

# Negative Air Ions Releasing Properties of Tourmaline Contained Ethylene Propylene Diene Terpolymer/Polypropylene Thermoplastic Elastomers

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Received 7 July 2007; accepted 9 July 2007

DOI 10.1002/app.27272

Published online 20 March 2008 in Wiley InterScience (www.interscience.wiley.com).

**ABSTRACT:** The releasing properties of negative air ions of tourmaline contained polypropylene (PP) and ethylene propylene diene terpolymer/polypropylene (EPDM/PP) composite films under varying testing conditions were investigated in this study. It is interesting to note that the  $C_{ion-}$  values of EPDM/PP/tourmaline specimens tested at varying conditions are significantly higher than those of the PP/tourmaline specimens with the same loadings of tourmaline powders. Moreover, all  $C_{ion-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens tested at dynamic impact mode are significantly higher than those of the corresponding specimens tested at static mode but the same temperature. A beneficial temperature effect on  $C_{ion-}$  values of the PP/tourmaline and EPDM/PP/tourmaline

film specimens tested at static and dynamic impact conditions was found. To understand these interesting negative air ion properties of PP/tourmaline and EPDM/PP/tourmaline film specimens, energy dispersive X-rays analysis of the tourmaline powders, scanning electron microscope morphology, and tensile property analysis of the PP/tourmaline and EPDM/PP/tourmaline film specimens were performed. Possible reasons account for the interesting negative air ion properties of the PP/tourmaline and EPDM/PP/tourmaline film specimens are discussed. © 2008 Wiley Periodicals, Inc. *J Appl Polym Sci* 109: 82–89, 2008

**Key words:** EPDM/PP/tourmaline film; dynamic impact mode; static mode

## INTRODUCTION

Tourmaline is a natural silicate mineral containing boron with a typical chemical formula of  $X_3Al_6(BO_3)_3Si_6O_{18}(OH)_4F_4$  ( $X = Li, Mg, Fe, etc.$ ).<sup>1</sup> The crystal bonds of tourmaline are mostly of ionic bonds, wherein the center of the ionic molecule at a lattice point of the crystal is fixed in a position apart from its "normal" position. In fact, the tourmaline crystals are present in a strained condition and maintain a pair of electrodes with no supply of external electric energy.<sup>2</sup> The polarization charge of the tourmaline crystal at room temperature is 5.34 V at a size of 20 mm, and a polarization charge of 2.34 V has been observed even at a size of 2 mm. Presumably, this is the reason why the tourmaline crystals are recognized as permanent electrodes that can

generate negative air ions without any ozone molecules, since the polarization charge is relatively low. In addition, it is worth noting that the efficiency of generating negative air ions of the tourmaline crystals can be improved significantly by increasing their ambient temperatures or pressures, since they are generally recognized as pyroelectric and piezoelectric materials. On the other hand, it was also reported that the tourmaline mineral can emit far-infrared light, deodorize, purify water, and serve as effective antibacterial agent.<sup>3–7</sup>

In view of the varying functional properties of tourmaline, investigations in preparing the new composite materials containing tourmaline capable of emitting negative air ions have drawn much attention for years. Many tourmaline-contained polymers were invented and filed as patents.<sup>2–4</sup> However, most tourmaline-contained polymer materials previously invented were fibrous products.<sup>2–4,8</sup> In our previous investigation,<sup>9</sup> the releasing properties of negative air ions of tourmaline contained polypropylene (PP) composite films under varying testing conditions were studied. It is interesting to note that the average concentrations of negative air ions ( $C_{ion-}$ ) emitted from PP/tourmaline film specimens

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Contract grant sponsor: National Science Council; contract grant numbers: NSC-92-2216-E-011-024, NSC-92-2622-E-002-014-cc3.

Contract grant sponsor: Taiwan Textile Research Industry.

*Journal of Applied Polymer Science*, Vol. 109, 82–89 (2008)

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tested at varying conditions reach a maximum value as the tourmaline contents present in PP/tourmaline film specimens approach the 5 wt % optimum value. Further morphology analysis of the PP/tourmaline film specimens indicates that significant aggregation of tourmaline powders start to occur as their contents are higher than 5 wt %. Presumably, the significantly reduced  $C_{ion-}$  values of PP/tourmaline film specimens with tourmaline contents more than 5 wt % is attributed to the aggregated tourmaline powders found at high tourmaline loadings, since the effective surface areas for generating negative air ions of tourmaline powders can be significantly reduced as the tourmaline powders are over-aggregated. Moreover, all  $C_{ion-}$  values of PP/tourmaline film specimens tested at dynamic impact mode are significantly higher than those of the corresponding specimens tested at static mode but the same temperature. In fact, the  $C_{ion-}$  value of the PP<sub>c5</sub> film specimens tested at 90°C and dynamic impact mode reaches about 300 particles/cc, which is about 10 times more than that of pure PP film specimen tested at 25°C and static mode. These interesting negative air ion properties are attributed to the pyroelectric and piezoelectric characteristics of the tourmaline powders present in PP/tourmaline film specimens, since the efficiency of generating negative air ions of the tourmaline crystals are expected to improve with the ambient temperatures or pressures.

