Enhanced thermo-mechanical performance and strain-induced band gap reduction of TiO₂@PVC nanocomposite films

MUDASSIR HASAN¹, ARGHYA NARAYAN BANERJEE² and MOONYONG LEE^{1,*}

¹School of Chemical Engineering, Yeungnam University, Gyeongsan 712-749, Republic of Korea

²School of Mechanical Engineering, Yeungnam University, Gyeongsan 712-749, Republic of Korea

MS received 30 April 2014

Abstract. The present paper reports the fabrication of TiO₂@PVC nanocomposites by incorporating TiO₂ in polyvinyl chloride (PVC) followed by solution casting to prepare TiO₂@PVC nanocomposite thin films. The as-prepared TiO₂@PVC nanocomposite films were characterized by Fourier transform infrared spectroscopy, X-ray diffraction, high-resolution transmission electron microscopy, thermogravimetric analysis, optical spectroscopy and mechanical strength analyses. The TiO₂@PVC nanocomposites were found to be thermally and mechanically more stable compared with pure PVC. The anatase TiO₂ in the TiO₂@PVC nanocomposite showed a lower indirect band gap compared with pure TiO₂, which can be attributed to the strain within the nanocomposite, thereby affecting the band-structure of the nanocomposite. Significant enhancement in the mechanical properties of TiO₂@PVC compared with pure PVC was observed with a 10 wt% TiO₂ loading, such as a 50% increase in Young's modulus and almost 100% improvement in the tensile strength.

Keywords. PVC; TiO₂; nanocomposite; band gap reduction; thermal stability; mechanical strength.

1. Introduction

The synthesis of new materials showing superior properties to the older ones has always been fascinating. New materials, such as organic–inorganic composites have opened new windows for applicability in the area ranging from electronics,¹ chemistry,² biology,³ medicine,⁴ etc. A large number of organic (such as different polymer) and inorganic materials (oxide particles) can be combined to form nanocomposites with enhanced electrical, optical and photocatalytic properties.

TiO₂ has largely been used as a photocatalyst because of its high reactivity and good photostability.⁵ In addition, it decomposes a range of organic compounds under UV irradiation. The wide band gap of TiO₂ (~3.2 eV) limits the photocatalytic activity of TiO₂ to the UV part of solar radiation. On the other hand, its activity and photocatalytic performance can also be extended to part of the visible spectrum through proper tuning of the band gap.⁶ Among the different routes for the modification of TiO₂, nanocomposite formulations using commodity polymers have been exciting because of its ease of formation and cost effectiveness. The electrical, optical and photocatalytic properties of TiO₂ are greatly affected when incorporated with a polymer, resulting in nanocomposites with a wide range of applications in future technologies.^{7–9}

Among the different commodity polymers, polyvinyl chloride (PVC) is a versatile and most widely used polymer after polyethylene and polypropylene. PVC has many

applications in construction,¹⁰ medicine,¹¹ capacitors,¹² etc. TiO₂@Ag/PVC with enhanced antibacterial activities and photocatalytic properties was reported.¹³ TiO₂-encapsulated PVC as an eco-friendly alternative to conventional PVC was also reported.¹⁴ A new type of photodegradable PVC-vitamin C-TiO₂ nanocomposite film that showed higher photodegradation efficiency under UV light irradiation than the TiO₂@PVC nanocomposite film and pure PVC film.¹⁵ On the other hand, there are few reports on the physico-chemical characterization and band gap narrowing of TiO₂@PVC.

In this study, TiO₂@PVC nanocomposites were prepared using a simple solution casting technique. The structure, morphology, thermal stability, mechanical strength and optical properties of the nanocomposites were examined in detail. The nanocomposite showed strain-induced band gap reduction, increased thermal stability and robust mechanical strength which are quite desirable for practical applications in photodegradation and construction. In particular, the strain-dependent band gap reduction of the TiO₂@PVC nanocomposites is very important for the visible light-induced photocatalytic performance. In general, doping is performed to reduce the band gap of TiO₂ by modifying the band structure.¹⁶ In recent times, few workers¹⁷ showed theoretically that for undoped anatase TiO₂, the induction of stress along a soft direction can effectively reduce the band gap of the material. In the present case, this phenomenon was observed experimentally, and to the best of the authors' knowledge, this is the first experimental finding of the strain-induced band gap reduction of TiO₂@PVC nanocomposites, which may open up a novel approach for tuning the band gap

