

# Thermal and frequency dependence dielectric properties of conducting polymer/ fly ash composites

Subhash B. Kondawar<sup>1\*</sup>, A. D. Dahegaonkar<sup>2</sup>, V. A. Tabhane<sup>3</sup>, D. V. Nandanwar<sup>4</sup>

<sup>1</sup>Department of Physics, Polymer Nanotech Laboratory, R.T.M. Nagpur University, Nagpur, India

<sup>2</sup>N. S. Science and Arts College Bhadrawati, Dist. Chandrapur, India

<sup>3</sup>Department of Physics, Pune University, Pune, India

<sup>4</sup>Department of Physics, Shri Mohata College of Science, Nagpur, India

\*Corresponding author. Tel: (+91) 712-2042086; E-mail: sbkondawar@yahoo.co.in

Received: 08 October 2013, Revised: 30 November 2013 and Accepted: 22 December 2013

## ABSTRACT

With more than 100 million tonnes of fly ash produced in India, use of fly ash for the preparation of polyaniline – fly ash composites will in no way help in its bulk utilization. Still the authors have made an effort towards the better utility of fly ash by synthesizing polyaniline –fly ash composites for electronic devices where the requirement of dielectric materials with good electrical conductivity. There is great challenge to use the waste of thermal power stations in the form of fly ash as reinforcement for the conducting polymers to be good dielectric materials. In this paper, we report the use of fly ash to prepare conducting polymer composite materials. In-situ polymerization of aniline was carried out in the presence of fly ash (FA) to synthesize conducting polyaniline–fly ash composites (PANI-FA) by chemical oxidation method. The PANI-FA composites have been synthesized with various compositions (10, 20, 30, 40 and 50 wt %) of fly ash in conducting polymer matrix. The surface morphology of these composites was studied by scanning electron microscopy (SEM). These composites were characterized by Scanning Electron Microscopy (SEM), X-Ray Diffractometry (XRD), Fourier Transform Infra-Red (FTIR) Spectroscopy to investigate surface morphology and structure of the composites. Thermal and frequency dependence dielectric properties of all the synthesized composites have been studied with the help of impedance analyzer. By incorporating fly ash into conducting polymers, dielectric constant of the composites was found to be improved as compared to that of pure conducting polymers. It was also noticed that the dielectric constant of all the composites found to be decreased with increasing frequency but increased with increasing temperature. The results obtained for these composites are of greater scientific and technological interest for good quality capacitors. Copyright © 2014 VBRI press.

**Keywords:** Conducting polymers; polyaniline; fly-ash; composites; dielectric constant.



**Subhash B. Kondawar** is currently working as Professor in Department of Physics, Rashtrasant Tukadoji Maharaj, Nagpur University, Nagpur, India. He did Ph.D. from Department of Physics, Institute of Science, Nagpur, India. His main research activities include the synthesis of advanced materials at nanoscale and conducting polymer nanocomposites.

His current research is focused on fabrication of electrospun nanofibers of conducting polymers and nanocomposites for gas sensors, biosensors and supercapacitors. He has published more than 35 research articles in journals of international repute. He has completed three major research projects funded by UGC, New Delhi (India).



**A. D. Dahegaonkar** is an Assistant professor in physics at N. S. Science and Arts College Bhadrawati, Dist: Chandrapur (M.S.), India. He has recently submitted his Ph.D. thesis to R. T. M. Nagpur University, Nagpur, under the guidance of Dr. S. B. Kondawar, Department of Physics, R. T. M. Nagpur University, Nagpur and Dr. V. A. Tabhane (D.Sc.), Department of Physics,

Pune University, Pune, India. His research interest includes synthesis and characterization of conducting polymer, fly-ash composites and studies their dielectric behavior.

## Introduction

Conducting polymers have received considerable attention because of their interesting electronic, physical properties, chemical stability and their potential technological applications [1-4]. Polyaniline (PANI) is one of the most promising conducting polymers because of its unique properties like ease of preparation in aqueous medium, good stability in air, simplicity in doping, improved electronic properties, controllable by oxidation and protonation state, excellent environmental stability, moderately high conductivity in the doped state and Potential applications in electronic devices [5, 6]. Polymers are typically utilized in electrical, optical and electronic devices as insulators because of their very high electrical resistivity. The dielectric properties of heterogeneous polymers [7] play an important role in device applications such as high performance capacitors, electrical cable insulation, electronic packaging etc. Polymers are usually polyconjugated structures, which are insulators in their pure state; but when treated with oxidizing or reducing agents they can be converted into polymer salts having reasonable electrical conductivity. Conjugated polymers are plastic semiconductors [8]. They have wide applications in devices such as solar cells, rechargeable batteries, light emitting diodes, micro-actuators, electrochromic displays, field effect transistors, sensors [9].