Dynamically vulcanized elastomers display not only elastomeric but also thermoplastic characteristics. The blend of dynamically vulcanized ethylene-propylene-diene (EPDM)/polypropylene (PP) is one of the well known dynamically vulcanized elastomers that can be molded, shaped, and/or reprocessed at temperatures above the melting or softening temperatures of the thermoplastic resins. Owing to their excellent elastomeric properties and easiness of processing without time consuming cure step required for conventional vulcanizates, the dynamically vulcanized elastomers have been widely used as automobile parts (e.g., bumper covers, sealing strip, gaskets, interior automotive components), tubing, hose, treadmill, and sheath of cable for the last two decades.<sup>10</sup> In contrast to thermoplastic resins, the EPDM/PP dynamically vulcanized elastomer are often used under constrained conditions, such as, serving as the conveyors or other accessories equipped on the sport facilities. In addition, as described above, the tourmaline ores are generally recognized as piezoelectric materials. Under such circumstances, the tourmaline filled EPDM/PP elastomers are expected to release negative air ions more effectively than those tourmaline filled PP specimens prepared in our previous investigation.<sup>9</sup> However, even up to the present time, no investigation has

ever been reported on the preparation and negative air ions releasing properties of the tourmaline filled EPDM/PP and/or other dynamically vulcanized elastomers/PP resins.

The main object of this study is to investigate the influence of tourmaline contents and testing conditions on the active-ion emitting properties of the tourmaline contained EPDM/PP film specimens. The concentrations of negative air ions emitted from tourmaline contained EPDM/PP film specimens under "static" or "dynamic" impact conditions were investigated at varying temperatures. In comparison with tourmaline contained PP film specimens,  $C_{ion-}$  values of tourmaline contained EPDM/PP film specimens are significantly higher than those of the PP/tourmaline film specimens with the same tourmaline contents tested at same conditions. Possible underlying mechanisms accounting for the interesting negative air ion properties observed in this study are proposed.

## EXPERIMENTAL

### Materials and sample preparation

The EPDM/PP blends were prepared via reactive extrusion using a Nanjing Jiant SHJ-36 corotating twin screw extruder, wherein the length to diameter ratio of the screw is 40. The basic polymers used to prepare EPDM/PP thermoplastic elastomers are PP and EPDM with ethyldiene 2-norbonene resins, which were obtained from Taiwan PP and Dupont Corporation, respectively. Meanwhile, dimethylol phenolic resin (SP 1405) and SnCl<sub>2</sub> were respectively obtained from Schenectady International and Mallinckrodt Baker, which were used as curing agents and accelerators to vulcanize the EPDM in the reactive extrusion processes, respectively. Table I lists the key characteristics of the commercially available polymers and curing agents used in this work. For every 60 parts by weight of EPDM, 40 parts of PP resins were melt-blended twice to shear and disperse the EPDM resins in the twin screw extruder, wherein the extruder was operated at 185°C in the feeding zone and at 190°C towards the extrusion die

TABLE I  
Compositions of EPDM/PP/Tourmaline Resins

Samples	Tourmaline (wt %)	EPDM/PP(wt %)
EPDM/PP <sub>c0.5</sub>	0.5	99.5
EPDM/PP <sub>c1</sub>	1.0	99.0
EPDM/PP <sub>c3</sub>	3.0	97.0
EPDM/PP <sub>c5</sub>	5.0	95.0
EPDM/PP <sub>c10</sub>	10.0	90.0

**TABLE II**  
**The Average Particle Sizes of Tourmaline Powders Present in EPDM/PP/Tourmaline and PP/Tourmaline Film Specimens Evaluated by the Particle Image Processor**

Samples (compositions)	$d_{50}$ ( $\mu\text{m}$ )
Tourmaline	0.5
EPDM/PP <sub>c0.5</sub>	0.5
EPDM/PP <sub>c1</sub>	1.5
EPDM/PP <sub>c3</sub>	2.1
EPDM/PP <sub>c5</sub>	5.0
EPDM/PP <sub>c10</sub>	12.0
PP <sub>c0.5</sub>	1.0
PP <sub>c1</sub>	2.0
PP <sub>c3</sub>	4.0
PP <sub>c5</sub>	6.0
PP <sub>c10</sub>	15.0

with a constant screw speed of 115 rpm. The preblended EPDM/PP resins were then quenched in cold water at 25°C and cut into pellet form. The preblended EPDM/PP resins prepared by two times of preblending processes were then melt-blended with 10, 2, and 10 parts of dimethylol phenolic resin, SnCl<sub>2</sub>, and naphthenic process oil, respectively, for further dynamical vulcanization of the EPDM resin. During the dynamical vulcanization processes, the extruder was operated at the same conditions as those of the preblending process, respectively. The vulcanized EPDM/PP resins were then quenched in cold water at 25°C and cut into pellet form.

