Flame-Retardant Properties of Magnesium Hydroxystannate and Strontium Hydroxystannate Coated Calcium Carbonate on Soft Poly(vinyl chloride)

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ABSTRACT: The flame-retardant and smoke-suppressant properties of soft poly(vinyl chloride) (PVC) treated with zinc hydroxystannate (ZHS), calcium carbonate ($CaCO_3$), magnesium hydroxystannate [$MgSn(OH)_6$], strontium hydroxystannate [$SrSn(OH)_6$], ZHS–$MgSn(OH)_6$, ZHS–$SrSn(OH)_6$, $MgSn(OH)_6$-coated $CaCO_3$, $SrSn(OH)_6$-coated $CaCO_3$, ZHS–$MgSn(OH)_6$-coated $CaCO_3$, and ZHS–$SrSn(OH)_6$-coated $CaCO_3$ were studied with the limited oxygen index, char yield, and smoke density rating methods; the mechanical properties were also studied. The results showed that, with the equivalent addition of the corresponding hydroxystannate, the soft PVC treated with hydroxystannate-coated $CaCO_3$ had a higher limited oxygen index than the corresponding hydroxystannate, and the soft PVC treated with the agents containing magnesium had a higher limited oxygen index than the soft PVC treated with the agents containing strontium, except for ZHS–$MgSn(OH)_6$-coated $CaCO_3$. The improvement in the char formation of the hydroxystannate-coated $CaCO_3$ was better than that of the corresponding hydroxystannate in most cases, and the aforementioned agents reduced the smoke density rating, decreased the tensile strength, and increased the elongation and impact strength basically. Thermal analysis showed that the additives promoted the evolution of hydrogen chloride, early crosslinking, and rapid charring through the strong catalyzing effect of Lewis acids. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 112: 36–43, 2009

Key words: additives; flame retardance; poly(vinyl chloride) (PVC); thermal properties

INTRODUCTION

Poly(vinyl chloride) (PVC) is extraordinarily useful as a commercial thermoplastic. Its total worldwide production volume and consumption have remained at a high level for many years,[1–4] although it is under attack because of the generation of chlorinated benzodioxins and benzodifurans during waste incineration as well as house and building fires.[5] Soft (or plasticized) PVC, as one of the main products of PVC, is easy to ignite, and fire results. Therefore, flame retardants have to be added to soft PVC resins.

In recent years, inorganic tin compounds, particularly zinc hydroxystannate (ZHS), zinc stannate (ZS), and tin(IV) oxide, have attracted considerable interest, mainly from the International Tin Research Institute, because of their nontoxicity and improved fire- and smoke-suppressant properties in a wide range of polymers,[6–14] and their study is flourishing at present. Moreover, ZHS- or ZS-coated inorganic fillers, as novel flame retardants and smoke suppressants for polymeric materials, have attracted increasing attention because, at a relatively low cost in comparison with ZHS or ZS, significantly enhanced flame-retardant and smoke-suppressant properties can be obtained with the same flame-retardant level.[8,15–20] The application of ZHS-coated inorganic fillers, particularly ZHS- or ZS-coated aluminum hydroxide or magnesium hydroxide,[8,15–18,20] allows a significant reduction of the overall filler loading with no loss in the flame-retardant properties.[18] In addition, ZHS- or ZS-coated calcium carbonate ($CaCO_3$) as a flame-retardant agent for semirigid PVC in our previous study[14] showed improved limited oxygen index (LOI) and smoke-suppressant properties in comparison with those of equivalent ZHS or ZS content. However, limited literature exists on the study of other hydroxystannates and $CaCO_3$ coated with other hydroxystannates. For this reason, a series of other hydroxystannates (e.g., magnesium, strontium, iron, cobalt, nickel, and copper) and their corresponding coated $CaCO_3$ were prepared, and their flame-retardant properties and smoke-suppressant properties were also studied by our team. The aim of this work was to investigate the flame-retardant and smoke-suppressant properties of magnesium

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hydroxy-stannate [$MgSn(OH)_6$], strontium hydroxy-stannate [$SrSn(OH)_6$], a composite of ZHS and $MgSn(OH)_6$ [ZHS–$MgSn(OH)_6$], a composite of ZHS and SrSn $(OH)_6$ [ZHS–$SrSn(OH)_6$], and corresponding coated $CaCO_3$ in comparison with those of ZHS; their mechanical properties were also studied.