Polyaniline (PANI) can be synthesized chemically or electrochemically in an acidic medium. For chemical synthesis, an appropriate oxidant is required. There are three forms of PANI, namely fully oxidized pernigraniline, half-oxidized emeraldine base (EB) and fully reduced leucoemeraldine base (LB). Emeraldine is said to be the most stable form of PANI and also the most conductive form when doped (emeraldine salt) [10, 11]. Incorporation of a new component into polymer matrix enhances the properties of the polymer. Kondawar et al have reported the enhancement of electrical properties of various conducting polymer composites [12-15]. The incorporation of FA into the polymeric network introduces uniform porosity and is expected to be advantageous for gas sensing and biosensing applications. Thermal studies of PANI conducting polymers are particularly important when one considers the use of elevated temperature to process PANI and its blends into technologically useful forms.

In India, substantial part of electric power (about 65%) is generated from coal or lignite fired thermal power stations. One of the major pollutants generated in a coal based thermal power plant is fly ash (FA). Silica (SiO<sub>2</sub>), alumina (Al<sub>2</sub>O<sub>3</sub>), iron oxide (Fe<sub>2</sub>O<sub>3</sub>) and titanium oxide (TiO<sub>2</sub>) are major constituents of FA. These metal oxides have been used in one way or the

other in the preparation of nanocomposites. For example, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> have been used as catalyst support for the production of organic-inorganic porous nanocomposites. In this paper we are using natural composition of metal oxides for the preparation of PANI-FA composite, which forms morphologically porous matrix and have improved thermal stability.

In this paper, we report the synthesis of PANI-FA composites with various weight percentage of fly ash by chemical oxidization method and characterization using SEM, XRD and FTIR to find the utilization of such multifunctional composites as dielectrics and to solve the problem of dumping of fly ash in coal industries.

## Experimental

### Materials

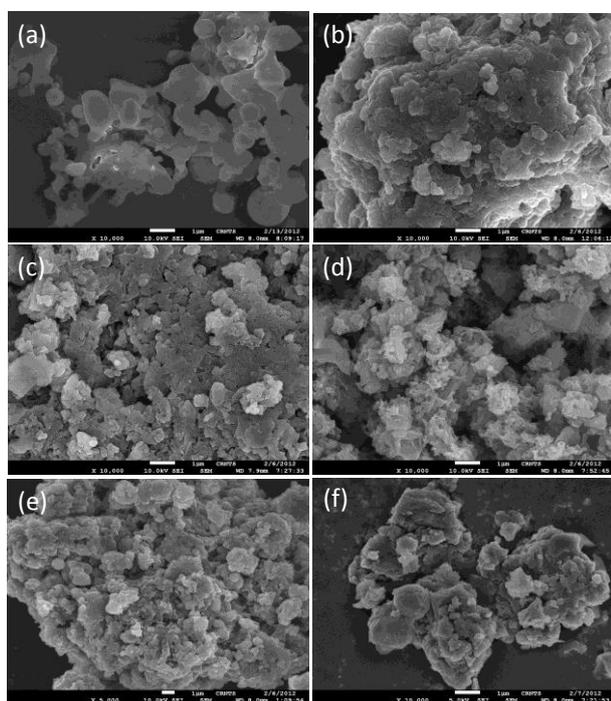
The monomer aniline was purchased from Sigma-Aldrich (purity 99.5%) and purified through distillation under reduced pressure and stored refrigerated before use. A fine fresh clean and pure FA powder was collected from the Thermal Power Station, Chandrapur, India. The cenosphere type FA was grounded and sintered at 600°C to remove moisture content and impurities present. Chemically, the FA was silica to an extent of 55–70% followed by alumina, 10–18%, iron oxide, 6–20% and lime magnesia and alkalis varied between 1 and 5% each. FA also contains elements like Cu, Pb, Cd, Ag, Mn, Ti, Na, Mo, S, P, Zn and Cl in different concentrations [16]. All other chemicals like ammonium peroxydisulfate with molecular weight 228.2gm/mole (APS, 98%), ethanol (99.9%), sulphuric acid with molecular weight 98.08gm/mole (98%) were bought from S. D. Fine-Chem. Ltd. and used as received without further purification. All chemicals were of analytical grade. Solutions were prepared in de-ionized water.