* Author for correspondence (mynlee@ynu.ac.kr)

of similar anisotropic and/or superlattice materials. In addition, mechanical analysis of TiO₂@PVC nanocomposites revealed a significant increase in the mechanical performance of the nanocomposite against pure PVC. Depending on the TiO₂ loading into the PVC matrix, an almost 50% increase in Young's modulus and approximately 100% enhancement in the tensile strength of 10 wt% TiO₂-loaded nanocomposites against pure PVC were observed. This study is expected to be very useful to the scientific community working in the field of composite materials for practical applications.

2. Experimental

2.1 Materials

PVC (mean molecular weight ~1020) purchased from Yakuri Pure Chemicals, Japan and TiO₂ (mean particle size ~25 nm) was purchased from Sigma Aldrich. Tetrahydrofuran (THF) was obtained from Duksan Pure Chemicals, Korea, and used as received.

2.2 Preparation of TiO₂@PVC nanocomposite film

The nanocomposite of TiO₂@PVC was prepared by mixing TiO₂ in a PVC matrix using THF as the solvent. In a typical process, PVC was first dissolved in 50 ml of THF with continuous stirring for 24 h for complete dissolution. TiO₂ was mixed with the above solution under continuous stirring and occasional shaking in an ultrasonic bath for the proper dispersion of TiO₂ inside the THF solution of PVC. Subsequently, films of the TiO₂@PVC nanocomposites were prepared on glass plates using a solvent casting technique, which were then peeled off from the glass plates after evaporating the solvent. Therefore, the prepared films were labeled as PVC, TiO₂@PVC-5%, TiO₂@PVC-10%, as evident from supplementary table S1.

2.3 Characterization and studies

Structural analyses of the samples were carried out using X-ray diffraction (XRD, PANalytical, X'pert PRO-MPD) in the range, 10–90° 2 θ , using Cu K α radiation (λ = 0.15405 nm). The optical properties were examined by ultraviolet–visible–near infrared (UV–vis–NIR, VARIAN, Cary 5000, USA) spectrophotometry. The microstructural properties and selected area electron diffraction (SAED) were examined by field emission transmission electron microscopy (FE-TEM, TecnaiG2 F20, FEI, USA) operating at an accelerating voltage of 200 kV. For high-resolution (HR)-TEM analysis of the TiO₂@PVC, PVC was first dissolved in THF to obtain the TiO₂ nanoparticles from the nanocomposite, which were then centrifuged and washed thoroughly with deionized water and sonicated in alcohol followed by drop casting onto a carbon-coated Cu grid and drying. Thermogravimetric analysis (TGA) was performed

by using a SDT Q600 (USA) instrument heating the samples from 25 to 800°C at a rate of 10°C min⁻¹ in a nitrogen atmosphere. The Fourier transform infrared (FTIR) spectra were recorded using a Nicolet 6700 FTIR instrument. The mechanical analysis was carried out using a tensile tester (Instron 4464, UK).

3. Result and discussion

3.1 X-ray diffraction studies

Figure 1 shows the XRD patterns of PVC, TiO₂ and TiO₂@PVC nanocomposite films. In case of PVC, a broad peak at 13° 2 θ was observed, which clearly shows its poor crystallinity owing to the high integrated area. The peaks at 16.5° and 24.6° 2 θ were also observed. These observations confirm that PVC is a multiphase, possessing both low-crystalline and amorphous regions. Some workers^{18,19} also reported a similar XRD pattern of PVC in their PVC/PEO electrolyte thin film and ZnO/PVC nanocomposite, respectively.

XRD of the pure TiO₂ nanoparticles (shown in the inset) clearly revealed the presence of anatase and rutile phases. All the characteristic peaks of anatase TiO₂ nanoparticles are in agreement with the JCPDS file no. 73-1764. The peaks for rutile in the XRD pattern are in good agreement with the JCPDS file no. 76-318. As shown in the XRD patterns, the (110) and (101) peaks shows the highest intensities for rutile and anatase, respectively, and the relative abundance of anatase to rutile was obtained using the following equation:²⁰

$$F_R = 1.26I_R / (I_A + 1.26I_R), \quad (1)$$

where I_R and I_A are the maximum intensities of rutile and anatase peaks, respectively. The anatase and rutile phases were approximately 80 and 20%, respectively. The Rietveld refinement technique was used to obtain the other lattice parameters, which are shown in table 1.

