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ORIGINAL RESEARCH

Synergistic effect of organically modified sepiolite clay in intumescent flame retardant polyolefin elastomer-based cable outer sheath compounds

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Abstract

The synergistic effect of organically modified sepiolite nanoclay (SP) in conjunction with aluminum polyphosphate/pentaerythritol as an intumescent flame retardant (IFR) additive on the polyolefin elastomer/linear low-density polyethylene compound has been systemically investigated. The mechanical, thermal, flame-retardant, and morphological properties of the obtained compounds were analyzed by tensile test, thermogravimetric analysis, fire testing technology limiting oxygen index analyzer, cone calorimeter, and scanning electron microscopy and compared with the reference compound containing 60% (by wt) of aluminum trihydroxide (ATH) as a flame-retardant additive. The reduction of IFR content from 40 to 25% not only improved the tensile strength and elongation-at-break values it furthermore provided the mandatory flammability requirements of the ST_8 type cable standard. The addition of 3 and 5% (by wt) of organomodified SP nanoclay as an anti-dripping agent into the compounds slightly improved the LOI values between 27 and 30%. Thermal properties of the compounds in the absence/presence of SP nanoclay were slightly improved by increasing IFR concentration. According to cone calorimeter results, the flammability parameters of the compounds such as heat release rate and total heat release values were significantly improved by incorporation of both IFR and SP nanoclay. Also, the addition of SP nanoclay as an anti-dripping agent reduced the burning rate and limited the heat and mass transfer on the surfaces. It was confirmed by SEM analysis that these surfaces were smoother and more compact carbonaceous residue with fewer cracks and holes.

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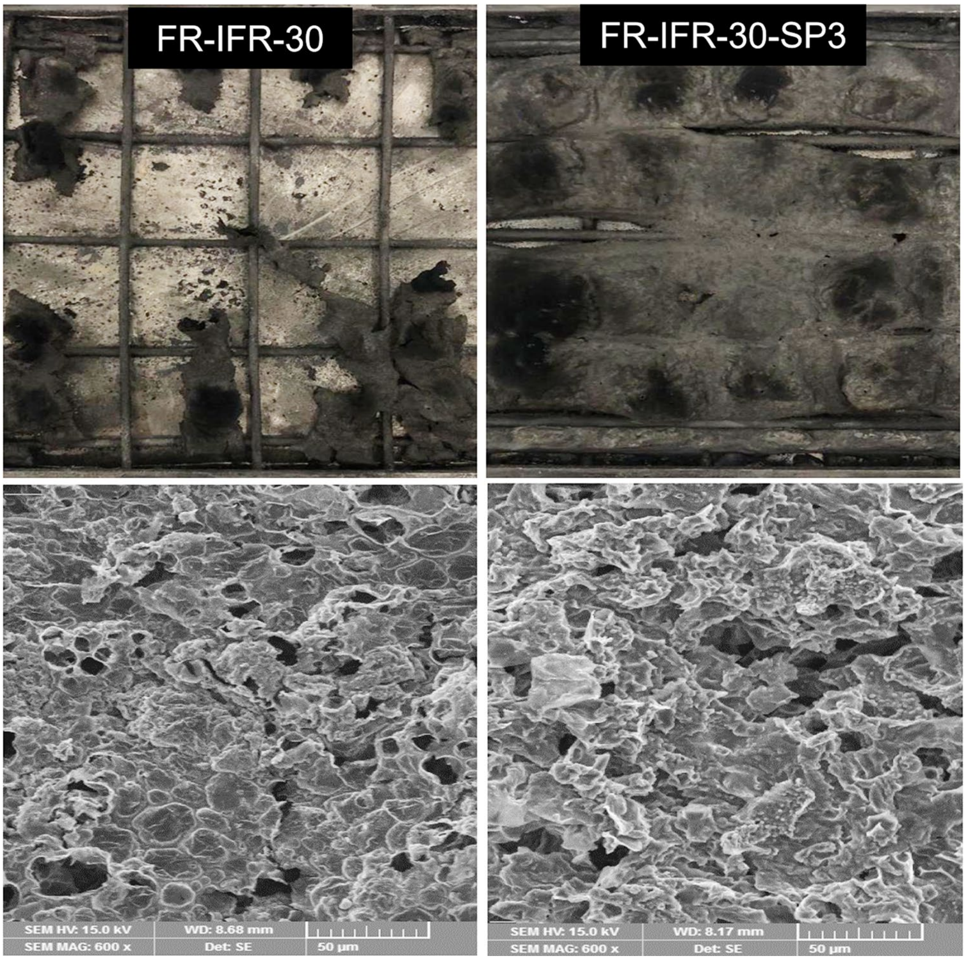
Graphical abstract