### Analytical methods

The surface morphology was studied with the help of Scanning Electron Microscope (JEOL Model JSM - 6390LV). X-ray diffraction (XRD) was carried on Philips PW1710 automatic X-ray diffractometer with Cu-K $\alpha$  radiation ( $\lambda=1.5404\text{\AA}$ ), with a scanning speed of 10° min<sup>-1</sup>. FTIR spectra were performed on Shimadzu FTIR-8101A Spectrophotometer in the wavelength range of 400–4000cm<sup>-1</sup>. The pellets were prepared with the help of hydraulic press (Kimaya Engineers, India) by applying a pressure of 5000 kg/cm<sup>2</sup>. The variation of impedance with frequency and temperature has been studied for all samples. The dielectric constant and dielectric loss were measured in frequency range from 100 Hz to 1 MHz using Hewlett-Packard impedance analyser 4192-A at room temperature.

### Preparation of PANI-FA composites

0.1 M aniline was dissolved in 100 ml of 1M HCl to form polyaniline (PANI). The varied wt% of fly ash powder (10, 20, 30, 40 and 50%) was added to the PANI solution with vigorous stirring in order to keep the FA powder suspended in the solution. 0.1 M  $[(\text{NH}_4)_2\text{S}_2\text{O}_8]$  was added drop wise with continuous stirring, which acts as the oxidant. The reaction mixture was stirred continuously for another 8 h. The precipitate formed was collected by filtration and washed with distilled water and acetone until the filtrate became colourless. After washing, the precipitate was dried at 70°C in vacuum oven for 12 h. Pure PANI was also synthesized without the use of FA in the similar process to compare the dielectric properties between the composites and pure PANI.



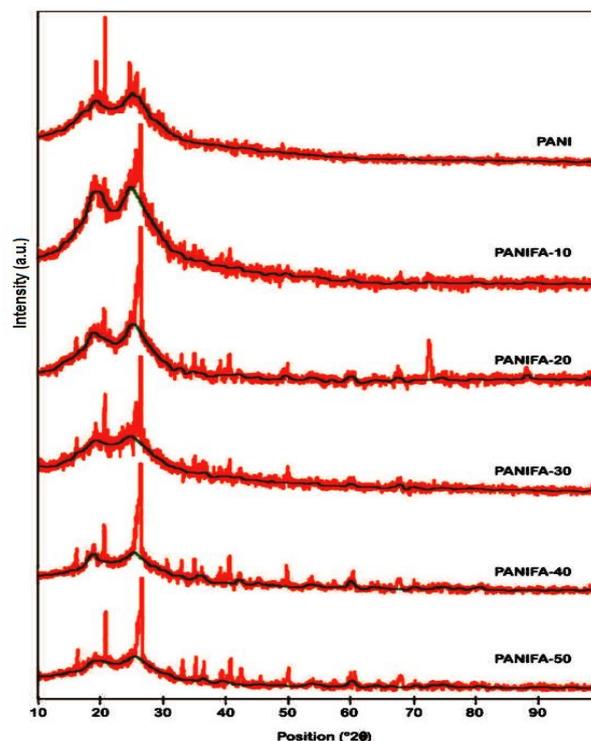
**Fig. 1.** SEM images of (a) FA, (b) PANI, (c) PANI-FA(10%), (d) PANI-FA(20%), (e) PANI-FA(30%) and (f) PANI-FA(40%) composites.

### Results and discussion

SEM images of PANI, FA and PANI-FA composites are shown in **Fig. 1(a-f)**. It can be seen from SEM image of FA **(a)** that the fly ash is mainly constituted by compact or hollowed spheres but with a regular smooth texture. Also, some quartz particles, residue of un-burnt coal or some vitreous unshaped fragments could be seen. SEM image of PANI **(b)** shows porous, non-uniform structure. PANI-FA **(c-f)** composites shows the formation of dine base form of PANI significantly changes the aggregate state of polymeric molecular chain. The incorporation of metal oxides into the polymeric network induces uniform porosity

and is expected to be advantageous for gas and biosensing applications. A very high magnification reveals the homogeneous distribution of fly ash (cenosphere) particles. It is seen from the micrograph that cluster and granular structure of polyaniline is maintained even after the addition of fly ash in polyaniline. Hence, a network of fly ash and granular polyaniline has been formed in case of composites [17].

**Fig. 2** shows the XRD pattern of pure PANI and PANI-FA composites. It has been observed from XRD that PANI undergoes interfacial interaction with FA crystallites and exhibits semi-crystalline behaviour. PANI-FA composites show peaks of fly ash as well as polyaniline indicating that fly ash crystallites have been uniformly mixed within the polymer chain. PANI-FA shows more crystalline for higher percentage of FA in PANI matrix. No structural change has been observed in fly ash due to its dispersion in polymerization reaction of polyaniline [18].