In the case of the TiO₂@PVC nanocomposites, all the peaks corresponding to TiO₂ were present, indicating that

Figure 1. XRD patterns of PVC and TiO₂@PVC nanocomposite films (the XRD pattern of pure TiO₂ is given in the inset).

PVC has little or no impact on the crystal structure of TiO₂. All the characteristic peaks of the anatase were present, but the intensity of the peak corresponding to rutile (110) was reduced. This decrease in peak intensity may be interpreted as the dispersion of the peak in the nanocomposite film. Few workers¹⁸ also reported similar peak dispersion, where some peaks for the KBr salt was missing in the complex polymer blend films of the PVC/PEO and KBr. As shown in figure 1, the nanocomposite film was also a blend of the crystalline and amorphous regions, where the crystallinity of the PVC was unaltered in the presence of the TiO₂ nanoparticles. Therefore, this peak dispersion cannot be ruled out in the present case.

To quantify the effective crystallite size, $L_{\text{cryst}}^{\text{eff}}$, and strain, ε^{eff} , within the nanocomposite film, the full-width-at-half-maximum (FWHM, β , measured in radians) of the XRD peaks for different 2θ values was obtained using the formula reported elsewhere²¹

$$\frac{\beta \cos \theta}{\lambda} = \frac{1}{L_{\text{cryst}}^{\text{eff}}} + \frac{\sin \theta}{\lambda} \varepsilon^{\text{eff}}, \quad (2)$$

where λ is the incident X-ray wavelength (1.5406 Å). The plot between $\beta \cos \theta / \lambda$ and $\sin \theta / \lambda$ (figure 2) is a straight line whose slope gives an estimation of the effective strain, whereas the intercept on the $\beta \cos \theta / \lambda$ axis provides information on the effective crystallite size. The effective strain and crystallite size were 5.8×10^{-3} and 24.44 nm, respectively. The effective crystallite size was less than the particle size (~ 25 – 30 nm, shown later), which is expected for a

polycrystalline material. In addition, a comparison of the (101) peak of pure TiO₂ and TiO₂@PVC nanocomposite film revealed an increase in the β -values of the nanocomposite ($\sim 0.61^\circ$) against pure TiO₂ ($\sim 0.46^\circ$), whereas the 2θ value of nanocomposite shifted to 25.32° from 24.95° for pure TiO₂. Similar trends were also observed for the other peaks. When a crystalline material is subjected to strain, its diffraction peaks are either broadened (due to non-uniform strain, also known as ‘strain broadening’, and is reflected by an increase in the β -value) and/or shift towards a high- 2θ value (for uniform compressive strain) or low- 2θ value (for uniform tensile strain).²¹ Therefore, the observed high- 2θ -shift and broadening of the diffraction peaks indicate the generation of compressive strain within the nanocomposite film with respect to pure TiO₂ nanoparticles. Owing to the presence of the PVC matrix, the growth of the TiO₂ nanoparticles was restricted within the nanocomposite, creating compressive stress within the nanomaterial. Obviously, for a naturally forming nanocomposite, such as the present case, the generation of both uniform and non-uniform strain is thermodynamically more probable, and is reflected by the changes in both the β - and 2θ -values.

3.2 Transmission electron microscope analysis

Figure 3a–d presents TEM and HRTEM images of the pure TiO₂ and TiO₂@PVC nanocomposite. Low-magnification TEM revealed a mean particle size of ~ 25 – 30 nm both for pure TiO₂ (figure 3a) and TiO₂@PVC nanocomposite (figure 3c), indicating no significant change in the particle size in both samples. The HRTEM images in figure 3b (for pure TiO₂) and figure 3d (for TiO₂@PVC) revealed the proper lattice spacing of TiO₂. The insets in figure 3b and d show the selected area electron diffraction (SAED) patterns of the pure TiO₂ and nanocomposite, respectively, indicating the characteristic circles originating from the corresponding crystal planes of anatase TiO₂. Supplementary figure S1 shows the SEM images of PVC and TiO₂@PVC nanocomposites.