EXPERIMENTAL

Materials

The materials were PVC SG-5 (Beijing Second Chemical Co., Beijing, China), di(2-ethylhexyl)phthalate (DOP) as the plasticizer (Shanghai Dongfang Chemicals Co., Shanghai, China), an organic tin compound as the stabilizer and calcium stearate as the lubricant (Hebei Baoding Chemical Co., Baoding City, China), $CaCO_3$ (Shanghai Yexing Pesticide Chemical Co., Shanghai, China), $Na_2Sn(OH)_6$ (Tianjin Suzhuang Chemical Co., Tianjin, China), NaOH (Tianjin Beifang Huabo Chemical Co., Tianjin, China), ZnO (Tianjin Chemical Co., Tianjin, China), $SrSO_4$ (Shanghai Chemical Co., Shanghai, China), and $MgCl_2·6H_2O$ (Tianjin Taixing Chemical Co., Tianjin, China). ZHS, the hydroxystannates, and the corresponding coated $CaCO_3$ were homemade.

Preparation of the flame retardants and the flame-retardant soft PVC sample

Preparation of the flame retardants

ZHS, $MgSn(OH)_6$, ZHS–$MgSn(OH)_6$, $SrSn(OH)_6$, ZHS–$SrSn(OH)_6$, 10% $MgSn(OH)_6$-coated $CaCO_3$, 10% ZHS–$MgSn(OH)_6$-coated $CaCO_3$, 10% $SrSn(OH)_6$-coated $CaCO_3$, and 10% ZHS–$SrSn(OH)_6$-coated $CaCO_3$ were prepared according to ref. [8].

Preparation of the flame-retardant soft PVC samples

The basic recipe of the samples was as follows: 100 parts PVC, 30 parts DOP, 3 parts stabilizer, 0.5 parts calcium stearate, 0.5 parts stearic acid, 1 part coupling agent, and some parts of flame retardants.

The soft PVC samples were prepared with the following steps. The first step was adequate mixing of the upper agents followed by blending in a two-roll mill at 473 K for 10 min. The second step was compression for 2 min at 483 K and 5 MPa and for 4 min with the pressure increased to 15 MPa; the third step was compression for 10 min at room temperature. The final products were $100 \times 50 \times 3$ mm^3. The test specimens were cut from the molded sheets.

Measurements and characterization

LOI

The LOI values were determined in accordance with ASTM D 2863 with a general model HC-1 LOI instrument (Nanjing Jiangning Analysis Instrument Factory, Nanjing, China).

Char yield

Char yield values were calculated with the following equation:

$$Char\, yield = w_2/w_1 \times 100\%$$

where w_1 and w_2 are the weights of the soft PVC sample before pyrolysis under N_2 and the residue after pyrolysis of the soft PVC sample, respectively. This experiment was carried out in a muffle furnace under N_2 at 673 K for 30 min.

Smoke density rating (SDR)

SDR was determined with a JCY-1 instrument (Nanjing Analysis Instrument Factory, Nanjing, China) according to ASTM D 2843; the size of the test specimens was $25.3 \times 25.3 \times 3$ mm^3.

Thermal analysis

Thermal analyses were carried out on a DT-40 thermal analyzer (Shimadzu Corp., Shimadzu, Japan); α-Al_2O_3 was taken as the reference material. The samples weighed about 5.0 mg, the heating speed was 20 K/min from the ambient temperature to 1073 K, and the atmosphere was air with a flow rate of 60 mL/min.

Tensile strength

The tensile strength and elongation measurements were carried out on an LJ-5000N mechanical instrument (Chengde Experimental Instrument Factory, Chengde, China) according to ISO 10810 methods. The cross speed was 50 mm/min. There were five tested specimens of every tested sample.

Impact strength

The impact strength measurements were carried out on an XCJ-40 Charpy impact test machine (Chengde Experimental Instrument Factory) according to ISO 179 methods.