Before the preparation of tourmaline contained EPDM/PP resins, EPDM/PP/tourmaline master resins were first prepared by feeding the EPDM/PP resins and tourmaline powders into the twin-screw extruder at a weight ratio of 80 : 20. To adhere the tourmaline powders onto the surfaces of EPDM/PP resins, 1 g of naphthalene oil was mixed with 100 g of the mixtures of EPDM/PP and tourmaline powders before compounding. The extruder was operated at 185°C in the feeding zone and at 195°C towards the extrusion die with a screw speed of 115 rpm. The extruded master resins were then quenched in cold water at 25°C and cut into the pellet form. The tourmaline contained EPDM/PP resins were then prepared by melt-blending the EPDM/PP/tourmaline master resins with varying amounts of pure EPDM/PP resins in the twin-screw extruder, in which the same processing conditions mentioned above were used. For comparison purposes, the tourmaline contained PP resins were also prepared by blending PP resins with the PP/tourmaline master resins in the twin-screw extruder operated at the same conditions, wherein the PP/tourmaline master resins were also prepared by feeding the PP resins and tourmaline powders into the twin-screw extruder at a weight ratio of 80 : 20. Table II summar-

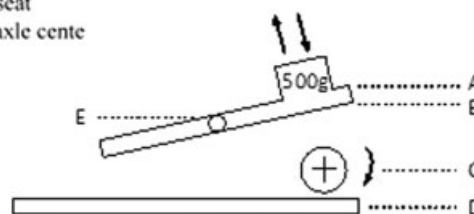
ized the compositions and specimen designations of the PP/tourmaline and EPDM/PP/tourmaline resins prepared above.

### Negative air ions analysis

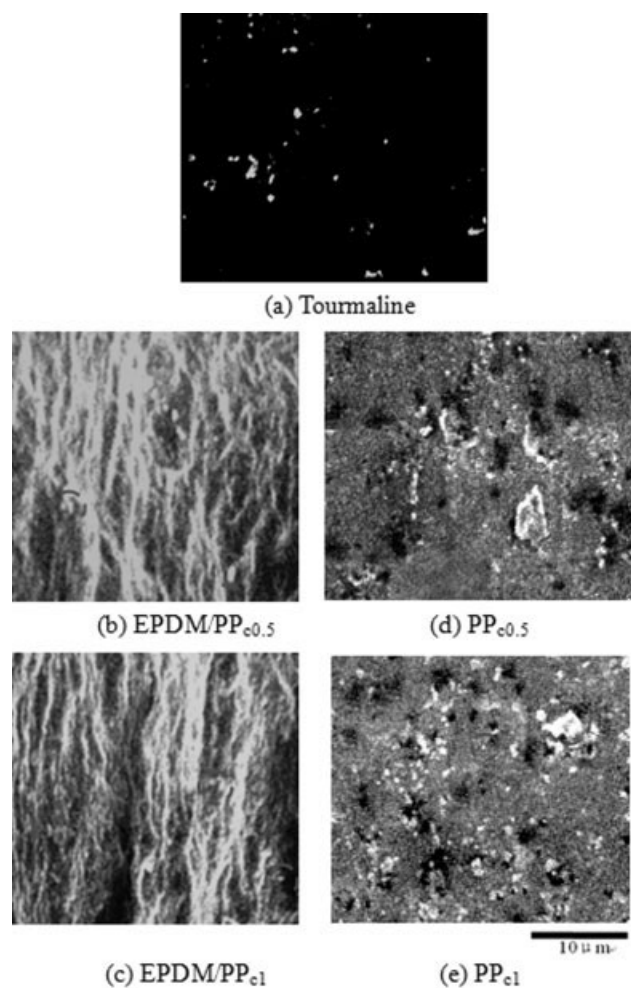
The film specimens used for negative air ion analysis were prepared by hot-pressing the PP/tourmaline and EPDM/PP/tourmaline resins prepared above at 180°C for 5 min. The hot-pressed film specimens were then cut into a dimension of 100 × 40 × 0.2 mm<sup>3</sup>, which are associated with a thickness of roughly 0.2 mm. The concentrations of negative air ions emitted from the PP/tourmaline and EPDM/PP/tourmaline film specimens were determined using an Andes air ion detector model INTI ITC-201A, which was purchased from Andes electrical corporation, Qingsen, Japan. Before negative air ion analysis, the PP/tourmaline and EPDM/PP/tourmaline film specimens were kept in a moisture regain box for 12 h, wherein the box was operated at 25°C and 40% relative humidity (RH). The concentrations of negative air ions emitted from EPDM/PP/tourmaline film specimens were then determined at 45% ± 5% RH and at temperatures ranging from 25 to 90°C. The average concentrations of negative air ions determined in the first minute were then used as the average concentrations of negative air ions emitted from PP/tourmaline and EPDM/PP/tourmaline film specimens in this study. Two types of testing methods were performed to determine the average concentrations of negative air ions emitted from the sectioned PP/tourmaline and EPDM/PP/tourmaline film specimens. In addition to the static method, the negative air ion concentrations of the film specimens were also detected under a "dynamic impact" mode. The dimensions of the "dynamic impact" instrument were described in our previous investigation and shown in Figure 1. During the testing, the film specimens were wrapped on the specimen holder and dynamically impacted by 500 g of loading at a frequency of 40 rpm. During the testing, the air ion detector was placed 10 cm above the film specimens.