**Fig. 2.** XRD pattern of pure PANI and PANI-FA composites.

FTIR spectra of PANI and PANI-FA composites are shown in **Fig. 3**. The characteristic bands observed at 1567 and 1482  $\text{cm}^{-1}$  in PANI are assigned respectively to the non-symmetric vibration mode of C=C in quinoid and benzenoid ring system in polyaniline. The C-N stretching vibration mode in aromatic amine nitrogen (quinoid system) in doped polyaniline was found at 1290  $\text{cm}^{-1}$  corresponding to the oxidation or protonation state. The peak at 1233  $\text{cm}^{-1}$  is attributed to C-N stretching vibration mode in benzenoid ring system of polyaniline due to the

conducting protonated form. In plane vibration of C-H bending mode in  $N = Q = N$ ,  $Q-N+H-B$  or  $B-N+H-B$  (where  $Q =$  quinoid and  $B =$  benzenoid) was observed at  $1146\text{ cm}^{-1}$ . The presence of this band is expected due to the polymerization of PANI, *i.e.*, polar structure of the conducting protonated form. The bands at  $874$  and  $799\text{ cm}^{-1}$  are attributed to the aromatic ring and out of plane C-H deformation vibrations for 1, 4-disubstituted aromatic ring system [19]. The characteristic band observed for PANI-fly ash at  $3440\text{ cm}^{-1}$  and  $1107\text{ cm}^{-1}$  are assigned to the N-H stretching vibration mode, and  $\text{NH}_2$  deformation in aniline unit respectively.

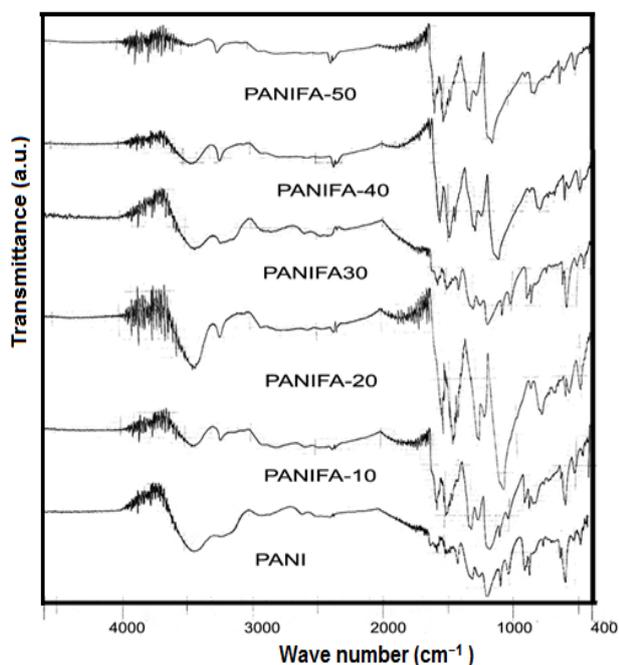


Fig. 3. FTIR spectra of pure PANI and PANI-FA composites.

In FTIR spectrum of purified FA, the characteristic  $3440\text{ cm}^{-1}$  band indicating the stretching vibration of the -OH group appears due to some components with an -OH group or crystal lattice water on the surface of FA. The decrease in broadening of FTIR bands in the range  $1560 - 3440\text{ cm}^{-1}$  was due to covalent and hydrogen bonding between  $-\text{NH}_2$  and  $-\text{OH}$  group of PANI and FA respectively. The very sharp FTIR peak at  $1560\text{ cm}^{-1}$  was associated with  $\text{C} = \text{O}$  stretch in  $-\text{HNCOCH}_3$  group of PANI-FA matrix. The IR spectra of PANI composite in presence of FA exhibit new peaks distinctly at  $1578, 1447, 1111, 1196$  and  $617\text{ cm}^{-1}$  which could be assigned to the presence of various metal oxides in the composite. The peak around  $1107\text{ cm}^{-1}$  may be attributed to the presence of silica within the composite. The FTIR peaks at  $1068\text{ cm}^{-1}$  for the FA corresponds to the internal  $\text{SiO}_4$  tetrahedra, especially the Si-O-Si chain structure. The peaks at

$1068 - 1111\text{ cm}^{-1}$  of the FA correspond to a cyclic Si-O-Si structure. The FA indicates the FTIR spectra of  $\text{Fe}_2\text{O}_3$ , where the bands around  $617-426\text{ cm}^{-1}$  are assigned to Fe-O stretch. It can be seen that the FTIR spectra of the PANI-FA composites are similar to that of pure PANI where the bands for  $\text{C}=\text{N}$ ,  $\text{C}=\text{C}$  and  $\text{C}-\text{N}$  are all shifted to lower wave numbers, *i.e.*  $1578, 1444, 1400$  and  $1111\text{ cm}^{-1}$  due to strong interaction of  $\text{Fe}_2\text{O}_3$  and PANI [20].

