Materials Research Express

PAPER

Application of β-diketone boron complex as an ultraviolet absorber in polyvinyl chloride film

Xiaohong Ma¹, Huazhi Gao¹, Yunhua Lu¹, Xingliang Liu¹, Li Dang¹ and Shiai Xu¹ ²

¹ School of Chemical Engineering, Qinghai University, Xining, 810016, People’s Republic of China
² Shanghai Key Laboratory of Advanced Polymeric Materials, Key Laboratory for Ultraline Materials of Ministry of Education, School of Materials Science and Engineering, East China University of Science and Technology, Shanghai, 200037, People’s Republic of China

E-mail: saxu@ecust.edu.cn

Keywords: polyvinyl chloride, β-diketone boron complex, UV absorber, UV aging

Abstract

In this paper, β-diketone boron complex (BF₂-TPE) was first used as an ultraviolet (UV) absorber for polyvinyl chloride (PVC), and then a series of PVC/BF₂-TPE composite films were prepared by solvent casting method. UV accelerated aging experiment was conducted to evaluate the effect of BF₂-TPE on the photooxidative degradation of PVC, the structure and properties of the composite films in the UV aging process were characterized by ultraviolet-visible absorption spectroscopy, Fourier transform infrared spectroscopy, scanning electron microscopy, thermogravimetric analysis, dynamic mechanical analysis and mechanical property analysis. The results show that BF₂-TPE can absorb UV light in the wavelength range of 220–450 nm. The yield strength of the PVC/BF₂-TPE composite film with 0.5% BF₂-TPE (PVC/BF₂-TPE0.5) decreases from 10.5 MPa to 7.8 MPa after 1200 h of UV irradiation, and its retention ratio is much higher compared with that of pure PVC film, indicating that BF₂-TPE can inhibit the photooxidative degradation PVC. The PVC/BF₂-TPE0.5 composite film shows higher temperature of onset decomposition, indicating that BF₂-TPE can also enhance the thermal stability of PVC/BF₂-TPE composite films.

1. Introduction

Polyvinyl chloride (PVC) is used in various fields because of its good chemical stability, excellent mechanical properties and low cost [1–3]. PVC can be divided into hard and soft products according to the content of plasticizer [4]. Hard PVC is mainly used in the production of pipes, while soft PVC is mainly used in the production of wires, cables and daily products. However, exposure of PVC products to sunlight can cause photooxidative degradation and thus reduce their outdoor service life [5]. One of the most effective methods to inhibit the photooxidative degradation of PVC is to add inorganic or organic light stabilizers into PVC matrix [6]. Unfortunately, most of the inorganic light stabilizers are pigments with strong coloring properties, making them unsuitable for application in transparent materials [7], while organic ones have the disadvantages of high mobility and easy extraction by solvents [8]. Therefore, it is necessary to synthesize new light stabilizers to improve the anti UV aging performance of PVC.

β-diketone boron complex (BF₂-TPE) is widely used in memory chips and light-emitting devices due to aggregation induced luminescence and suppressed fluorescence discoloration properties [9]. β-diketone compounds can also be used as ultraviolet (UV) absorbers due to their optical tautomerism [10]. Therefore, the addition of BF₂-TPE as an UV absorber to PVC is expected to improve the UV aging resistance of PVC.

In this study, BF₂-TPE is first used as an UV absorber for PVC. BF₂-TPE was synthesized according to the procedures described previously [9], and its chemical structure is shown in scheme 1. A series of PVC/BF₂-TPE composite films were prepared by solvent casting method, and UV accelerated aging experiment was performed in a UV test chamber for 1200 h. Changes in the microscopic morphology and physical properties of these PVC/BF₂-TPE composite films were characterized by ultraviolet-visible (UV–vis) absorption spectroscopy, Fourier transform infrared (FTIR) spectroscopy, thermogravimetric analysis and dynamic mechanical analysis;
while changes in the macroscopic properties were characterized by scanning electron microscopy (SEM) and mechanical property analysis.

2. Experimental

2.1. Materials

PVC (SG-5) was provided by Inner Mongolia Wuhai Chemical Co., Ltd (Inner Mongolia, China). Tetrahydrofuran (THF, analytically pure) was supplied by Tianjin Fuyu Fine Chemical Co., Ltd (Tianjin, China). Deionized water was produced using an AXLK1820-2 water purifier (Asura Chongqing Technology Development Co., Ltd, Chongqing, China).