#### Dynamic impact instrument

- A: the loading
- B: the lever arm
- C: the heating roller
- D: the seat
- E: the axle center



**Figure 1** Illustration of the dynamic impact instrument.



**Figure 2** SEM micrographs of the fracture surfaces of (a) pure tourmaline powders, (b) EPDM/PP<sub>c0.5</sub>, (c) EPDM/PP<sub>c1</sub>, (d) PP<sub>c0.5</sub>, (e) PP<sub>c1</sub> specimens. (The dot-lines circulate the tourmaline particles distributed in the specimens).

#### Morphology and surface composition analysis of PP/tourmaline and EPDM/tourmaline film specimens

To understand the distribution of tourmaline particles in the PP/tourmaline and EPDM/PP film specimens, the PP/tourmaline and EPDM/PP/tourmaline film specimens prepared in the previous section were observed using a HITACHI S-3000N scanning electron microscope (SEM). The specimens were gold-coated at 15 Kev for 30 s before SEM examinations. The particle sizes and distribution of the tourmaline powders present in the tourmaline contained film specimens were determined using an optical microscope equipped with a Winner 99 micro particle image processor, which was purchased from Jinan winner instruments Corporation, Jinan, China. On the other hand, the compositions on the surface of the film specimens were determined with a Siemens D5000S energy dispersive X-rays (EDX) equipped on the scanning electron microscope described above.

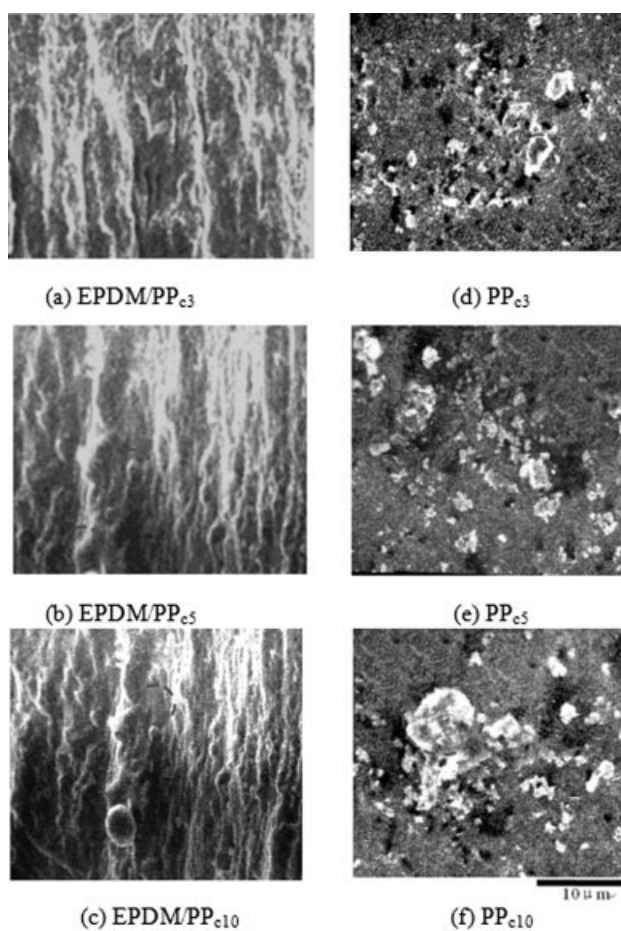
#### Mechanical property measurements

The tensile properties of the unvulcanized and vulcanized EPDM/PP and EPDM/PP/tourmaline film specimens were determined using a Hungta Instron testing machine model HT-9112 at 25°C and a cross-head speed of 100 mm/min. A 35-mm gauge length was used during each tensile experiment. The dimensions of the dog-bone shaped specimens were prepared according to ASTM D638 Type IV standard. The values of tensile strength and elongation at break were obtained based on the average tensile results of at least five tensile specimens.

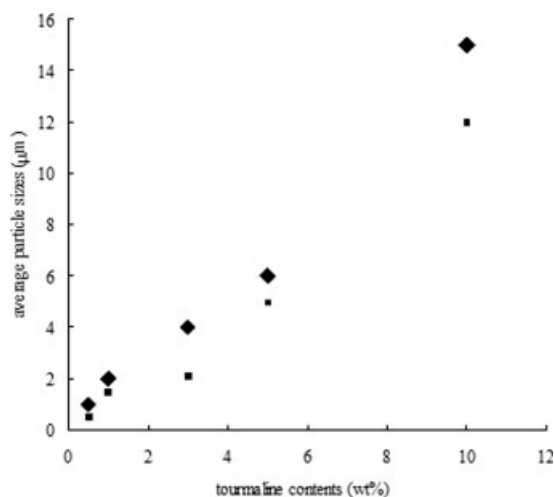
## RESULTS AND DISCUSSION

#### Morphology and surface composition analysis

Typical SEM micrographs of the fracture surfaces of PP/tourmaline and EPDM/PP/tourmaline film specimens are summarized in Figure 2(a–e) and Figure 3(a–e), respectively. As shown in Figure 2(a) and/or Figure 3(a), the average diameter of the orig-



**Figure 3** SEM micrographs of the fracture surfaces of (a) EPDM/PP<sub>c3</sub>, (b) EPDM/PP<sub>c5</sub>, (c) EPDM/PP<sub>c10</sub>, (d) PP<sub>c3</sub>, (e) PP<sub>c5</sub>, and (f) PP<sub>c10</sub> specimens. (The dot-lines circulate the tourmaline particles distributed in the specimens).



