust, when compared with that of neat epoxy matrix. The values of calculated dielectric strength of 0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt% and 100 wt% of granite dust reinforced ER-2 composites are 14.0,14.5, 15.0,16.0, 17.0 and 17.0 ± 0.5 kV/mm, respectively. From the results, it was observed that the value of dielectric strength was increased with increasing concentration of granite dust reinforced composites. It was also noticed that above 80 wt% of granite dust reinforced composites possess saturated value of dielectric strength. Among the granite dust filled epoxy composites, the composites reinforced with more than 80wt% of granite dust exhibit better dielectric strength than that of other granite dust filled epoxy composites.

The resulted data was compared with previously reported data which was shown in Table 5. The breakdown voltage of poly(DGEBA-teta) was improved through the hybridisation of cardanol-aniline benzoxazine (poly(C-a/DGEBA-teta)) and bio-silica reinforcement. From the results, the value of dielectric strength of 100 wt% of bio-silica reinforced poly(C-a/DGEBA-teta) was noticed at 15.5 ± 0.5 kV/mm [2]. Relatively, the composites developed in the present work reaches the higher value of dielectric strength (17.0 ± 0.5 kV/mm) value than that of previously reported for poly(C-a/DGEBA-teta) composites.

From the electrical studies, it is suggested that the materials developed in the present work can be used in the form of sealants, adhesives, and also to fabricate the different electrical components and accessories capable of withstanding under adverse environmental conditions. These materials can be used in the field of electrical engineering viz., dry type transformer sealant, high voltage power room wall covering panels, floor panels and high voltage switch board fittings and cable packing material to avoid electrical leakage risk.

Table 5 – Comparative statement of breakdown voltage and dielectric strength of neat and 100 wt% bio-silica reinforced hybrid benzoxazine/epoxy polymer composites [2].

Sample	BDV (±1 kV)	Dielectric strength (±0.5 kV/mm)
Poly(DGEBA-teta)	24	12.0
Poly(C-a/DGEBA)	28	14.0
100 wt% silica/poly(DGEBA-teta)	26	13.0
100 wt% silica/poly(C-a/DGEBA-teta)	31	15.5
Present work		
Poly(DGEBA-phk)	27	13.5
Poly(DGEBA-mhhpa)	28	14.0
100 wt% GD/poly(DGEBA-phk)	31	15.5
100 wt% GD/poly(C-a/DGEBA-mhhpa)	34	17.0

4. Conclusion

In the present work, two type of epoxy composites were prepared using different weight percentages (20, 40, 60, 80 and 100 wt%) of cutting waste granite dust separately reinforced with bisphenol-A diglycidyl ether-phenalkamine (ER-1) and bisphenol-A diglycidyl ether-methylhexahydrophthalic anhydride (ER-2). The values of thermal conductivity, surface resistivity, volume resistivity, breakdown voltage, dielectric strength of composites are increased with increasing weight percentage concentration of granite dust. Among the composites 100 wt% of cutting waste granite dust reinforced ER-2 possess better thermal stability, mechanical strength and electrical insulation properties than those of ER-1 composites. The composites with 100 wt% of cutting waste granite dust reinforced ER-2 possesses the higher values of electrical surface resistivity (5.22×10^{12} Ω), electrical volume resistivity

(5.60×10^{13} Ω), higher break down voltage (34 ±1 kV) and higher dielectric strength (17.0 ± 0.5 kV/mm) than those of other composites. Data resulted from different studies suggest that, the composite samples prepared in the present work can be utilised for the fabrication of wide range of electrical insulation components and products for improved performance and enhanced longevity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to express their sincere appreciation to the Second Century Fund (C2F), Chulalongkorn University, Bangkok-10330, Thailand for the financial support. In addition, this research is supported by Thailand science Research and Innovation Fund Chulalongkorn University (BCG66210018). The NSRF via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation (PMU-B), Thailand [grant number B05F640086] and National Research Council of Thailand are also acknowledged.

REFERENCES

[1] Lopes MMS, Pedroti LG, de Oliveira AF, Ribeiro JCL, Franco de Carvalho JM, Fiorini de Carvalho A, et al. Optimization of performance of sustainable paints using granite waste through the variation of particle size and pH. J Clean Prod 2021;326. https://doi.org/10.1016/j.jclepro.2021.129418.

[2] Iqbal MM, Appasamy S, Krishnasamy B, Arumugam H, Maheshwari RV, Vigneshwaran B, et al. Development of sustainable polybenzoxazine-based organic–inorganic hybrid nanocomposites for high voltage insulator applications. J Mater Sci Mater Electron 2023;34. https://doi.org/10.1007/s10854-022-09805-2.

[3] Ramakrishnan T, Raja Karthikeyan K, Tamilselvan V, Sivakumar S, Gangodkar D, Radha HR, et al. Study of various epoxy-based surface coating techniques for anticorrosion properties. Adv Mater Sci Eng 2022;2022. https://doi.org/10.1155/2022/5285919.