2.2. Preparation of PVC/BF₂-TPE composite films

PVC and BF₂-TPE with a total mass of 1 g were dissolved in 30 ml of THF, and the mass fraction of BF₂-TPE was 0.1, 0.3, 0.5, 0.7 and 1.0 wt%, respectively. The mixed solution was subjected to ultrasonic treatment for 20–30 min, and then spread on a horizontal glass plate and evaporated at room temperature for 16 h. The resultant composite films were peeled off in cold water and dried in vacuum at 40 °C for 24 h to remove excess THF. The PVC/BF₂-TPE composite films of about 40 μm thick were obtained. Pure PVC film was prepared as a control following the same procedure.

2.3. UV accelerated aging test

UV accelerated aging test was carried out using a FUD-UV1150 accelerated aging tester (Beijing Fuyoudi Mechanical Equipment Co., Ltd, China) under the following conditions: light source: type I fluorescent UV lamp UV-A340 (40 W), average irradiation intensity: 0.76 W m⁻², irradiation and condensation temperature: 50 °C, a cycle period of 240 h, including 160 h of irradiation and 80 h of condensation, irradiation time: 0, 240, 480, 720, 960 and 1200 h, respectively. In order to ensure uniform UV irradiation, samples were rearranged and shifted around the lamp array in turn.

2.4. Characterization and measurements

The UV–vis absorption spectra were recorded using a UV–vis spectrophotometer (UV-2550, Shimadzu Company, Japan) with a wavelength range of 200–800 nm. The FTIR spectra were characterized by an infrared spectrometer (Spectrum Two, PerkinElmer Company, USA) with a scanning range of 400–4000 cm⁻¹. The morphologies of PVC and PVC/BF₂-TPE composite films before and after UV accelerated aging were observed using a JSM-6610LV field emission scanning electron microscopy (FE-SEM, Japan), and all samples were gold sprayed before observation. Thermogravimetric analysis (TGA) was conducted by a thermogravimetric analyzer (HCT-3, Beijing Hengjiu Scientific Instrument Factory, China) from room temperature to 700 °C at a heating rate of 10 °C min⁻¹ in nitrogen atmosphere. Dynamic mechanical analysis (DMA) was performed by a dynamic mechanical analyzer (Q800, USA) with a scanning frequency of 1 Hz and a heating rate of 3 °C min⁻¹ in the temperature range from 40 to 120 °C. The yield strength was measured by a microcomputer controlled electronic universal testing machine (104B-EX, Shenzhen Wance Test Equipment Co., Ltd, China) according to Chinese standard GB/T1040.2-2006.
3. Results and discussion

3.1. UV absorption properties of BF₂-TPE

Figure 1 shows the UV–vis absorption spectra of pure PVC and PVC/BF₂-TPE composite films. A weak absorption band is observed in the wavelength range of 250–300 nm in pure PVC, which is mainly attributed to the complex formed by a trace of residual THF and O₂ during the photooxidative degradation [11]. Two strong absorption bands are observed at 306 nm and 421 nm in PVC/BF₂-TPE composite films, indicating that BF₂-TPE can be used as an UV absorber. The absorption band at about 306 nm may originate from the π-π* transition of C=C in enol, while that at about 421 nm may originate from the charge transfer transition from the electron donor tetrastyrene to the electron acceptor β-diketone boron [9]. The UV absorption intensity of PVC/BF₂-TPE composite films increases gradually with the increase of BF₂-TPE content, suggesting that BF₂-TPE can significantly enhance the UV absorption properties of PVC.

3.2. Transparency of PVC/BF₂-TPE composite films

Figure 2 shows the transmittance of pure PVC and PVC/BF₂-TPE composite films in the wavelength range of 200–800 nm. The transmittance of PVC/BF₂-TPE composite films below 500 nm wavelength decreases greatly with the increase of BF₂-TPE content, suggesting that BF₂-TPE can obviously improve the UV barrier property of PVC. However, the transmittance of these PVC/BF₂-TPE composite films is very close to that of PVC in visible wavelength range, especially in the wavelength range above 555 nm, to which the human eye is most sensitive [12]. Figure 2 shows that the transmittance of the composite films below 555 nm is higher than 80%, which is very close to that of PVC. Even for PVC/BF₂-TPE1 composite film, its transmittance is higher than 70%, suggesting that the PVC/BF₂-TPE composites have good transparency.