**Figure 4** The average particle sizes of tourmaline powders Present PP/tourmaline (■) and EPDM/PP/tourmaline (□) film specimens evaluated by the particle image processor.

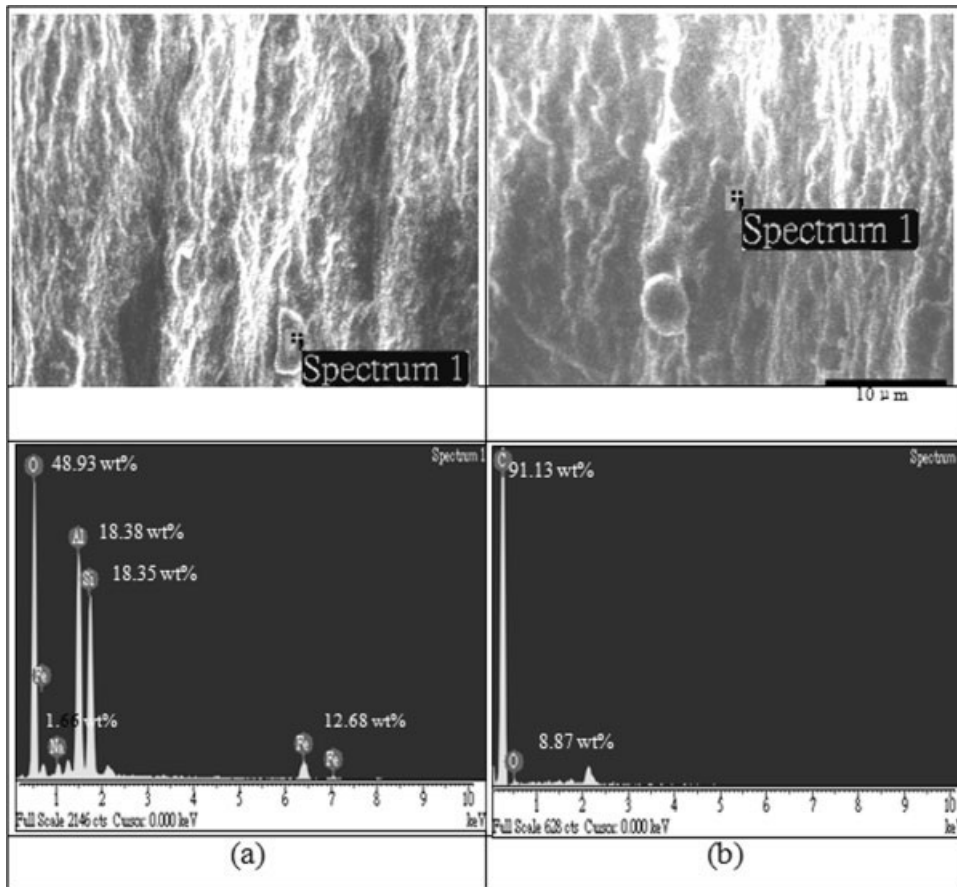
inal tourmaline powders is about 0.5  $\mu\text{m}$  with relatively small size distribution. Apparently, some of the tourmaline powders significantly coagulated during the preparation processes of PP/tourmaline and EPDM/PP/tourmaline film specimens. As shown in Figure 4, the average particle sizes of tourmaline powders of PP/tourmaline and EPDM/PP/tourmaline film specimens evaluated by particle image processor increase slightly from 1 to 5  $\mu\text{m}$  and from 0.5 to 3  $\mu\text{m}$ , respectively. As their tourmaline contents increase from 0.5 to 5 wt %. However, the average particle sizes of the tourmaline powders present in PP/tourmaline and EPDM/PP/tourmaline specimens start to aggregate rapidly as their tourmaline contents are higher than 5 and 3 wt %, respectively. As shown in Figure 4, the average particle sizes of tourmaline powders increase significantly from 5 to 15  $\mu\text{m}$  and 3 to 12  $\mu\text{m}$ , as the tourmaline contents of PP/tourmaline and EPDM/PP/tourmaline film specimens increase from 5 and 3 to 10 wt %, respectively. These results clearly suggest that, at tourmaline contents lower than 5 and 3 wt %, the tourmaline powders can be relatively well dispersed in PP and EPDM/PP matrices by melt blending, respectively. However, significant aggregation of the tourmaline powders start to occur as their contents are higher than 5 and 3 wt %. Presumably, these significantly aggregated tourmaline particles can significantly reduce their effective surface areas for emitting negative air ions at high tourmaline loadings. Figure 5 summarizes the EDX analysis of the compositions of tourmaline particles on the surface of PP/tourmaline and EPDM/PP/tourmaline film specimens. As shown in Figure 5(a), similar to those found in other investigation,<sup>11</sup> the aggregated tour-

maline particles present on the surfaces of EPDM/PP/tourmaline film specimens are composed of O, Al, Si, Fe, and Na elements. More than 98 wt % of the tourmaline powders are composed of O, Al, Si, and Fe elements.