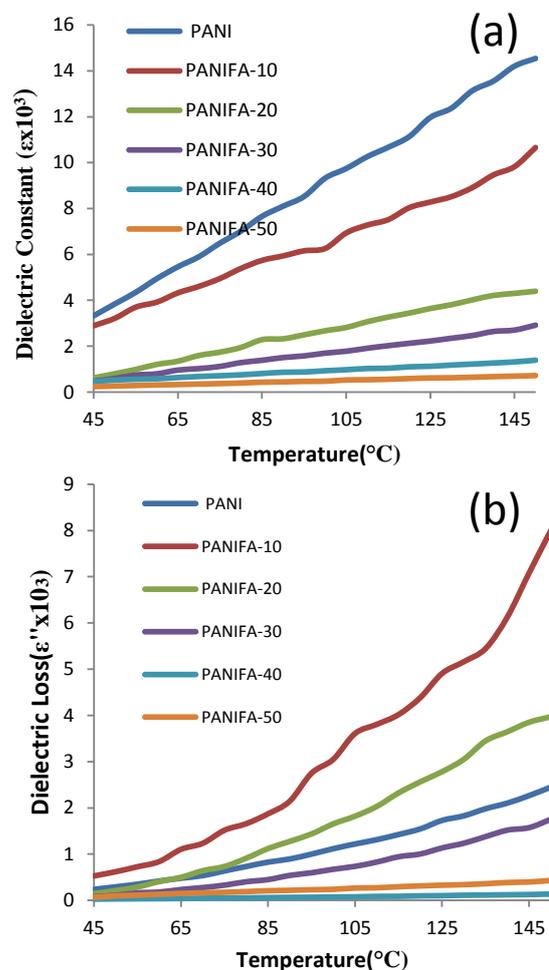


Fig. 4 (a). Dielectric constant vs temperature and (b) Dielectric loss vs temperature of PANI and PANI-FA composites.

Fig. 4(a) and (b) shows variation of dielectric constant ( $\epsilon'$ ) and dielectric loss ( $\epsilon''$ ) as a function of temperature at constant frequency  $1000\text{ Hz}$  of polyaniline and polyaniline fly ash composites (10 to 50 wt%) respectively. It is observed that dielectric constant ( $\epsilon'$ ) and dielectric loss ( $\epsilon''$ ) increases with increasing temperature. As the temperature of the sample increased there is no dispersion in dielectric constant. This is because of tight binding forces between the number of ions or atoms. As temperature increases the dipoles comparatively become free and they respond to the applied electric field. Thus

polarization increased and hence the dielectric constant also increases with temperature. The polyaniline particles generally act as minute capacitors which decrease due to increases in content of fly ash in PANI matrix. Increment fly ash content decreases number of such capacitors of PANI which is turn decrease the magnitude of dielectric constant. The dielectric constant for PANI is about  $4 \times 10^6$  and for FA is about 10. The addition of various weight percentage of FA i.e. (10% to 50%) shows decreases in dielectric constant from  $4.04 \times 10^6$  to  $0.40 \times 10^3$  at 100 Hz. Therefore, use of FA in PANI matrix leads to decrease in dielectric constant as compared to that of pure PANI. The dielectric loss ( $\epsilon''$ ) of PANI-FA composites is due to the tubular PANI phase, interfacial polarization between PANI and FA phase. Further, the dielectric losses by  $\text{SiO}_2$ ,  $3\text{Al}_2\text{O}_3$ ,  $2\text{SiO}_2$  and  $\text{Fe}_2\text{O}_3$  constituents of FA and multiple scattering play a crucial role for dielectric loss. The percentage dielectric loss of the PANIFA shows similar trend as that of dielectric constant [21].