RESULTS AND DISCUSSION

LOI analysis

As shown in Figure 1, the LOI of the PVC samples increased along with the increase in the corresponding flame retardants. With the equivalent content of hydroxystannate, the flame-retardant effect of the agents containing magnesium was better than that
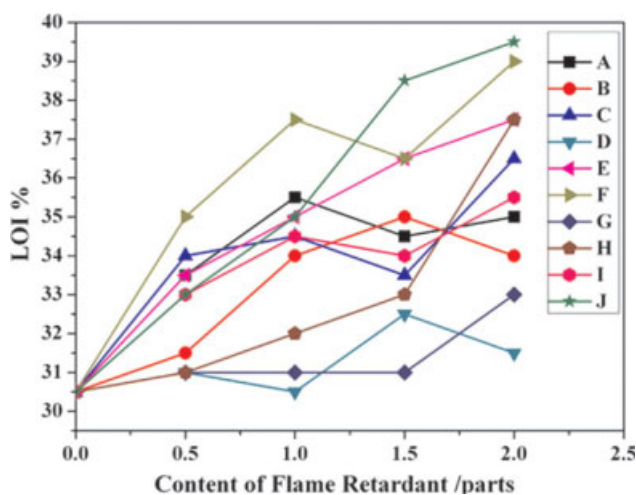
Figure 1 LOI values of the soft PVC samples. Samples A–J were flame-retardant soft PVC samples treated with ZHS, $MgSn(OH)_6$, $ZHS-MgSn(OH)_6$, $CaCO_3$, 10% $MgSn(OH)_6$-coated $CaCO_3$, 10% $ZHS-MgSn(OH)_6$-coated $CaCO_3$, $SrSn(OH)_6$, $ZHS-SrSn(OH)_6$, 10% $SrSn(OH)_6$-coated $CaCO_3$, and 10% $ZHS-SrSn(OH)_6$-coated $CaCO_3$, respectively. The flame-retardant content of samples A, B, C, G, and H is shown in the figure, and that of samples D, E, F, I, and J was 10 times what is shown in the figure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

of those containing strontium; the flame-retardant effect of hydroxystannate-coated $CaCO_3$ was better than that of the corresponding hydroxystannate.

The LOI of sample A increased by 3–5 units along with the addition of 0.5–2 parts of ZHS versus the LOI of the neat PVC sample. With the same addition, the LOI of samples B, D, G, and H was lower by 0.5–4.5 units than the LOI of sample A; the LOI of samples E, F, and J was higher by 1–3.5 units than the LOI of sample A; and the LOI of samples C and I was basically similar to the LOI of sample A. This showed that the flame-retardant property of $MgSn(OH)_6$, $CaCO_3$, $SrSn(OH)_6$, and $ZHS-SrSn(OH)_6$ was poorer than that of ZHS, and this may indicate that the synergetic effect of magnesium and tin, strontium and tin, and zinc, strontium, and tin was poorer than the synergetic effect of zinc and tin separately. The synergetic effect of $MgSn(OH)_6$-coated $CaCO_3$, $ZHS-MgSn(OH)_6$-coated $CaCO_3$, and $ZHS-SrSn(OH)_6$-coated $CaCO_3$ was better than the synergetic effect of ZHS, and this suggested that the coated processing craft was beneficial for improving the flame-retardant effect. The synergetic effect of $ZHS-MgSn(OH)_6$- and $SrSn(OH)_6$-coated $CaCO_3$ was similar to the synergetic effect of ZHS, and this showed that the synergetic effect of zinc, magnesium, and tin and strontium, tin, and calcium was similar to the synergetic effect of zinc and tin.

The LOI order from high to low of samples B, C, E, and F was F, E, C, and B; that of samples G, H, I,

and J was J, I, H, and G. This showed that, with the equivalent addition of the hydroxystannate, the flame-retardant property of the hydroxystannate-coated $CaCO_3$ was better than that of the corresponding hydroxystannate; the flame-retardant property of the composite hydroxystannate [ZHS–$MgSn(OH)_6$ or ZHS–$SrSn(OH)_6$]-coated $CaCO_3$ was better than the flame-retardant property of the corresponding hydroxystannate [$MgSn(OH)_6$ or $SrSn(OH)_6$]-coated $CaCO_3$. This showed that there may be some cooperative effect of ZHS and $MgSn(OH)_6$ or ZHS and $SrSn(OH)_6$.

A comparison of sample B with sample G, sample C with sample H, and sample E with sample I shows that the LOI of the former was higher than that of the later, and this indicated that the cooperative effect of magnesium and tin was better than that of strontium and tin and that the cooperative effect of magnesium, zinc, and tin was better than that of strontium, zinc, and tin; this may have been caused by the different atomic structures of magnesium and strontium. A comparison of sample F with sample J, when the addition was 0.5 parts or 1.0 part, shows that the LOI of the former was higher than that of the later; when the addition was 1.5 or 2.0 parts, the result was the reverse. This indicated that the different proportions of the cooperative element and the PVC resin may have resulted in different flame-retardant effects.