[4] Du Y, Zhang Z, Wang D, Zhang L, Cui J, Chen Y, et al. Enhanced tribological properties of aligned graphene-epoxy composites. Friction 2022;10:854–65. https://doi.org/10.1007/s40544-021-0496-2.

[5] Emami A, Khaleghian S, Taheri S. Asperity-based modification on theory of contact mechanics and rubber friction for self-affine fractal surfaces. Friction 2021;9:1707–25. https://doi.org/10.1007/s40544-021-0485-5.

[6] Zhang Z, Du Y, Zhu C, Guo L, Lu Y, Yu J, et al. Unprecedented enhancement of wear resistance for epoxy-resin graphene composites. Nanoscale 2021;13:2855–67. https://doi.org/10.1039/d0nr08600b.

[7] Ahmadi Z. Nanostructured epoxy adhesives: a review. Prog Org Coating 2019;135:449–53. https://doi.org/10.1016/j.porgcoat.2019.06.028.

[8] Schrand AM, Tolle TB. Carbon nanotube and epoxy composites for military applications. 2006. https://doi.org/10.1016/B978-044451855-2/50021-8. xxx.

[9] Rahman MM, Akhtarul Islam M. Application of epoxy resins in building materials: progress and prospects. Polym Bull 2022;79:1949–75. https://doi.org/10.1007/s00289-021-03577-1.

[10] Kan Y, Yue Q, Gao B, Li Q. Preparation of epoxy resin-based activated carbons from waste printed circuit boards by steam activation. Mater Lett 2015;159:443–6. https://doi.org/10.1016/j.matlet.2015.07.053.

[11] Li B, Salcedo-galan F, Xidas PI, Manias E. Improving electrical breakdown strength of polymer nanocomposites by tailoring hybrid-filler structure for high- voltage dielectric applications. 2018. https://doi.org/10.1021/acsanm.8b01127.

[12] Deepak P, Kumar RV, Badrinarayanan S, Sivaraman H, Vimal R. ScienceDirect effects of polyamide and/or phenalkamine curing agents on the jute fibre reinforcement with epoxy resin matrix. Mater Today Proc 2017;4:2841–50. https://doi.org/10.1016/j.matpr.2017.02.164.

[13] Chu D, Wang J, Han Y, Wang Z. RSC Advances High performance epoxy protective coatings incorporated with polyaniline nanowires using cardanol-based phenalkamine as the curing agent. 2015. p. 11378–84. https://doi.org/10.1039/c4ra13176b.

[14] Benega MAG, Raja R, Blake JIR. ScienceDirect ScienceDirect A preliminary evaluation of bio-based epoxy resin hardeners for maritime application. Procedia Eng 2017;200:186–92. https://doi.org/10.1016/j.proeng.2017.07.027.

[15] Barabanova AI, Lokshin BV, Kharitonova EP, Karandi IV, Afanasyev ES, Askadskii AA, et al. Cycloaliphatic epoxy resin cured with anhydride in the absence of catalyst. 2019. p. 409–16.

[16] Barabanova AI, Lokshin BV, Kharitonova EP, Afanasyev ES, Askadskii AA, Philippova OE. Curing cycloaliphatic epoxy resin with 4-methylhexahydrophthalic anhydride : catalyzed vs . uncatalyzed reaction. Polymer 2019;178:121590. https://doi.org/10.1016/j.polymer.2019.121590.

[17] Adnan MM, Tveten EG, Glaum J, Ese MG, Hvidsten S, Glomm W, et al. Epoxy-based nanocomposites for high-voltage insulation : a review. 2019, 1800505. https://doi.org/10.1002/aelm.201800505. 1–23.

[18] Lee DW, Yoo BR. Advanced silica/polymer composites: materials and applications. J Ind Eng Chem 2016;38:1–12. https://doi.org/10.1016/j.jiec.2016.04.016.

[19] Hsissou R, Seghiri R, Benzekri Z, Hilali M, Rafik M, Elharfi A. Polymer composite materials: a comprehensive review. Compos Struct 2021;262. https://doi.org/10.1016/j.compstruct.2021.113640. 0–3.

[20] Zdarta J, Jesionowski T. Silica and silica-based materials for biotechnology, polymer composites, and environmental protection. Materials 2022;15:7703. https://doi.org/10.3390/ma15217703.

[21] Gao F. Clay/polymer composites: the story. Mater Today 2004;7:50–5. https://doi.org/10.1016/S1369-7021(04)00509-7.

[22] Kangishwar S, Radhika N, Sheik AA, Chavali A, Hariharan S. A comprehensive review on polymer matrix composites: material selection, fabrication, and application, vol. 80. Springer Berlin Heidelberg; 2022. https://doi.org/10.1007/s00289-022-04087-4.

[23] Bertetto AM, Grosso B, Ricciu R, Rizzu D. Anisotropic and impulsive neutron emissions from brittle rocks under mechanical load. Meccanica 2015;50:1177–88. https://doi.org/10.1007/s11012-014-9987-9.