3.3 Thermogravimetric analysis

TGA is an analytical technique used to determine the thermal stability of a material. The fraction of the volatile components present in the material can also be determined by monitoring the weight change that occurs as the sample is heated.²² In the case of PVC (figure 4), the weight loss occurred in three temperature zones. The initial weight loss started at $\sim 70^\circ\text{C}$ due to the loss of moisture, residual THF and other volatile impurities. The second weight loss began from $\sim 270^\circ\text{C}$, and reached a maximum rate at $\sim 295^\circ\text{C}$, and then ended at $\sim 360^\circ\text{C}$. The second weight loss may correspond to thermal decomposition of PVC. At this stage, dehydrochlorination occurs with the subsequent formation of conjugated polyenes. The third weight loss began at $\sim 400^\circ\text{C}$ and ended at $\sim 520^\circ\text{C}$. The third stage involved the scission of polyene sequences in different ways, such as cracking, crosslinking and

Table 1. Lattice parameters of TiO₂ nanoparticle, obtained by the Rietveld refinement technique.

Phase	Anatase	Rutile
Crystal structure	Tetragonal	Tetragonal
Space group	<i>I41/amd</i>	<i>P42/mnm</i>
$a = b$ (Å)	4.78	3.78
c (Å)	2.53	9.44
Phase %	80	20

Figure 2. Size-strain analyses of the TiO₂@PVC-5% nanocomposite film.

Figure 3. HRTEM images of (a), (b) pure TiO_2 and (c), (d) TiO_2 @PVC nanocomposite at two different magnifications. The inset in **b** and **d** corresponds to the SAED patterns of pure TiO_2 and the TiO_2 @PVC nanocomposite, respectively.

Figure 4. TGA of the PVC and TiO_2 @PVC nanocomposite films.

aromatization, producing a wide range of hydrocarbons, such as benzene, toluene and xylene.²³

TGA of the TiO_2 @PVC nanocomposite films also showed a similar weight loss pattern to that observed in the case of PVC. The temperature ranges for the second and third weight loss shifted from 270 to 275°C and 400 to 420°C, and a higher residue was obtained at 800°C, suggesting that TiO_2 @PVC has higher thermal stability through the incorporation of TiO_2 . A possible reason for the enhanced stability

may be the stabilizing interactions between TiO_2 with PVC.

The activation energy (E_a) for the thermal degradation of the nanocomposite and pure PVC was evaluated using the well known integral method reported by Broido^{24,25}

$$\ln \left(\ln \left(\frac{1}{Y} \right) \right) = \frac{-E_a}{RT} + C, \quad (3)$$

$$Y = \frac{W_T - W_\infty}{W_0 - W_\infty}, \quad (4)$$

where Y is the fraction of the samples not yet decomposed, W_0 and W_∞ the initial and final weights, respectively, and W_T the weight at a particular temperature. The plots (as shown in figure 5) of $\ln(\ln(1/Y))$ vs. $1000/T$ (K^{-1}) followed a straight line, whose slope gave the activation energy for the degradation process. The activation energies of PVC and TiO_2 @PVC nanocomposites were 35.8 and 33.6 kJ mol^{-1} , respectively, indicating low thermal stability for TiO_2 @PVC nanocomposites when compared with pure PVC, contradicting the high thermal stability of TiO_2 @PVC nanocomposites obtained experimentally from TGA curve (figure 4). The possible reason for this contradiction in thermal stability behaviour may be attributed to inefficacy and limitation of

Figure 5. Plot of $\ln(\ln(1/Y))$ vs. $1000/T$ (K⁻¹) to estimate the activation energy for thermal degradation of (a) PVC and (b) TiO₂@PVC-5% nanocomposite films.

Figure 6. Plot of relative weight loss vs. temperature of PVC and TiO₂@PVC nanocomposite film.

Broido's integral method to obtain the activation energies neglecting actual kinetics for thermal degradation and calculating activation energies by a simplified model. A worker⁷ also reported a similar decrease in the activation energy after the incorporation of TiO₂ in their *p*TSA-doped TiO₂@PANI nanocomposite.