All in all, the flame-retardant effect of the agents containing magnesium was better than that of those containing strontium, and the reason may be the different abilities of lost electrons to form cations. With the same addition of the hydroxystannate, the flame-retardant effect of hydroxystannate-coated $CaCO_3$ was better than that of the corresponding hydroxystannate, and this may have been caused by the corresponding hydroxystannate dispersing on the surface of $CaCO_3$, which then resulted in better contact with PVC; a better flame-retardant effect was shown. The flame-retardant effect of the composite hydroxystannate was better than that of the single hydroxystannate, and this may have been caused because the cooperative effect of magnesium (or strontium), zinc, and tin was better than that of magnesium (or strontium) and tin.

Analysis of the char yield

As shown in Figure 2, the char yield of the PVC samples did not have a good rule along with the increases in the corresponding flame retardants. In most cases, the improvement in the char formation of the hydroxystannate-coated $CaCO_3$ was better than that of the corresponding ones, except for $ZHS-MgSn(OH)_6$-coated $CaCO_3$, and this can be described from two angles. First, the hydroxystannate
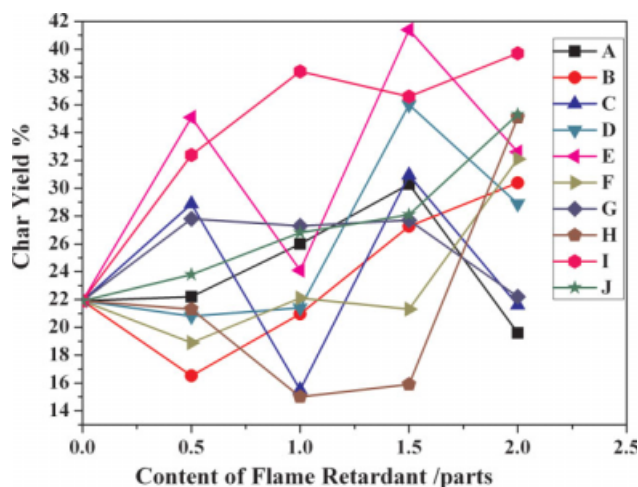
Figure 2 Char yields of soft PVC samples. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

that was dispersed on the surface of $CaCO_3$ was beneficial for displaying its role in reacting with the matrix and then promoting char formation; second, $CaCO_3$ was present. Similar results were found in our previous work on tin dioxide coated $CaCO_3$[2] and ZHS- or ZS-coated $CaCO_3$.[14]

With every addition, the char yield of samples A, E, I, and J was higher than that of the neat PVC sample; this indicated that ZHS, $MgSn(OH)_6$-coated $CaCO_3$, $SrSn(OH)_6$-coated $CaCO_3$, and ZHS–$SrSn(OH)_6$-coated $CaCO_3$ could help the PVC sample to form char, and the char covered the surface of the PVC resin and insulated the oxygen and heat to improve the flame-retardant property. This suggested that the flame-retardant action of ZHS, $MgSn(OH)_6$-coated $CaCO_3$, $SrSn(OH)_6$-coated $CaCO_3$, and ZHS–$SrSn(OH)_6$-coated $CaCO_3$ mainly reacted in the solid phase to some degree. The char yield of samples B, D, F, and H presented a trend that first descended and then ascended; the char yield of sample G presented the reverse trend, and that of sample C presented an "M" shape. This also indicated that an integrated effect was responsible for the phase in which the flame-retardant action mainly operated.

The char yield of sample E was basically higher than that of samples B, C, and F with the equivalent content of hydroxystannate, and this showed that the ability of $MgSn(OH)_6$-coated $CaCO_3$ to improve char formation was better than the ability of the two kinds of hydroxystannates; the ability of ZHS–$MgSn(OH)_6$-coated $CaCO_3$ was poorer. The char yield of sample I was higher than that of samples G, H, and J with the equivalent content of hydroxystannate, and this showed that the ability of $SrSn(OH)_6$-coated $CaCO_3$ to improve char formation was better than ability of the two kinds of hydroxystannates and ZHS–$SrSn(OH)_6$-coated $CaCO_3$.