3.3. Mechanical properties of PVC/BF₂-TPE composite films

Figure 3 shows the yield strength of pure PVC and PVC/BF₂-TPE composite films at different irradiation time. The yield strength of all composite films shows an increasing trend before 480 h of UV irradiation, and the yield strength of pure PVC is increased by about 27.9% compared with that before irradiation due to the formation of a compact cross-linked structure at the beginning of UV irradiation [13, 14]. However, the yield strength of all composite films exhibits a decreasing trend from 480 h to 1200 h, because the molecular chain can be broken with the increase of irradiation time, and thus a large number of defects are formed on the surface [15]. As a result, the microstructure of the polymer is destroyed, resulting in the degradation of film performance. Compared with PVC composite films with different BF₂-TPE contents, the yield strength is decreased more obviously in pure PVC after 1200 h of irradiation. Thus, BF₂-TPE plays a role in UV absorption. The yield strength of pure PVC decreases from 10.8 MPa to 5.6 MPa after 1200 h of UV irradiation, with a decrease of 48.1% compared to that irradiated for 480 h, while that of PVC/BF₂-TPE0.5 composite film decreases from 10.5 MPa to 7.8 MPa after 1200 h of UV irradiation, with a decrease of 25.7% compared with that irradiated for 480 h. It is indicated that the retention ratio of the yield strength for PVC/BF₂-TPE0.5 composite film is the highest, thus it is selected for further analysis and characterization.

Figure 1. UV absorption spectra of PVC and its composite films.
3.4. UV absorption properties of PVC/BF₂-TPE composite films
The UV–vis absorption spectra can be used for the detection of unsaturated conjugated double bonds [16]. In order to gain more insight into the reactions involved in the UV accelerated aging process, the UV absorption properties of PVC and PVC/BF₂-TPE0.5 composite films before and after irradiation are analyzed, as shown in figure 4. The UV absorption intensity of all composite films increases with the increase of irradiation time, indicating that unsaturated conjugated double bonds are formed in the photooxidation process [17]. The characteristic absorption peaks of PVC/BF₂-TPE0.5 composite film disappear in the UV region after irradiation, which may be related to the interconversion between keto and enol in β-diketone molecules. β-diketone can absorb UV light to destroy the intramolecular hydrogen bond of enol and leads to the shift of isomerization equilibrium towards keto under long-term UV irradiation. Thus, the number of enol isomers is decreased and that of keto isomers is increased under long-term UV irradiation [18, 19].

3.5. FTIR spectra of PVC/BF₂-TPE composite films
Figure 5 shows the FTIR spectra of PVC and PVC/BF₂-TPE0.5 composite film at different irradiation time. As can be seen from figure 5(a), the sharp peak at 1429 cm⁻¹ belongs to the C–H bending vibration in the R-CH₂-R’ structure of PVC molecular chain. After 480 h of UV irradiation, several weak peaks can be found at 1606 and
1700–1800 cm\(^{-1}\). The weak peak at 1606 cm\(^{-1}\) belongs to the characteristic absorption of C=O, while that at 1700–1800 cm\(^{-1}\) belongs to the stretching vibration of C=O [20, 21]. The absorption peak intensities of C=O and C=C of the pure PVC film increase gradually at 480–1200 h compared with that before irradiation. These results show that UV irradiation can lead to photodegradation of PVC and formation of the unsaturated bonds. As shown in figure 5(b), a new absorption peak is observed at 1540 cm\(^{-1}\) in the FTIR spectra of PVC/BF\(_2\)-TPE0.5 composite film, which corresponds to the stretching vibration of C=C in the \(\beta\)-diketene alcohol structure [22]. The characteristic absorption peaks of C=O and C=C can also be observed in the PVC/BF\(_2\)-TPE0.5 composite film after UV irradiation for 480 h, and the absorption peak intensity of C=O increases significantly at 480–1200 h compared with that before irradiation. Thus, UV irradiation can accelerate the photooxidative degradation of PVC composite films.