[24] Zou H, Wu S, Shen J. Polymer/silica nanocomposites : preparation, characterization, properties. Chem Rev 2008;108:3893–957.
[25] Sadek DM, El-Attar MM, Ali HA. Reusing of marble and granite powders in self-compacting concrete for sustainable development. J Clean Prod 2016;121:19–32. https://doi.org/10.1016/j.jclepro.2016.02.044.
[26] Singh S, Khan S, Khandelwal R, Chugh A, Nagar R. Performance of sustainable concrete containing granite cutting waste. J Clean Prod 2016;119:86–98. https://doi.org/10.1016/j.jclepro.2016.02.008.
[27] Zafar MS, Javed U, Khushnood RA, Nawaz A, Zafar T. Sustainable incorporation of waste granite dust as partial replacement of sand in autoclave aerated concrete. Construct Build Mater 2020;250:118878. https://doi.org/10.1016/j.conbuildmat.2020.118878.
[28] Abd Elmoaty AEM. Mechanical properties and corrosion resistance of concrete modified with granite dust. Construct Build Mater 2013;47:743–52. https://doi.org/10.1016/j.conbuildmat.2013.05.054.
[29] Awad AH, El-gamasy R, El-wahab AAA, Abdellatif MH. Assessment of mechanical properties of HDPE composite with addition of marble and granite dust. Ain Shams Eng J 2020;11:1211–7. https://doi.org/10.1016/j.asej.2020.02.001.
[30] Subhash C, Krishna MR, Raj MS, Sai BH, Rao SR. Development of granite powder reinforced epoxy composites. Mater Today Proc 2018;5:13010–4. https://doi.org/10.1016/j.matpr.2018.02.286.
[31] Reddy RM, Reddy BM, Reddy PV, Krishnudu DM, Reddy RVS. Granite powder influence on the static mechanical properties of tapsi fiber-reinforced hybrid composites: a comparative study. J Nat Fibers 2022;19:12688–704. https://doi.org/10.1080/15440478.2022.2073503.
[32] Gupta LK, Vyas AK. Impact on mechanical properties of cement sand mortar containing waste granite powder. Construct Build Mater 2018;191:155–64. https://doi.org/10.1016/j.conbuildmat.2018.09.203.
[33] Chen JJ, Li BH, Ng PL, Kwan AKH. Adding granite polishing waste to reduce sand and cement contents and improve performance of mortar. J Clean Prod 2021;279. https://doi.org/10.1016/j.jclepro.2020.123653.
[34] Shen J, Liang J, Lin X, Lin H, Yu J, Wang S. The flame-retardant mechanisms and preparation of polymer composites and their potential application in construction engineering. Polymers 2022;14. https://doi.org/10.3390/polym14010082.
[35] Lopez M. Flame-retardant polymer nanocomposites. Woodhead Publishing Limited; 2012. https://doi.org/10.1533/9780857096241.3.540.
[36] van Krevelen DW. Some basic aspects of flame resistance of polymeric materials. Polymer 1975;16:615–20. https://doi.org/10.1016/0032-3861(75)90157-3.
[37] Shimamura A. Improving the thermal conductivity of epoxy composites using a combustion - synthesized aggregated β - Si 3 N 4 filler with randomly oriented grains. Sci Rep 2020:1–9. https://doi.org/10.1038/s41598-020-71745-w.
[38] Chen H, Ginzburg VV, Yang J, Yang Y, Liu W, Huang Y, et al. Progress in polymer science thermal conductivity of polymer-based composites : fundamentals and applications. Prog Polym Sci 2016;59:41–85. https://doi.org/10.1016/j.progpolymsci.2016.03.001.
[39] Krause B, Rzeczkowski P, Pötschke P. Thermal conductivity and electrical resistivity of melt-mixed polypropylene composites containing mixtures of carbon-based fillers. 2019.
[40] Mohammed MA, Erlend GT, Julia G, Marit-Helen G, Sverre H, Wilhelm G. Mari-ann E, epoxy-based nanocomposites for high-voltage insulation A review. Adv Elect Materials 2019;5:1800505.
[41] Bakshi P, Pappu A, Patidar R, Gupta MK, Thakur VK. Transforming marble waste into high-performance, water-resistant, and thermally insulative hybrid polymer composites for environmental sustainability. Polymers 2020;12. https://doi.org/10.3390/polym12081781.
[42] Ilyas RA, Hazrol MD, Sapuan SM. Electrical and surface resistivity of polymer composites : a Review Electrical and surface resistivity of polymer composites : a Review. 2018. p. 6–10. email : hazrolpostgrad@gmail.com.
[43] Hirahara T. Designable core–shell graphite particles for thermally conductive and electrically insulating polymer composites. 2018. p. 16781–7. https://doi.org/10.1039/c8ra01946k.
[44] Tan DQ. The search for enhanced dielectric strength of polymer- based dielectrics : a focused review on polymer nanocomposites. 2020. p. 1–32. https://doi.org/10.1002/app.49379.