Analysis of the smoke-suppressant properties

As shown in Table I, the addition of the aforementioned flame retardants decreased the SDR and multiple smoke density rating (MSDR) of the soft PVC, and this indicated that they had a smoke-suppressant effect on the soft PVC. Except for sample A, the SDR of the samples could meet practical requirements because it was lower than the standard 75%. Sample B had the lowest SDR and MSDR, and this indicated that the smoke-suppressant property of $MgSn(OH)_6$ was the best of the aforementioned agents.

The SDR order of samples B, C, E, and F from low to high was B, C, E, and F. This indicated that the smoke-suppressant property of hydroxystannate-coated $CaCO_3$ containing magnesium was poorer than that of the corresponding hydroxystannate; this was contrary to the LOI results, and the reason may be that $CaCO_3$ could decrease the cooperative smoke-suppressant effect of Mg, Zn, and Sn. The SDR order of samples G, H, I, and J from low to high was J, I, H, and G. This indicated that the smoke-suppressant property of hydroxystannate-coated $CaCO_3$ containing strontium was better than that of the corresponding hydroxystannate; this was consistent with the LOI results, and the reason may be that the cooperative effect of Sr, Zn, Sn, and Ca was different from that of Mg, Zn, Sn, and Ca.

In conclusion, the aforementioned agents were good smoke-suppressant agents for the soft PVC, and $MgSn(OH)_6$ was the best.

Flame-retardant and smoke-suppressant mechanism research

Useful information regarding the mode of action of flame retardants can be deduced from thermoanalytical

TABLE I
Smoke-Suppressant Properties of the Flame-Retardant PVC Samples

Sample	SDR (%)	MSDR (%)
K	89.13	100
A	79.87	92.71
B	41.19	51.65
C	46.69	60.36
D	76.05	90.70
E	49.55	64.71
F	52.41	89.50
G	69.11	87.31
H	62.42	76.29
I	46.45	57.35
J	45.12	63.03

The flame-retardant content of samples A, B, C, G, and H was 2 parts, and that of samples D, E, F, I, and J was 20 parts.
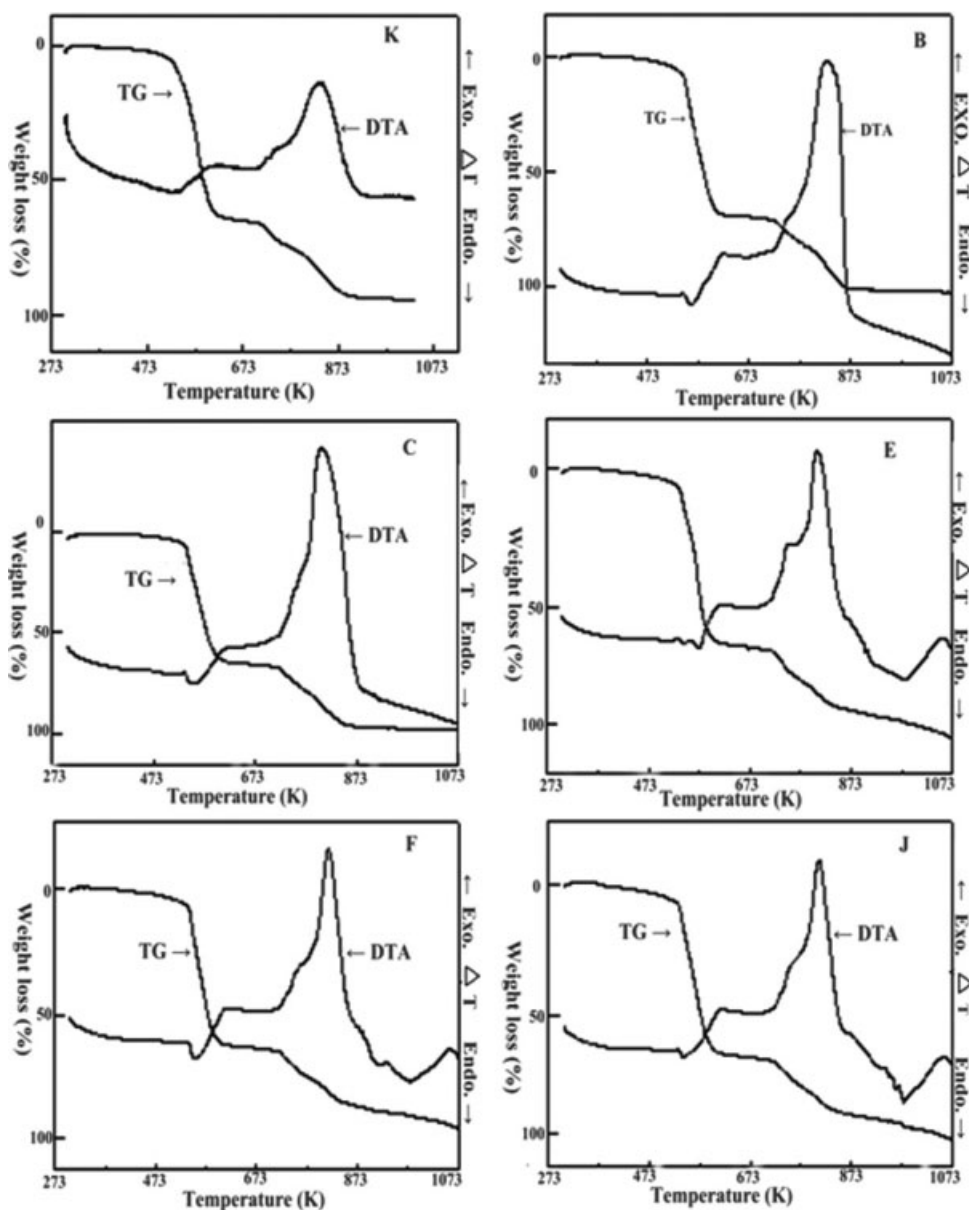
Figure 3   TG and DTA curves of PVC samples B, C, E, F, J, and K.