The relative weight loss rate of PVC and TiO₂@PVC was also plotted as a function of temperature, as shown in figure 6. The curve clearly revealed three distinct regions for the degradation of PVC and the TiO₂@PVC nanocomposites. In the second weight loss region, the degradation reached a maximum at ~295 and ~310°C for the PVC and TiO₂@PVC nanocomposites, respectively. Supplementary figure S2 shows the heat flow vs. temperature plot for PVC and TiO₂@PVC nanocomposites.

3.4 FTIR analysis

Figure 7 shows the FTIR spectra of PVC and TiO₂@PVC nanocomposite. In the case of pure PVC (figure 7), absorption bands were observed at 611, 964, 1251, 1631 and 2913 cm⁻¹.²⁶ Supplementary table S2 provides details of the characteristic absorption bands of pure PVC. In the case of TiO₂ nanoparticles, the band at approximately 1630 cm⁻¹ corresponds to the H–O–H bending vibration, whereas that at 657 cm⁻¹ was assigned to Ti–O–Ti stretching vibrations. As expected, the FTIR spectrum of the TiO₂@PVC nanocomposite was found to be an admixture

Figure 7. FTIR spectra of PVC, TiO₂ and TiO₂@PVC nanocomposite film.

of both PVC and TiO₂ nanoparticles with the presence of most of the absorption bands of both materials. Interestingly, there was no shift in the bands of TiO₂@PVC nanocomposite compared with the pure PVC spectrum, suggesting no (or almost negligible covalent or co-ordinate interaction) interactions between the TiO₂ nanoparticles and pure PVC in terms of chemical bonding.

3.5 Optical property analysis

Figure 8 shows the UV–vis–NIR spectrophotometry measurements of TiO₂@PVC nanocomposite and pure TiO₂. Figure 8a shows the spectral variation of reflectance (*R*) graphs of the TiO₂@PVC nanocomposite and pure TiO₂. In both cases, the strong absorption edge, which corresponds to the near-band-edge emission, was less than 400 nm and typical of anatase TiO₂. Similar findings in gallium-doped anatase TiO₂ used for the degradation of organic dyes also reported.^{27,28} Figure 8b presents the visible part of the reflectance spectra, which shows that pure TiO₂, there was almost no absorption in the visible region, whereas for the TiO₂@PVC nanocomposite film some visible radiation was absorbed. This is mainly due to the PVC matrix that absorbs and scatters the incident radiation significantly.

To determine the band gap of pure TiO₂ nanoparticles and TiO₂@PVC nanocomposites, an approximate relationship

Figure 8. (a) Plot of the reflectance vs. wavelength for TiO₂ nanoparticle and TiO₂@PVC nanocomposite film, (b) the visible part of the reflectance spectrum, (c) direct band gap calculation for TiO₂ and TiO₂@PVC nanocomposite film and (d) indirect band gap calculation for TiO₂ and TiO₂@PVC nanocomposite film.

between the reflectance (R), absorption coefficient (α), and scattering coefficient (s), based on Kubelka–Munk theory, was adopted, assuming no transmission within the nanomaterials because of the use of a sub-mm thick film for the nanocomposite and mm-thick powdered pellets for pure TiO₂ nanoparticles²⁹

$$\alpha = \frac{s}{2} \left(\frac{[1 - R]^2}{R} \right). \quad (5)$$

Although both α and s are functions of the energy of incident radiation ($h\nu$), s is far less wavelength dependent than α at the region of strong absorption (supplementary figure S3). Therefore, s can be considered a constant at the onset of the absorption edge. The band gap of TiO₂@PVC nanocomposite was determined from the absorption coefficient (α) according to the following equation:³⁰

$$(\alpha h\nu)^{1/x} = A (h\nu - E_g). \quad (6)$$

This equation was formularized by the relation for the parabolic bands at the onset of absorption edge, where $h\nu$ is the incident photon energy, A is a constant relative to the material, and x is an exponent that depends on the type of transition. In the case of a direct allowed transition, indirect allowed transition and direct forbidden transition, $x = 1/2$, 2 and 3/2, respectively. The band gap was determined by a plot between $(\alpha h\nu)^{1/x}$ and $h\nu$ at approximately the fundamental absorption region (figure 8c and d).