Keyword Flame retardant · Intumescent flame retardant · Nanoclay · Polyolefin elastomer · Sepiolite

Introduction

Polyolefin elastomers (POEs) commonly used in film, building pipe, wire, and cable industries are copolymers of ethylene and butene or octene [1, 2]. In addition to their unique mechanical properties, low cost, availability, and processability, POEs provide excellent impact properties in blends with polypropylene and polyethylene. Besides, they contain side-chain double bonds that can be easily cross-linked by silane, peroxide, or irradiation. The cross-linking of POEs provides exceptional mechanical properties such as good weather resistance, higher thermal aging and compression set making them excellent materials for electrical insulation [3]. The limiting oxygen index (LOI) values of POEs, which are flammable polymers in their pure state, are around 17%, so their industrial application is greatly restricted. Many halogenated and non-halogenated (halogen-free) flame-retardants are widely used to overcome this problem and improve their flammability properties [4]. The brominated (such as pentabromodiphenyl ether, decarbomodiphenyl oxide, and brominated epoxy) and chlorinated (such as dodecachlorodimethanodibenzocyclo-octane and chlorinated paraffins) compounds, organophosphorus (triaryl phosphates and alkyl phosphates), and inorganic metal hydroxides (aluminum trihydroxide (ATH) and magnesium dihydroxide (MDH)) are commercially available halogenated and halogen-free flame-retardant additives [5, 6]. Among these, halogenated flame retardants are the most effective to improve the flame retardancy of polyolefins, though their use in many applications is strictly limited due to the release of hazardous and corrosive by-products [7]. Therefore, many researchers have mainly focused on developing alternatives to halogenated flame retardants to find less toxic and more environmentally friendly halogen-free flame retardants [8]. Currently, both ATH and MDH are widely used as halogen-free flame retardants acting by absorbing heat, releasing water, and forming a protective oxide layer that could slow down the release of the polymer degradation products into the flame zone. However, a high loading rate (at least 60% by mass) is required in the polyolefin system to achieve high flame retardant efficiency [9]. Such a high level of loading deteriorates the mechanical properties and processing of the composites, and this limits the application of both ATH and MDH as flame retardants [10, 11]. Compared to metal hydroxides, intumescent flame retardants (IFRs) provide more effective flame retardant polyolefins by the formation of intumescent char layers through a series of chemical reactions including esterification, carbonization, expansion, and solidification [12]. The IFRs mainly consist of an acid source (e.g., ammonium polyphosphate, APP), a carbon source (e.g., pentaerythritol, PER) and a gas source (e.g., melamine, MEL) to form an intumescent char layer that suppresses heat and mass transfer from the surface of the material [13]. The main advantage of the IFRs is the reduction of heat generated during combustion due to the formation of carbon rather than the release carbon monoxide and carbon dioxide [14]. Recently, the addition of nanoparticles such as nanoclays [15, 16] (montmorillonite, sepiolite) and carbon nanotubes [17] in the IFRs system has significantly increased flame-retardant properties and anti-drip behavior of the thermoplastics [18].