measurements.[21] The effect of the hydroxystannates and their corresponding coated $CaCO_3$ on the thermal degradation of soft PVC was studied with thermogravimetry/differential thermal analysis (TG–DTA); the TG–DTA curves and the relevant data are presented in Figure 3 and Table II, respectively. As shown in Figure 3, the TG curves of the given samples could be divided into two stages, and weight was lost mainly in the first stage, as can also be seen from Table II. The DTA curve of the aforementioned samples presented only an endothermic peak in the first stage and n exothermic peak in the second stage separately. The temperature of the endothermic peak was higher and that of the exothermic peak was lower than those of the neat soft PVC sample. The first degradation stage ranged from 400 to 630 K,

which corresponded to the process of dehydrochlorination of PVC and the degradation of DOP;[5,22] the second degradation stage ranged from 706 to 903 K, which corresponded to the process of crosslinking of aromatic volatiles, Diels–Alder reactions, and eventually charring.[5]

The weight losses and average weight losses of the soft PVC samples treated with hydroxystannate-coated $CaCO_3$ (samples E and F) were basically lower than those of the corresponding hydroxystannate-treated samples (samples B and C) and the neat soft PVC (sample K) in the two stages (this was consistent with the higher LOI and char yield values of the former vs the later). The weight loss and average weight loss of sample J were higher than those of sample F in the first stage and lower in the second

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TABLE II
Parameters of the TG and DTA Curves of the Soft PVC Samples

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		Sample					
		K	B	C	E	F	J
First stage	T_1 (K)	450.00	473.19	479.30	439.53	402.80	459.26
	T_2 (K)	622.00	627.4	627.57	623.24	611.73	605.25
	$\Delta m/m$ (%)	63.87	68.53	66.93	63.93	64.80	65.53
	AR (%/K)	0.37	0.44	0.45	0.35	0.31	0.45
	T_{endo} (K)	523.00	560.09	547.10	571.78	550.51	540.26
Second stage	T_1 (K)	712.00	714.97	713.52	706.86	717.83	713.95
	T_2 (K)	902.00	873.70	864.29	861.49	898.57	901.72
	$\Delta m/m$ (%)	27.36	30.60	31.46	22.04	24.19	23.13
	AR (%/K)	0.14	0.19	0.21	0.14	0.13	0.12
	T_{exo} (K)	833.00	828.07	804.12	804.58	815.68	809.37

The flame-retardant content of samples B and C was 1 part, and that of samples E, F, and J was 10 parts. $\Delta m/m$ (%) = percentage of weight loss; AR [$\Delta m/m$ (%)/($T_2 - T_1$)], the average percent of weight-loss; T_1 = initial decomposition temperature; T_2 = final decomposition temperature at the corresponding stage; T_{endo} = temperature of the endothermic peak; T_{exo} = temperature of the exothermic peak.