Because the UV aging reaction occurs initially on the surface, the thickness of samples is an important parameter affecting the distribution of photodegradation products [23]. The carbonyl index (CI) is introduced here to quantify the photodegradation degree. The absorption peak area at 1429 cm\(^{-1}\) is taken as the internal standard [24]. CI is the ratio of the peak area in the carbonyl region (1700–1800 cm\(^{-1}\)) to the internal standard peak area. CI can be calculated according to formula (1):

\[
CI = \frac{A_{1700-1800 \text{ cm}^{-1}}}{A_{1380-1480 \text{ cm}^{-1}}}
\]  

Where \(A_{1700-1800 \text{ cm}^{-1}}\) is the absorption peak area in the range of 1700–1800 cm\(^{-1}\), and \(A_{1380-1480 \text{ cm}^{-1}}\) is the absorption peak area in the range of 1380–1480 cm\(^{-1}\). The variation of CI of pure PVC and PVC/BF\(_2\)-TPE0.5 composite film as a function of irradiation time is shown in figure 6. It shows that the CI value increases with the UV irradiation time for both pure PVC and PVC/BF\(_2\)-TPE0.5 composite film, indicating that both of them undergo photodegradation to varying degrees under UV irradiation. The CI of pure PVC film reaches a
maximum of 3.0 after 1200 h of UV irradiation. However, the CI of PVC/BF$_2$-TPE0.5 composite film is 2.6 after 1200 h of UV irradiation, and it is much lower than that of pure PVC film, indicating that BF$_2$-TPE can effectively inhibit photooxidative degradation of PVC. This is because BF$_2$-TPE absorbs UV light and causes molecular thermal movement, which destroys the intramolecular hydrogen bonds, opens chelate ring and releases incoming radiation in the form of thermal dissipation.

3.6. Morphology of PVC/BF$_2$-TPE composite films

Figure 7 shows the surface SEM images of PVC composite films before and after UV irradiation. The surfaces of pure PVC and PVC/BF$_2$-TPE0.5 composite film are smooth before irradiation (figures 7(a) and (c)), but obvious cracks are observed after irradiation (figures 7(b) and (d)). This is mainly due to the chain breakage and cross-linking of PVC in the photooxidation aging, which lead to the degradation of films and affect their morphology [25]. However, the surface cracking of PVC/BF$_2$-TPE0.5 composite film is weaker than that of pure PVC, suggesting that BF$_2$-TPE can inhibit photooxidative degradation of PVC.

The molar contents of C and Cl elements in pure PVC and PVC/BF$_2$-TPE0.5 composite film before and after irradiation were measured by EDS, as shown in table 1. It can be seen that the molar content of Cl in pure PVC is decreased by 16.3% after 1200 h of UV irradiation, while that of PVC/BF$_2$-TPE0.5 composite film is decreased by only 4.4%, which further illustrates that BF$_2$-TPE can prevent the dehydrochlorination of PVC and thus may play a role as an UV absorber.

3.7. Thermal stability of PVC/BF$_2$-TPE composite films

Figure 8 shows the TG and derivative TG (DTG) curves of PVC/BF$_2$-TPE composite films in nitrogen atmosphere. Pure PVC exhibits a slight weight loss (7.0%) in the temperature range of 70–260 °C, which is due to the volatilization of the solvent in the PVC film rather than the degradation of PVC [26]. Therefore, the decomposition of PVC and its composite films consists of two stages. In the first stage, a large weight loss (68.2%) occurs in the temperature range of 260–390 °C, which is due to the chain dehydrogenation of PVC and the formation of a large number of conjugated polyene sequences [27]. A lower weight loss (24.3%) occurs in the temperature range of 390–700 °C due to the chain breaking and cross-linking reactions of PVC [28].

Relevant important parameters such as the temperature of onset decomposition ($T_{\text{Onset}}$), the temperature of maximum loss rate ($T_{\text{max}}$) and residual yield are summarized in table 2. The $T_{\text{Onset}}$ and $T_{\text{max}}$ of PVC/BF$_2$-TPE0.5 composite film in the first stage are higher than that of PVC matrix before UV irradiation, indicating that the addition of BF$_2$-TPE can improve the thermal stability of PVC. However, after UV irradiation for 1200 h, the $T_{\text{Onset}}$ of pure PVC and its composite films in the two stages shows a decreasing trend. The $T_{\text{Onset}}$ of pure PVC is decreased by 13.8 °C from 257.5 °C to 243.7 °C in the first stage, while that of PVC/BF$_2$-TPE0.5 composite film is decreased by 6.5 °C from 261.0 °C to 254.5 °C. This is due to the thermal degradation of PVC. On the other hand, PVC photodegradation can also promote the autocatalytic reaction of dehydrochlorination of PVC to produce a large number of conjugated polyene sequences, which accelerates the degradation rate of PVC [13, 29]. The $T_{\text{Onset}}$ of pure PVC is decreased by 10.8 °C from 408.3 °C to 397.5 °C in the second stage, while that of PVC/BF$_2$-TPE0.5 composite film is decreased by 4.8 °C from 403.6 °C to 398.8 °C. This further confirms that
UV irradiation can reduce the $T_{\text{Onset}}$ of polymer. It is noteworthy that the addition of UV absorber BF$_2$-TPE to PVC results in a decrease in the degradation rate of PVC/BF$_2$-TPE0.5 composite film, suggesting that BF$_2$-TPE can inhibit the photodegradation of PVC and thus slow down the thermal degradation rate.