It is not completely clear what accounts for these interesting morphology properties observed for PP/tourmaline and EPDM/PP/tourmaline specimens. However, it is generally recognized that the tourmaline powders can only be dispersed into PP matrices of EPDM/PP specimens, since the vulcanized EPDM phase cannot be melted and/or be barely melted again during the melt-blending processes of tourmaline powders and EPDM/PP resins. Under such circumstances, tourmaline powders are mostly expelled by EPDM vulcanizates into the melting fronts of PP and dispersed in PP and/or the interfacial areas between EPDM and PP matrices during the melt-blending processes. The amounts of tourmaline powders needed to be well dispersed in PP matrices of EPDM/PP/tourmaline specimens are expected to be significantly smaller than those needed in PP/tourmaline specimens. On the basis of these premises, it is reasonable to believe that the optimum tourmaline content of EPDM/PP/tourmaline specimens is significantly lower than that of the PP/tourmaline specimens (i.e., 3 vs. 5 wt %).

### Negative air ions releasing properties

Figures 6 and 7 summarized the average concentrations of negative air ions ( $C_{\text{ion}^-}$ ) emitted from PP, EPDM/PP, PP/tourmaline, and EPDM/PP/tourmaline film specimens tested at varying conditions, respectively. As shown in Figure 6, only about 30 particles/cc of negative air ions were emitted from the pure PP and EPDM/PP film specimen respectively tested at static mode and 25°C. After blending tourmaline powders in PP and EPDM/PP resins, the  $C_{\text{ion}^-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens increase significantly with the increasing tourmaline contents. In fact, it is worth noting that the  $C_{\text{ion}^-}$  values of EPDM/PP/tourmaline specimens are significantly higher than those of the PP/tourmaline specimens with the same loadings of tourmaline powders. The  $C_{\text{ion}^-}$  values of PP/tourmaline film specimens reach the maximum as their tourmaline contents approach the optimum value of 5 wt %. In contrast, the optimum tourmaline content of EPDM/PP/tourmaline film specimens is only 3 wt %. As shown in Figure 6, the  $C_{\text{ion}^-}$  values of PP<sub>c5</sub> and EPDM/PP<sub>c3</sub> specimens reach the maximum values at about 130 and 230 particles/cc, which is four and five times more than those of the pure PP and EPDM/PP specimens tested under static mode and at 25°C respectively. At tourmaline loadings higher than 5 and 3 wt %,

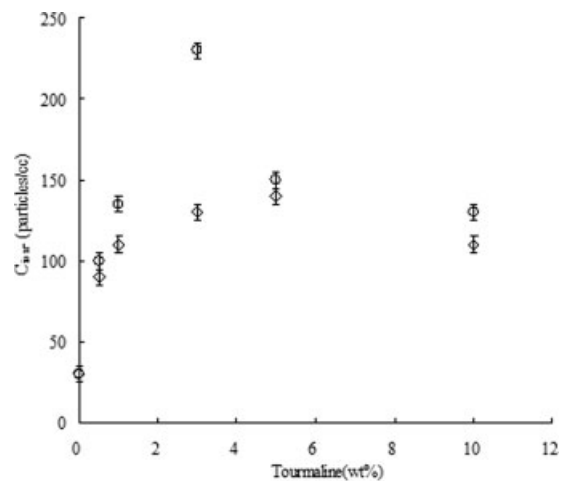


**Figure 5** The morphology of the EPDM/PP/tourmaline film specimen (b) EDX showing spectrum 1 on elemental composition information of the tourmaline particle present in (a).

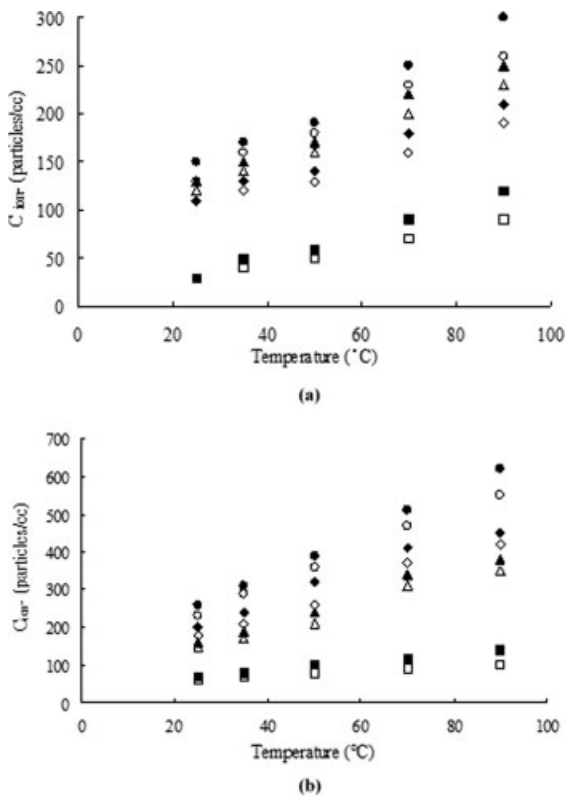
the  $C_{ion-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens reduce significantly with further increase in tourmaline contents, respectively.