stage, and this was consistent with the lower char yield of the former versus the later. This showed that the flame retardants mainly played their role in the condensation phase, and this agreed with the results in the literature.[11,13,20–22]

Hydrogen chloride is beneficial for extinguishing flames, and the faster it is formed, the more easily the flame will be extinguished.[5] Therefore, the higher weight losses of soft PVC treated with flame retardants versus those of neat PVC in the first decomposition stage showed the promoting action of dehydrochlorination for the flame retardants, which then resulted in better flame-retardant properties. The smoke-suppressant properties of the hydroxystannates and their corresponding coated $CaCO_3$ can be attributed to the reaction with hydrogen chloride forming metal chlorides and strong Lewis acids, which promote early crosslinking and rapid charring.[5] The flame-retardant effect of the hydroxystannate-coated $CaCO_3$ was better than that of the corresponding hydroxystannate, and this may be mainly ascribed to the even dispersion of the effective component of the hydroxystannates on the surface of $CaCO_3$, which then promoted contact with the PVC matrix and finally led to enhanced flame retardancy.[2,5,12,14,22] The flame-retardant effect of ZHS–SrSn(OH)$_6$-coated $CaCO_3$ was better than that of ZHS–MgSn(OH)$_6$-coated $CaCO_3$, and this may be attributed to the synergetic effect of zinc, tin, and strontium, which was better than that of zinc, tin, and magnesium.

and this may be attributed to the following: first, the effects of the additives on the crystallization and orientation behavior of PVC molecules, and second, the effect of the stress concentration.[23]

The tensile strength order of samples B, C, E, and F from high to low was C, E, B, and F. This showed that ZHS–MgSn(OH)$_6$-coated $CaCO_3$ had a very bad effect on the tensile strength of the soft PVC sample. As for samples G, H, I, and J, the decrease in the tensile strength was small. This indicated that SrSn(OH)$_6$, ZHS–SrSn(OH)$_6$, SrSn(OH)$_6$-coated $CaCO_3$, and ZHS–SrSn(OH)$_6$-coated $CaCO_3$ had only a slightly bad effect on the tensile strength of the soft PVC sample. Among the agents, ZHS–MgSn(OH)$_6$ had the least bad effect on the tensile strength of the PVC sample, and ZHS–MgSn(OH)$_6$-coated $CaCO_3$ had the worst effect.
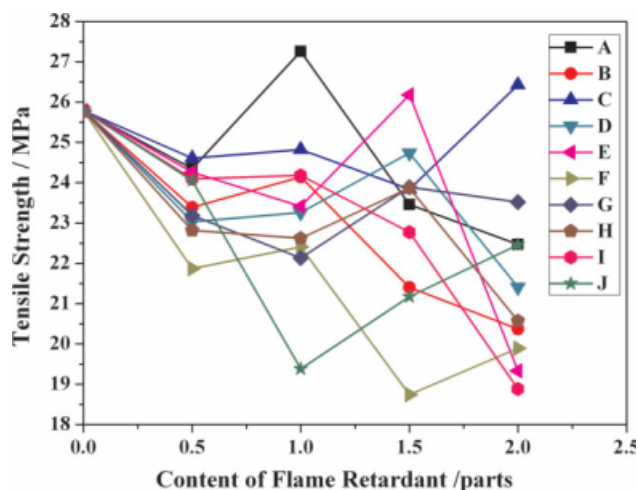

Figure 4 Tensile strength of soft PVC samples. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Analysis of the tensile strength

As shown in Figure 4, the tensile strength of the PVC samples basically decreased with the increasing addition of the aforementioned flame retardants,
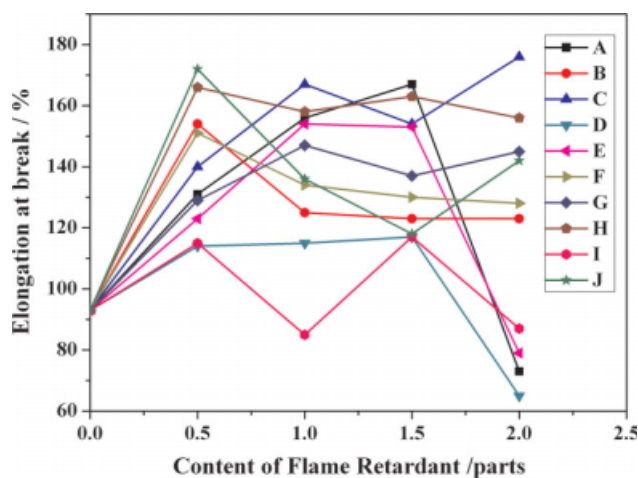
Figure 5 Elongation at break of soft PVC samples. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Analysis of the elongation