Table 1. The molar contents of C and Cl elements in pure PVC and PVC/BF$_2$-TPE0.5 composite film after 0 and 1000 h of UV radiation from EDS.

| Elements | Pure PVC − 0 h | −1200 h | Increase (%) | PVC/BF$_2$-TPE0.5 − 0 h | PVC/BF$_2$-TPE0.5 − 1200 h | Increase (%) |
|----------|----------------|---------|---------------|--------------------------|-----------------------------|---------------|
| C        | 62.75 ± 3.4    | 68.85 ± 5.8 | 9.7           | 71.25 ± 6.5              | 72.54 ± 7.3               | 1.8           |
| Cl       | 37.25 ± 1.2    | 31.15 ± 1.4 | −16.3         | 28.75 ± 1.3              | 27.46 ± 1.3               | −4.4          |

Figure 7. SEM images of PVC composite films irradiated for 0 h and 1200 h. (a) Pure PVC-0 h, (b) pure PVC-1200 h, (c) PVC/BF$_2$-TPE0.5-0 h and (d) PVC/BF$_2$-TPE0.5-1200 h.

Figure 8. (a) TGA and (b) DTG curves of pure PVC and PVC/BF$_2$-TPE0.5 composite film irradiated for 0 h and 1200 h.
3.8. Dynamic mechanical analysis of PVC/BF₂-TPE composite films

Figure 9 shows the relationship of the storage modulus ($E'$) and loss factor (tan δ) of pure PVC and PVC/BF₂-TPE composite films with temperature. As shown in figure 9(a), the $E'$ of PVC/BF₂-TPE composite films is higher than that of pure PVC below the glass transition temperature ($T_g$) of PVC, and it increases with the BF₂-TPE content. Compared with pure PVC, the $E'$ of PVC/BF₂-TPE0.5 and $E'$ of PVC/BF₂-TPE1 at 40°C are increased by 51.5% and 56.0%, respectively. BF₂-TPE is a rigid molecule with a conjugated structure, and F atoms in BF₂-TPE can form hydrogen bond interaction with tertiary H atoms in PVC (figure 10), which can improve the miscibility between BF₂-TPE and PVC. Thus, the rigid BF₂-TPE molecule can reinforce PVC matrix. As depicted in figure 9(b), the similar phenomenon is also observed for PVC/BF₂-TPE composite films irradiated for 1200 h.

The $T_g$ of PVC obtained from tan δ peak position is shown in table 3. The $T_g$ values of all composite films, irradiated or not irradiated alike, are lower than that of pure PVC. This may be because BF₂-TPE is a small organic molecule with fast molecular motion, and its thermal movement speeds up with the increase of temperature, which can increase the free volume of PVC matrix. On the other hand, the strength of hydrogen bond between BF₂-TPE and PVC decreases with the increase of temperature. Both of them can increase the flexibility of the PVC molecular chain, and thus results in lower $T_g$. However, there is no significant difference in

| Samples                  | First stage | Second stage | Residual mass/% |
|--------------------------|-------------|--------------|-----------------|
|                          | $T_{onset}$/°C | $T_{max}$/°C | $T_{onset}$/°C | $T_{max}$/°C | Residual mass/% |
| Pure PVC-0 h             | 257.5       | 282.0        | 408.3          | 463.2        | 9.7             |
| Pure PVC-1200 h          | 243.7       | 314.4        | 397.5          | 458.0        | 10.8            |
| PVC/BF₂-TPE0.5-0 h       | 261.0       | 282.8        | 403.6          | 462.4        | 6.3             |
| PVC/BF₂-TPE0.5-1200 h    | 254.5       | 306.0        | 398.8          | 459.2        | 9.9             |