The  $C_{ion-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens tested at varying temperatures and testing modes (i.e., static and dynamic impact) are summarized in Figure 7. The  $C_{ion-}$  values increase significantly as the testing temperatures of PP/tourmaline and EPDM/PP/tourmaline film specimens increase from 25 to 95°C. For example, the  $C_{ion-}$  values of PP<sub>c5</sub> and EPDM/PP<sub>c3</sub> film specimen tested at static mode increase from 130 to 260 particles/cc and 230 to 550 particles /cc as the temperatures increase from 25 to 90°C. On the other hand, it is interesting to note that the  $C_{ion-}$  values of all PP/tourmaline and EPDM/PP film specimens tested at dynamic impact mode are significantly higher than those of the same specimens tested at static mode but the same temperature (see Fig. 7). For instance, the  $C_{ion-}$  value of PP<sub>c5</sub> and EPDM/PP<sub>c3</sub> film specimen tested at dynamic impact mode and 90°C reaches near 300 and 620 particles/cc, respectively, which are two times more than those of the PP<sub>c5</sub> and EPDM/PP<sub>c3</sub> film specimens tested at dynamic impact mode and 25°C, respectively. Pre-

sumably, these interesting negative air ion properties of PP/tourmaline and EPDM/PP/tourmaline film specimens are attributed to the pyroelectric and pie-



**Figure 6** Average concentrations of negative air ions ( $C_{ion-}$ ) emitted from EPDM/PP/tourmalines (O) and PP/tourmaline film specimens ( $\square$ ) with varying contents of tourmaline powders at 25°C. (Error bars of the negative air ions tests are indicated).



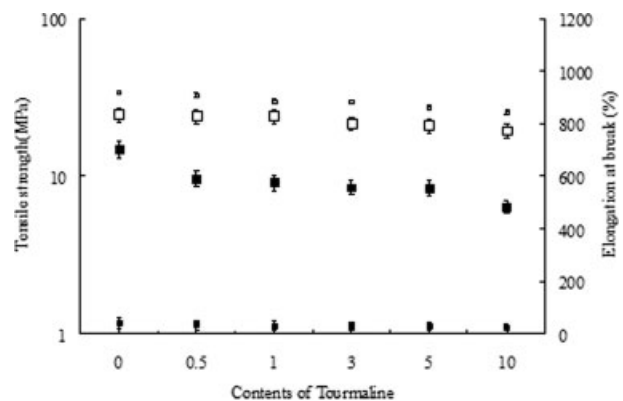
**Figure 7** Average concentrations of negative air ions ( $C_{ion-}$ ) emitted from (a) PP ( $\square$ ,  $\blacksquare$ ), PP<sub>c1</sub> ( $\diamond$ ,  $\blacklozenge$ ), PP<sub>c5</sub> ( $\circ$ ,  $\bullet$ ), and PP<sub>c10</sub> ( $\triangle$ ,  $\blacktriangle$ ); (b) EPDM/PP ( $\square$ ,  $\blacksquare$ ), EPDM/PP<sub>c1</sub> ( $\diamond$ ,  $\blacklozenge$ ), and EPDM/PP<sub>c3</sub> ( $\circ$ ,  $\bullet$ ), EPDM/PP<sub>c10</sub> ( $\triangle$ ,  $\blacktriangle$ ) film specimens tested under static and dynamic impact modes and at varying temperatures. (Hollow and solid symbols represent specimens tested under static and dynamic impact modes, respectively.)

zoelectric characteristics of the tourmaline powders present in the film specimens, since the efficiency of releasing negative air ions of the tourmaline crystals are expected to improve with the ambient temperatures or pressures. On the other hand, as mentioned previously, the tourmaline dispersed PP phases are not miscible and are expelled by the EPDM vulcanizates during the melt-blending processes of EPDM/PP/tourmaline resins. Presumably, certain degrees of residual strains can be present between the interfacial regions of tourmaline dispersed PP and EPDM phases. Under such circumstances, the tourmaline powders dispersed in PP phases of EPDM/PP/tourmaline film specimens are expected to confront with higher degrees of deformation and/or piezoelectric effect than those tourmaline particles dispersed in PP/tourmaline film specimens with the same tourmaline loadings. On the basis of these premises, it is reasonable to understand that at the same testing condition, the  $C_{ion-}$  values of EPDM/PP/tourmaline specimens are always higher than those of the PP/tourmaline specimens with the same loadings of tourmaline powders.