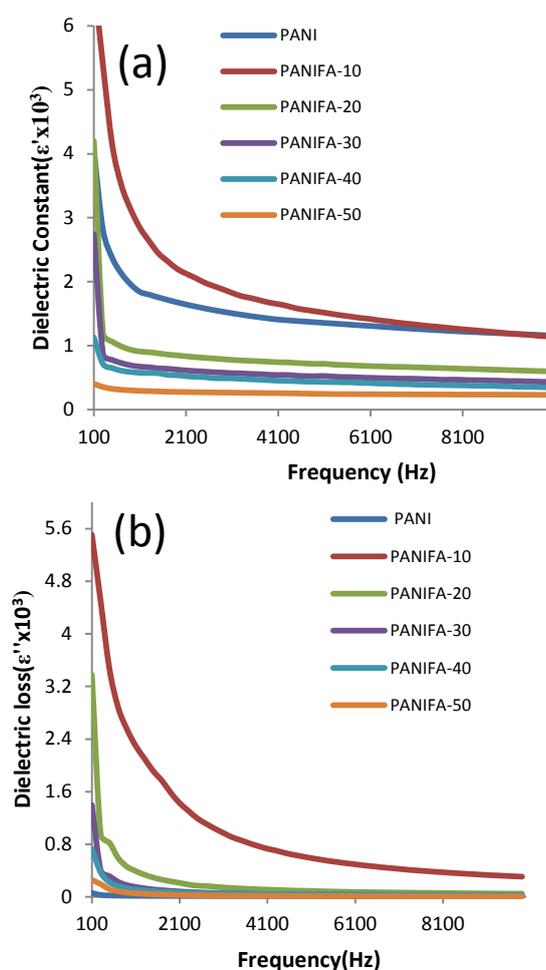


Fig. 5. (a) Dielectric constant vs frequency and (b) dielectric loss vs frequency of PANI and PANI-FA composites.

Fig. 5(a) and (b) shows the variation of dielectric constant ( $\epsilon'$ ) and dielectric loss of ( $\epsilon''$ ) as a function of

frequency of pure polyaniline and polyaniline fly ash composites (different wt%). It is observed that at low frequency dielectric constant was found to be decreased with increasing the frequency. This could be due to fact that ions are unable to oppose the effect of the field and/or tightly pinned to the polymer chain. Both polyaniline and its composites exhibit small value of dielectric loss at higher frequency, therefore these samples of polyaniline and its composites are used in present study. The real part of the dielectric permittivity or dielectric constant ( $\epsilon'$ ) and imaginary part of dielectric permittivity or dielectric loss ( $\epsilon''$ ) for PANI-FA sample measured in the frequency range 100 Hz to 1MHz room temperatures. It is observed that the dielectric constant  $\epsilon'$  is decreased rapidly at lower frequencies and showed almost frequency independent behavior at higher frequency region [22]. The bulk polarization of the sample results from the presence of electrodes, which do not allow transfer of the charge species into the external circuit. The behavior of the dielectric permittivity with frequency is related to the applied field, which assists electron hopping between two different sites of the sample. At higher frequency region, the charge carriers will no longer be able to rotate sufficiently rapidly, so their oscillation will begin to lay behind this field resulting in a decrease of dielectric permittivity,  $\epsilon'$ . Generally, the relaxation phenomena in dielectric materials are associated with frequency dependent orientation polarization. At low frequency region, the permanent dipoles align themselves along the field and contribute fully to the total polarization of the dielectric. At higher frequency region, the variation in the field is very rapid for the dipoles to align themselves, so their contribution to the polarization and hence, to dielectric permittivity can become negligible. Therefore, the dielectric permittivity,  $\epsilon'$  decreases with increasing frequency. The decrease of the dielectric constant  $\epsilon'$  can also explain from interfacial polarization. The interfacial polarization arises as a result of difference in conducting phase, but is interrupted at grain boundary due to lower conductivity. Generally in polycrystalline materials, the grains exhibits semi conducting behavior while the grain boundary are insulators. The maximum in the  $\epsilon''$  peak is shifts towards higher frequency region as the temperature increase indicating a thermally activated behavior. Generally, the dielectric losses at high frequencies are much lower than those occurring at lower frequencies at specific temperature. This kind of dependence of  $\epsilon''$  on frequency is typically associated with losses by conduction [23].

## Conclusion

With more than 100 million tonnes of fly ash produced in India, use of fly ash for the preparation of polyaniline – fly ash composites will in no way help in its bulk utilization. Still the authors have made an effort towards the better utility of fly ash by synthesizing polyaniline–fly ash composites for

electronic devices where the requirement of dielectric materials with good electrical conductivity. Conducting polyaniline and polyaniline / fly ash were synthesized successfully by using an in-situ chemical oxidation polymerization method. The interaction of FA with the polymer was confirmed from their XRD, SEM and FTIR. The results of dielectric constant show strong dependence on the weight per cent of fly ash in polyaniline. The dielectric constant and loss was found to be decreased with weight percent of FA in composites. Further the dielectric constant of all the composites was found to be decreased with increasing frequency but increased with increasing temperature.