Figure 9. Temperature dependent (a) and (b) storage modulus, (c) and (d) tan δ curves of pure PVC and PVC/BF₂-TPE composite films as obtained from DMA analysis.
between PVC/BF$_2$-TPE composite films with different content of BF$_2$-TPE, suggesting that BF$_2$-TPE has no obvious effect on the glass transition behavior of PVC due to its low content [30]. After irradiation for 1200 h, the $T_g$ of PVC and PVC/BF$_2$-TPE composite films increases compared with that without irradiation. This is due to the formation of cross-linking and conjugated structures in the UV aging process [13, 14], which hinder the movement of chain segments of PVC and reduce the flexibility of the molecular chain.

4. Conclusions

In this study, a series of PVC/BF$_2$-TPE composite films were prepared by solvent casting method, and their UV absorption properties, mechanical properties, thermal stability and the morphology during UV accelerated aging were studied. The results indicate that the UV light in the wavelength range from 220 to 450 nm can be absorbed by BF$_2$-TPE, and the UV resistance of PVC/BF$_2$-TPE composite films is improved with the addition of BF$_2$-TPE. After irradiation for 1200 h, the yield strength of pure PVC film and PVC/BF$_2$-TPE0.5 composite film is decreased by 48.1% and 25.7%, respectively. BF$_2$-TPE can effectively inhibit the photodegradation of PVC, increase the thermal degradation temperature and reduce the thermal degradation rate of PVC/BF$_2$-TPE composite films.

Acknowledgments

The study was supported by the National Natural Science Foundation of China (No. 21764011 and No. 21662028) and the Foundation from Qinghai Science and Technology Department (2020-HZ-808, 2020-ZJ-923 and 2018-HZ-817).