## Mechanical properties

Figure 8 displays the tensile properties of PP/tourmaline and EPDM/PP/tourmaline film specimens, respectively. Both values of tensile strengths ( $\sigma_f$ ) and elongation at break ( $\epsilon_f$ ) of PP/tourmaline and EPDM/PP/tourmaline specimens reduce significantly as their tourmaline contents increase, respectively. On the other hand, it is interesting to note that EPDM/PP/tourmaline film specimens exhibit significantly higher  $\epsilon_f$  but slightly lower  $\sigma_f$  values than the PP/tourmaline film specimens with the same tourmaline contents. As shown in Figure 8, the  $\epsilon_f$  values of EPDM/PP/tourmaline film specimens only reduce from 589.0 to 484.5% and 35.0 to 25.0% as their tourmaline contents increase from 0.5 to 10 wt %, respectively. However, the  $\epsilon_f$  values of PP/tourmaline film specimens are only 35.0 and 25.0% as their tourmaline contents remain at 0.5 and 10 wt %, respectively.

Presumably, during the tensile experiments of EPDM/PP/tourmaline specimens, the presence of tourmaline particles can cause "stress concentration" and "early breakage of EPDM/PP molecules" at the boundaries between tourmaline powders and the EPDM/PP resins, since the interfacial adhesion between the tourmaline powders and EPDM/PP resins is poor. The degree of stress concentration is expected to increase as the filler loadings increase. It is, therefore, reasonable to understand that the  $\sigma_f$  and  $\epsilon_f$  values of the EPDM/PP/tourmaline samples continue to reduce with increasing the tourmaline particles contents. On the other hand, the presence of EPDM phases can significantly improve the flexibility of EPDM/PP/tourmaline film specimens, since the EPDM phases can be easily deformed under relatively low loadings. Under such circumstance, the



**Figure 8** The values of tensile strength ( $\square$ ) and elongation at break ( $\blacksquare$ ) of PP/tourmaline and EPDM/PP/tourmaline film specimens. (Large hollow and solid symbols represent the tensile strength and elongation at break of EPDM/PP/tourmaline film specimens, respectively.) (Error bars of the mechanical tests are indicated).

tourmaline powders present in the interfacial regions of EPDM/PP phases are likely deformed to higher degrees than those present in the PP/tourmaline specimens. It is, therefore, reasonable to believe that EPDM/PP/tourmaline film specimens can emit higher  $C_{ion-}$  values than PP/tourmaline film specimens with the same tourmaline content and tested at the same condition.

### CONCLUSIONS

The  $C_{ion-}$  values of pure PP and EPDM/PP film specimens, respectively, tested at 25°C and static mode are only about 30 particles/cc. After blending tourmaline powders, the efficiency of generating negative air ions of PP/tourmaline and EPDM/PP/tourmaline film specimens improves significantly. The  $C_{ion-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens tested at varying conditions increase initially with the increasing tourmaline contents, and reach a maximum value as their tourmaline contents approach the 5 and 3 wt % optimum value, respectively. Further morphology analysis of the PP/tourmaline and EPDM/PP/tourmaline film specimens indicates that significant aggregation of tourmaline powders start to occur as their contents are higher than 5 and 3 wt %. Presumably, the significantly reduced  $C_{ion-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens with tourmaline contents more than 5 and 3 wt % are attributed to the aggregated tourmaline powders found at high tourmaline loadings, since the effective surface areas for generating negative air ions of tourmaline powders can be significantly reduced as the tourmaline powders are over-aggregated. Moreover, all  $C_{ion-}$  values of PP/tourmaline and EPDM/PP/tourmaline film specimens tested at dynamic impact mode are significantly higher than those of the corresponding specimens tested at static mode but the same temperature. In fact, the  $C_{ion-}$  value of the PP<sub>c5</sub> and EPDM/PP<sub>c3</sub> film specimens tested at 90°C and dynamic impact mode reaches about 300 and 620 particles/cc, which is about 10 and 20 times more than that of pure PP and EPDM/PP film specimen tested at 25°C and static mode. Presumably, these interesting negative air ions are attributed to the pyroelectric and piezoelectric characteristics of the tourmaline powders present in PP/tourmaline

and EPDM/PP/tourmaline film specimens, respectively, since the efficiency of generating negative air ions of the tourmaline crystals are expected to improve with the ambient temperatures or pressures. On the other hand, as mentioned previously, the tourmaline dispersed PP phases are not miscible, and are expelled by the EPDM vulcanizates during the melt-blending processes of EPDM/PP/tourmaline resins. Presumably, certain degrees of residual strains can be present between the interfacial regions of tourmaline dispersed PP and EPDM phases. Under such circumstances, the tourmaline powders dispersed in PP phases of EPDM/PP/tourmaline film specimens are expected to confront with higher degrees of deformation and/or piezoelectric effect than those tourmaline particles dispersed in PP/tourmaline film specimens with the same tourmaline loadings. On the basis of these premises, it is reasonable to understand that at the same testing condition, the  $C_{ion-}$  values of EPDM/PP/tourmaline specimens are always higher than those of the PP/tourmaline specimens with the same loadings of tourmaline powders.

Moreover, the tensile strength and elongation of PP/tourmaline and EPDM/PP/tourmaline film specimens at break decreased rapidly as their tourmaline contents increase, respectively. Presumably, the presence of tourmaline powders can cause "stress concentration" and "early breakage of polymer molecules" at the boundaries between tourmaline powders and the resins.

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