#### Acknowledgements

The authors express their gratitude to University Grants Commission, Western Region Office, Pune (India) for financial support to carry out this research work under minor research project UGC F. No. 47-1337/10 (WRO).

#### Reference

- Kondawar, S. B.; Thakare, S. R.; Bompilwar, S.; Khati, V. *Int. J. Mod. Phys. B*, **2009**, *23*, 3297.  
DOI: [10.1142/S02179792090525832](https://doi.org/10.1142/S02179792090525832)
- Lei, J.; Menon, V.P.; Martin, C.R. *Polym. Adv. Tech.*, **1993**, *41*, 24.  
DOI: [10.1002/pat.1993.220040211](https://doi.org/10.1002/pat.1993.220040211)  
Tiwari, A.; Prabaharan, M.; Pandey, R.R.; Li, S. *J Inorg Organomet Polym*, **2010**, *20*, 380-386.
- Yang, C.H.; Wang, T.L.; Shieh, Y.T.; *Electrochemistry Communications* **2009**, *11*, 335.  
DOI: [10.1016/j.elecom.2008.12.014](https://doi.org/10.1016/j.elecom.2008.12.014)  
Tiwari, A.; Sen, V.; Dhakate, S.R.; Mishra, A.P.; Singh, V. *Polymers for Advanced Technologies*, **2008**, *19*, 909-914.  
Tiwari, A.; Singh, V. *Carbohydrate Polymers*, **2008**, *74*, 427-434.  
Tiwari, A. *Journal of Macromolecular Science Part-A: Pure and Applied Chemistry*, **2007**, *44*, 735-745.
- Horie, M.; Yamaguchi, I.; Yamamoto, T. *Macromolecules* **2006**, *39*, 7493.  
DOI: [10.1021/ma0611265](https://doi.org/10.1021/ma0611265)  
Shukla, S.K.; Tiwari, A. *Advanced Materials Research*, **2011**, *306-307*, 82-86.  
Singh, R.P.; Tiwari, A.; Pandey, A.C. *J Inorg Organomet Polym*, **2011**, *21*, 788-792.  
Shukla, S. K.; Vamakshi, Minakshi, Bharadavaja, A.; Shekhar, A.; Tiwari, A. *Advanced Materials Letters*, **2012**, *3*, 421-425.  
Tiwari, A.; Sharma, Y.; Hattori, S.; Terada, D.; Sharma, A.K.; Turner, A. P. F.; Kobayashi, H. *Biopolymers*, **2013**, *99*, 334-341.
- Shukla, S.K.; Bharadavaja, A.; Tiwari, A.; Parashar, G.K.; Dubey, G.C. *Adv. Mat. Lett.* **2010**, *1*(2), 129.  
DOI: [10.5185/amlett.2010.3105](https://doi.org/10.5185/amlett.2010.3105)  
Tiwari, A.; Singh, V. *Express Polymer Letters*, **2007**, *1*, 308-317.  
Tiwari, A. *J Polym Res*, **2008**, *15*, 337-342.  
Tiwari, A.; Gong, S. *Talanta*, **2009**, *77*, 1217-1222.
- Tiwari, A.; Singh, S.P. *J Appl Polym Sci*, **2008**, *108*, 1169-1177.
- Gupta, M. C.; Borkar, A. D.; Umare, S. S.; *Polym. Plast. Technol. Eng.* **2001**, *40*, 225.  
DOI: [10.1081/PPT-100000067](https://doi.org/10.1081/PPT-100000067)
- Kumari, K.; Ali, V.; Rani, G.; Kumar, S.; Lakshmi, G.; Zulfiqar, M. *Materials Science and Application*, **2011**, *2*, 1047-1057  
DOI: [10.4236/msa.2011.28142](https://doi.org/10.4236/msa.2011.28142)
- Friend, R.H.; Gymer, R. W.; Holmes, A.B.; *Nature*, **1997**, *397*, 121-128.  
DOI: [10.1038/16393](https://doi.org/10.1038/16393)
- Saraswathi, R., Gerard, M. Malhotra, B.; *Journal of Applied Polymer Science*, **1999**, *74*, 145  
DOI: [10.1002/\(SICI\)10974628\(19991003\)74:1<145::AID-APP18>3.0.CO;2-C](https://doi.org/10.1002/(SICI)10974628(19991003)74:1<145::AID-APP18>3.0.CO;2-C)
- Chandrakanthi, R. L. N.; Careem, M. A.; *Thin Solid Films*, **2002**, *417*, 51-56.  
DOI: [10.1016/S0040-6090\(02\)00600-4](https://doi.org/10.1016/S0040-6090(02)00600-4)
- Rosaiah, P.; Hussain, O.; M. *Adv. Mat. Lett.* **2013**, *4*(4), 288-295  