ORCID iDs

Shiai Xu  https://orcid.org/0000-0002-6011-8911

References

[1] Wang S W, Liu Y Q, Chen K, Xue P, Lin X D and Jia M Y 2020 Thermal and mechanical properties of the continuous glass fibers reinforced PVC composites prepared by the wet powder impregnation technology J. Polym. Res. 27 82–93
[2] Mindivan F and Göktaş M 2020 Preparation of new PVC composite using green reduced graphene oxide and its effects in thermal and mechanical properties Polym. Bull. 77 1929–49
[3] Mazhar S, Qarni A A, Ul Haq Y, Ul Haq Z and Murtaza I 2020 Promising PVC/MXene based flexible thin film nanocomposites with excellent dielectric, thermal and mechanical properties Ceram. Int. 46 12593–605
[4] Guo Y B, Ozaydin M F, Wang D G and Liang H 2018 Friction heating and effect on tribological properties of soft polyvinyl chloride sliding against steel Eur. Polym. J. 106 85–91
[5] Zhu K C, Jia H Z, Zhao S, Xia T J, Guo X T, Wang T C and Zhu L Y 2019 Formation of environmentally persistent free radicals on microplastics under light irradiation Environ. Sci. Technol. 53 8177–86
[6] Jin D D and Xu S A 2018 The effects of polybenzimidazole and polyacrylic acid modified carbon black on the anti-UV-weathering and thermal properties of polyvinyl chloride composites Compos. Sci. Technol. 167 388–95
[7] Shi Q F, Gao J Y, Zhao D D and Xu S A 2010 Synergism effect between modified carbon black and organic ultraviolet absorber in polymer matrix for ultraviolet protection J. Appl. Polym. Sci. 116 2566–72
[8] Zhang Y, Han J R, Wu S Y, Qi Z G, Xu J and Guo B H 2017 Synthesis, physical properties and photodegradation of functional poly (butylen succinate) covalently linking UV stabilizing moieties in molecular chains Colloids Surf., A 524 160–8
[9] Gao H Z, Xu D F, Liu X L, Han A X, Zhou L, Zhang C, Li Z and Dang J 2017 Tetraphenylethene-based β-diketone boron complex: efficient aggregation-induced emission and high contrast mechanofluorochromism Dyes Pigm. 139 157–65
[10] Sergeeva E V, Punstus L N, Katzur F, Rau I, Sabraoui B, Pekareva I S, Suponitsky K Y, Bushmarinov I S and Lyssenko K A 2013 Keto-ened tautomerism and nonlinear optical properties in β-diketones containing [2-2] paracyclophane Opt. Mater. 36 47–52
[11] Lala D, Rabek F and Banhy B 1980 The effect of 1,3-diphenylisobenzofuran on the photo-oxidative degradation of cis-1,4-polybutadiene Eur. Polym. J. 16 735–44
[12] Berson D M, Dunn F A and Takao M 2002 Phototransduction by retinal ganglion cells that set the circadian clock SCL. 295 1070–3
[13] Owen E D 1984 Degradation and Stabilisation of PVC (London: Elsevier Applied Science Publishers Ltd) (https://doi.org/10.1007/978-94-009-5618-6)
[14] Yu J, Sun L S, Ma C, Qiao Y and Yao H 2016 Thermal degradation of PVC: A review Waste Manage. 48 300–14
[15] Lu T, Solis-Ramos E, Yi Y and Kumusa M 2018 UV degradation model for polymers and polymer matrix composites Polym. Degrad. Stab. 154 203–10
[16] Luo Z D, Wang H Y, Chen K, Liu J, Wu C L and Wei Z 2015 UV-Visible spectrophotometry for the determination of conjugated polynye structures of poly(vinyl chloride) in 1,2-dichlooroethane Int. J. Polym. Anal. Charact. 20 240–9
[17] Shieh Y T, Hsieh K C and Cheng C C 2017 Carbon nanotubes stabilize poly(vinyl chloride) against thermal degradation Polym. Degrad. Stab. 144 221–30
[18] Markov P, Shishkova L and Zdravkova Z 1972 On the influence of UV-irradiation on the keto–enol equilibrium of ethylacetoacetate in solution Tetrahedron Lett. 13 4017–9
[19] Markov P 1984 Cheminform abstract: light-induced tautomerism of β-dicarbonyl compounds Chem. Informationdienst 15 69–96
[20] Greco A, Ferrari F and Maffezzoli A 2017 UV and thermal stability of soft PVC plasticized with cardanol derivatives J. Cleaners Prod. 164 757–64
[21] Dai J, Yan H, Guo J J, Hu Z D, Yang J and Zhang H S 2017 Study on the effect of density on the photooxidation aging properties of polyethylene Polym. Bull. 2 46–55
[22] Wang D, Wan Y P, Liu H, Wang D J and Yin G D 2018 Synthesis, photoluminescent and electrochemical properties of diacetoxyboron derivatives for bis-β-diketonate linked thiophosphine Dyes Pigm. 149 278–35
[23] Xiang X Q, Chen S J, Zhang J and Huang X 2010 Effect of relatively nontoxic thermal stabilizers on photodegradation of poly(vinyl chloride) Polym. Eng. Sci. 50 1095–104
[24] Chai R D, Chen S J and Zhang J 2012 Combined effect of hindered amine light stabilizer and ultraviolet absorbers on photodegradation of poly(vinyl chloride) J. Vinyl Addit. Technol. 18 17–25
[25] Lu T, Solis-Ramos E, Yi Y B and Kumusa M 2017 Particle removal mechanisms in synergistic aging of polymers and glass reinforced polymer composites under combined UV and water Compos. Sci. Technol. 153 273–81
[26] Hasan M and Lee M 2014 Enhancement of the thermo–mechanical properties and efficiency of mixing technique in the preparation of graphene/PVC composites compared to carbon nanotubes/PVC Prog. Nat. Sci.: Mater. Int. 24 579–87
[27] Gao Z H, Lu L H, Shi C L, Qian X D, Wang X B, Zhang G Y, Zhou M T and Pan Y H 2020 The study of ZnAl and ZnFe layered double hydroxide on the catalytic dechlorination and fire safety of polyvinyl chloride J. Therm. Anal. Calorim. 140 115–23
[28] Gao Z H, Lu L H, Shi C L and Qian X D 2020 The effect of OCoAl-LDH and OCoFe-LDH on the combustion behaviors of polyvinyl chloride Polym. Adv. Technol. 31 675–85
[29] Davies D W 1982 Manufacture and Processing of PVC (London: Applied Science Publishers) (https://doi.org/10.1016/0141-3910(82)90045-3)
[30] Zhang X D, Cai Y B, Teng X, Nan B H and Xu S A 2019 Application of polybenzimidazole as a panchromatic ultraviolet absorber in poly (vinyl chloride) film Constr. Build. Mater. 194 171–8