Figure 8c shows the direct band gap calculation for the TiO₂ and TiO₂@PVC nanocomposite. The obtained direct band gap for TiO₂ and TiO₂@PVC nanocomposite were 3.54 and 3.40 eV, respectively. In general, there is some controversy over the exact band gap transition (direct or indirect) within anatase TiO₂, where many workers predicted an indirect transition.³¹ On the other hand, some have also reported a direct band gap transition within anatase TiO₂ nanoparticles.^{27,28,32} In either case, the reported band gap of anatase TiO₂ falls within the range of 2.86–3.34 eV.³¹ Therefore, the calculated direct band gap in the present case (3.54 eV for TiO₂ and 3.40 eV for TiO₂@PVC) was much higher than the reported values, and does not appear to be feasible.³¹ Therefore, the indirect band gap calculation was performed (cf. figure 8d), which gave band gaps for TiO₂ and the TiO₂@PVC nanocomposite of 3.16 and 2.94 eV, respectively. The indirect band gap obtained fell within the expected range, which is in agreement with the reported literature value of 3.23 eV.³³ Therefore, in the present case, TiO₂ and TiO₂@PVC nanocomposite possess indirect-type band gap. In addition, the decrease in the band gap for TiO₂@PVC (~2.94 eV) compared with pure TiO₂ (~3.16 eV) is believed to be due to the generation of strain within the nanocomposite, as observed by XRD. The well-known band gap modification *via* the size effect, which is often found in the semiconductor nanostructure,^{27,28} was discarded in the present case, because there was no significant change in the

mean particle size between the pure TiO₂ nanoparticles and TiO₂@PVC nanocomposites (cf. figure 3). Therefore, the strain-induced band-structure modification is believed to be a possible reason for the band gap reduction of TiO₂@PVC. Previously, a researcher¹⁷ predicted the band gap reduction in layered-structured anatase TiO₂ through the induction of stress along a soft direction perpendicular to the lattice plane. This paper already discussed that within TiO₂@PVC nanocomposite film, excess strain is generated within the TiO₂ nanocrystals (with respect to pure TiO₂ nanoparticles) due to the presence of a PVC matrix that inhibits the growth of the TiO₂ crystals within the nanocomposite. Therefore, this strain-induced band gap reduction cannot be excluded in the current case.

3.6 Mechanical analysis

The incorporation of TiO₂ in the PVC matrix would strengthen the mechanical properties of PVC (supplementary table S3), because of the good dispersion and strong interfacial adhesion. The mechanical performance of the TiO₂@PVC nanocomposite film was significantly higher than that of pure PVC. Young's modulus also improved with the increase in TiO₂ weight percentage (figure 9). The enhancement in the modulus might be attributed to the resistance to segmental movement of the polymer chains offered by the presence of TiO₂ molecules within the PVC matrix. For the nanocomposite film with a 10 wt% TiO₂ loading, Young's modulus increased to 841.77 MPa, corresponding to a 45% increase (relative to the pure PVC film).

Figure 10 shows the percentage elongation at break. The addition of TiO₂ has a significant effect on the mechanical behavior of the PVC. The mean percentage elongation decreased to 90% for a 5 wt% TiO₂ loading from 159% for the pure PVC film. On the other hand, a further increase in the TiO₂ loading reduced the percentage elongation before fracture (figure 10). This can be attributed to the interaction between TiO₂ and the polymer matrix, which restricts movement of the polymer chains.³⁴

Figure 9. Calculated Young's modulus of the elastic region with different TiO₂ weight% in TiO₂@PVC nanocomposite film.

Figure 10. Elongation (%) with a TiO₂ weight% in the TiO₂@PVC nanocomposite film.

Figure 11. Tensile strength of the TiO₂@PVC nanocomposite film with different TiO₂ loadings.

Figure 11 shows the tensile strength. The tensile strength increased with the increase in TiO₂ content. The mean tensile strength of pure PVC film was 20.26 MPa. The strength increased gradually to 29.56 MPa for a 5 wt% TiO₂ loading and further to 40.52 MPa for a 10 wt% TiO₂ loading, which corresponds to 100% improvement. Supplementary figure S4 shows stress vs. strain curve for PVC TiO₂@PVC nanocomposites.