DOI: [10.5185/amlett.2012.8416](https://doi.org/10.5185/amlett.2012.8416)
- Kondawar, S.B., Agrawal, S.P., Nimkar, S.H., Sharma, H.J., Patil, P.T., *Adv. Mat. Lett.* **2012**, *3*(5), 393-398  
DOI: [10.5185/amlett.2012.6361](https://doi.org/10.5185/amlett.2012.6361)
- Kondawar, S.B.; Deshpande, M.D.; Agrawal, S.P.; *International Journal of Composite Materials*, **2012**, *2*(3), 32-36  
DOI: [10.5923/j.comaterials.20120203.03](https://doi.org/10.5923/j.comaterials.20120203.03)
- Nandapure, B.I., Kondawar, S.B., Salunkhe, M.Y., Nandapure, A.I., *Adv. Mat. Lett.* **2013**, *4*(2), 134-140  
DOI: [10.5185/amlett.2012.5348](https://doi.org/10.5185/amlett.2012.5348)
- Nandapure, B.I., Kondawar, S.B., Salunkhe, M.Y., Nandapure, A.I., *J. Compo. Mater.*, **2012**, *47*(5), 559-567  
DOI: [10.1177/0021998312442559](https://doi.org/10.1177/0021998312442559)
- Iwuoha, E. I., Mavundla, S. E., Somers, V. S., Petrik, L. F., Klink, M. J., Sekota, M.; Bakers P.; *Microchimica Acta*, **2006**, *155*, 453-458.  
DOI: [10.1007/s00604-006-0584-z](https://doi.org/10.1007/s00604-006-0584-z)
- Khan, R.; Khare, P., Prasad, B., Dey, A.; *Advances in Chemical Engineering and Sciences*, **2011**, *1*, 37-44  
DOI: [10.4236/aces.2011.12007](https://doi.org/10.4236/aces.2011.12007)
- Kondawar, S.B., Acharya S.A., Dhakate S.R. *Adv. Mat. Lett.* **2011**, *2*(5), 362-367  
DOI: [10.5185/amlett.2011.9107am2011](https://doi.org/10.5185/amlett.2011.9107am2011)
- Rees C. A., Provis J. L., Lukeya G. C. and Deventer J. S., *Langmuir*, Vol. , **2007**, *23*, 8170-8179.  
DOI: [10.1021/la700713g](https://doi.org/10.1021/la700713g)
- Glasel H., Hartmann J., E. and Hormes J. *Journal of Materials Science*, **1999**, *34*, 1-5.  
DOI: [10.1023/A:1004533926099](https://doi.org/10.1023/A:1004533926099)
- Sathiyarayanan S., Azim S. S. and Venkatachari G., *Synthetic Metals*, **2007**, *157*, 751-757.  
DOI: [10.1016/j.synthmet.2007.08.004](https://doi.org/10.1016/j.synthmet.2007.08.004)  
Tiwari, A.; Gong, S. *Electroanalysis*, **2008**, *20*, 1775-1781.  
Tiwari, A.; Kumar, R.; Prabaharan, M.; Pandey, R.R.; Kumari, P.; Chaturvedi, A.; Mishra, A. K. *Polymers for Advanced Technologies*, **2010**, *21*, 615-620.
- Louati, B.; Guindara, K. *Mater. Sci. Eng. B*, **2012**, *117*, 838.  
DOI: [10.1016/j.mseb.2012.03.050](https://doi.org/10.1016/j.mseb.2012.03.050)
- Cao, Y., Li, S.Z., Xuea, Z. J., Guo, D., *Synthetic Metals*, **1986**, *16*(3), 305-315  
DOI: [10.1016/0379-6779\(86\)90167-0](https://doi.org/10.1016/0379-6779(86)90167-0)

#### Advanced Materials Letters

Publish your article in this journal

ADVANCED MATERIALS Letters is an international journal published quarterly. The journal is intended to provide top-quality peer-reviewed research papers in the fascinating field of materials science particularly in the area of structure, synthesis and processing, characterization, advanced-state properties, and applications of materials. All articles are indexed on various databases including DOAJ and are available for download for free. The manuscript management system is completely electronic and has fast and fair peer-review process. The journal includes review articles, research articles, notes, letter to editor and short communications.