As shown in Figure 5, except for some cases, the addition of the aforementioned agents increased the elongation of the PVC sample, and this may have been caused by the toughened effect of nanometer additives; moreover, the increment decreased along with the increased addition, and this may be attributed to the increase in the stress concentration with the increase in additives.

Analysis of the impact strength

As shown in Figure 6, the addition of the aforementioned agents increased the impact strength, and this may be attributed to the formation of small crystals of PVC.[23] Except for samples B, C, and H, the impact strength of the samples was 2–5 times that of the non-flame-retardant PVC sample. The impact strength of sample B was 20–25 times that of the non-flame-retardant PVC sample; the impact strength of sample C was 26 times that with the addition of 2 parts and 2–5 times that with the other addition; and the impact strength of sample H was 3.32 times that with the addition of 2 parts and 24–25.2 times that with the other addition. This indicated that $MgSn(OH)_6$ and $ZHS–SrSn(OH)_6$ greatly increased the impact strength with some addition.

CONCLUSIONS

$MgSn(OH)_6$, $ZHS–MgSn(OH)_6$, $SrSn(OH)_6$, $ZHS–SrSn(OH)_6$, $MgSn(OH)_6$-coated $CaCO_3$, $ZHS–MgSn(OH)_6$-coated $CaCO_3$, $SrSn(OH)_6$-coated $CaCO_3$, and $ZHS–SrSn(OH)_6$-coated $CaCO_3$ were effective flame-retardant and smoke-suppressant agents for soft

PVC. The hydroxystannate-coated $CaCO_3$ had a better flame-retardant effect than the corresponding hydroxystannate, and this was attributed to the fine dispersion of the effective hydroxystannates on the surface of $CaCO_3$; moreover, the agent containing magnesium was better than the agent containing strontium.

In most cases, the improvement of the char formation of the hydroxystannate-coated $CaCO_3$ was better than that of the corresponding hydroxystannate.

The aforementioned agent was an effective smoke-suppressant agent for soft PVC, and $MgSn(OH)_6$ showed the best performance.

The thermal analysis results combined with the char yield data indicated that the hydroxystannates and their corresponding coated $CaCO_3$ mainly played their roles in the condensed phase and promoted the action of dehydrochlorination, early cross-linking, and rapid charring through the strong catalyzing effect of Lewis acids.

The tensile strength of the PVC samples basically decreased with the increasing addition of the aforementioned flame retardants, and this may be attributed to the imperfect crystals of PVC and the increase in the stress concentration; the addition of most of the aforementioned agents increased the elongation of the PVC sample, and this may be ascribed to the toughed effect of the nanometer flame retardants. The increment decreased along with the increased addition, and this may be due to the increase in the stress concentration; the addition of the aforementioned agents increased the impact strength, and this may be due to the formation of small crystals of PVC.
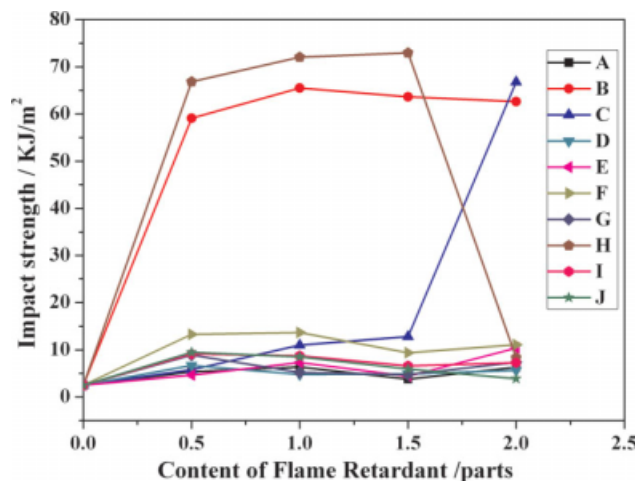

Figure 6 Impact strength of soft PVC samples. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

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