4. Conclusions

TiO₂@PVC nanocomposites were synthesized using the solution casting technique and characterized. The thermo-optical and mechanical behaviours of the nanocomposite film were also examined. The TiO₂@PVC nanocomposite film compared with pure TiO₂ showed a lower band gap for the anatase due to the generation of strain within the nanocomposite, which might find interesting applications in visible-light-induced photocatalytic activities. Moreover, the nanocomposite film compared with pure PVC showed more stability towards thermal degradation as well as more robustness towards the mechanical strength. Owing to its better optical, thermal and mechanical performance, this nanocomposite material is expected to find suitable roles for

a range of practical applications, such as photodegradation and construction.

Acknowledgement

This work was supported by Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2014R1A6A1031189).

Electronic Supplementary Material

Supplementary material pertaining to this article is available on the Bulletin of Materials Science website (www.ias.ac.in/matursci).

References

- Wang C, Cheng R, Liao L and Duan X 2013 *Nanotoday* **8** 514
- Zuo J, Wang Y and Chung T S 2013 *J. Membr. Sci.* **433** 60
- Rezwan K, Chen Q Z, Blaker J J and Boccaccini A R 2006 *Biomaterials* **27** 3413
- Abdal-hay A, Dewidar M, Lim J and Lim J K 2014 *Ceram. Int.* **40** 2237
- Mills A and Hunte S A 1997 *J. Photochem. Photobiol. A: Chem.* **108** 1
- Banerjee A N 2011 *Nanotechnol. Sci. Appl.* **4** 35
- Ansari M O and Mohammad F 2011 *Sens. Actuators B* **157** 122
- Irimpan L, Krishnan B, Nampoore V P N and Radhakrishnan P 2008 *J. Colloid. Interface Sci.* **324** 99
- Kun R, Mogyrosi K and Dekany I 2006 *Appl. Clay Sci.* **32** 99
- Hakkarainen M 2003 *Polym. Degrad. Stabil.* **80** 451
- Real L P and Gardette J 2001 *Polym. Test.* **20** 789
- Yang C and Wu G M 2009 *Mater. Chem. Phys.* **114** 948
- Liu F, Liu H, Li X, Zhao H, Zhu D, Zheng Y and Li C 2012 *Appl. Surf. Sci.* **258** 4667
- Yoo H and Kwak S 2011 *Appl. Catal. B: Environ.* **104** 193
- Yang C, Gong C, Peng T, Deng K and Zan L 2010 *J. Hazard. Mater.* **178** 152
- Zaleska A 2008 *Rec. Patents Eng.* **2** 157
- Yin W J, Chen S, Yang J H, Gong X G, Yan Y and Wei S H 2010 *Appl. Phys. Lett.* **96** 221901
- Reddeppa N, Sharma A K, Rao V V R N and Chen W 2013 *Microelectron. Eng.* **112** 57
- Elashmawi I S, Hakeem N A, Marei L K and Hanna F F 2010 *Physica B: Condensed Matter* **405** 4163
- Spurr A R and Myers H 1957 *Anal. Chem.* **29** 760
- Cullity B D 1978 *Elements of X-ray diffraction* (CA: Addison-Wesley)
- Dobkowski Z 2006 *Polym. Degrad. Stabil.* **91** 488
- Xu Z P, Saha S K, Braterman P S and D'Souza N 2006 *Polym. Degrad. Stabil.* **91** 3237
- Rangraj A, Vangani V and Rakshit K 1997 *J. Appl. Polym. Sci.* **66** 45
- Abthagir P S, Saraswathi R and Sivakolunthu S 2004 *Thermochim. Acta* **411** 123
- Gregorio R Jr. and Capitao R C 2000 *J. Mater. Sci.* **35** 299
- Banerjee A N, Joo S W and Min B K 2012a *J. Nanomater.* **2012** 14
- Banerjee A N, Joo S and Min B 2012b *J. Appl. Phys.* **112** 114329
- Lindberg J D and Synder D G 1973 *Appl. Opt.* **12** 573
- Pankove J I 1971 *Optical process in semiconductors* (New Jersey: Printice-Hall)
- Valencia S, Marin J M and Restrepo G 2010 *Open Mater. Sci. J.* **4** 9
- Reddy K M, Manorama S V and Reddy A R 2003 *Mater. Chem. Phys.* **78** 239
- Welte A, Waldauf C, Brabec C and Wellmann P J 2008 *Thin Solid Films* **516** 7256
- Vadukumpully S, Paul J, Mahanta N and Valiyaveetti S 2011 *Carbon* **49** 198