In this study, the effect of IFR (APP/PER) in the presence of sepiolite (SP) nanoclay on the mechanical properties, thermal stability, flame-retardant properties, and morphology of the POE/linear low-density polyethylene (LLDPE) blends [19] as a cable outer sheath compound was entirely investigated by tensile test, thermogravimetric analysis, fire testing technology limiting oxygen index analyzer, cone calorimeter, and scanning electron microscopy. The nine different compounds were prepared using POE and LLDPE as polymer matrix, antioxidant, lubricant as additives, and APP/PER as IFRs with various loading ratios. The mechanical and physical properties of the obtained compounds were compared with reference sample containing 60% ATH as inorganic flame retardant in terms of thermogravimetric analysis (TGA), limiting oxygen index (LOI), heat release rate (HRR) and total heat release (THR), smoke production rate (SPR) and total smoke production (TSP), tensile strength and elongation-at-break and density.

Experimental

Materials

POE (ethylene octene copolymer, Engage™ 8003, Dow Chemical Company, Italy) $d = 0.885$ g/mL, MFI: 1 g/10 min, 2.16 kg at 190 °C, LLDPE (Clearflex CL B0, MFI, 2.16 kg, 190 °C) $d = 0.911$ g/mL, 3 g/10 min, Versalis S.p.A, Italy) and coupling agent (Fusabond® E226, DuPont Company, Switzerland), $d = 0.930$ g/cm^3, MFI: 1.75 g/10 min, 2.16 kg at 190 °C), were purchased, respectively. APP (Exolit AP 423, Clariant, Switzerland) having particle size $n > 1000$, and PER (MKS Marmara Entegre Kimya Sanayi AS, Turkey) having particle size max 70% above 100 µm were kindly supplied. Sepiolite clay (SP, Adins Clay 80 T, organomodified silane, Tolsa Group, Spain), antioxidant (Great Lakes, Germany), lubricant (Sinar Mas, Indonesia) and aluminum trihydroxide (ATH, $Al(OH)_3$, Albemarle Corporation, Germany) were purchased and used as received.

Preparation of compounds

In this study, nine different cable outer sheath compounds were prepared according to the formulations given in Table 1. APP and PER were used as IFR components. APP acted as both the acid source and blowing agent, while PER was used as a carbonizing agent during the combustion [13]. Compounds with 25–60% IFR as flame retardant additive and a reference sample containing ATH were prepared. The ratio of APP/PER mixture was adjusted to 3:1, which gives the maximum flame retardancy performance for APP + PER combinations [20]. Additionally, sepiolite clay was added to 4 different compounds containing IFRs to examine the synergistic effect for the droplet. The compounds were prepared by mixing in one step. First, POE, LLDPE, and coupling agent were mixed with a twin-screw counter-rotating Brabender until the temperature of 120 °C increased to 130 °C. The APP, PER, and clay were then added to the molten mixture. The mixing process was continued until the temperature reached 185 °C. Antioxidants and lubricants were added, and the final compound was obtained at 195 °C (Scheme 1). The extrudate compounds were cut into pellets and hot-pressed by Polystat 200 T at 185 °C for 5 min without pressure and then for an additional 3 min at 200 bar on test strips for mechanical and flammability tests. Finally, with a guillotine trimmer, the test specimens with dimensions of $150 \times 10 \times 4$ mm^3 for LOI test and $100 \times 100 \times 1$ mm^3 for cone calorimeter test were prepared.

Table 1 Formulations of the compounds under study

No[a]	POE % (by wt)	LLDPE % (by wt)	CA % (by wt)	APP[b] % (by wt)	PER[b] % (by wt)	AOx % (by wt)	LUB % (by wt)	SP % (by wt)	Total[c] % (by wt)
FR-ATH-60[d]	25.47	9.80	3.92	–	–	0.27	0.55	–	100
FR-IFR-60	25.47	9.80	3.92	45	15	0.27	0.55	–	100
FR-IFR-40	38.2	14.69	5.88	30	10	0.41	0.82	–	100
FR-IFR-30	44.56	17.14	6.86	22.5	7.5	0.48	0.96	–	100
FR-IFR-25	47.75	18.36	7.35	18.75	6.25	0.51	1.03	–	100
FR-IFR-30-SP3	42.66	16.41	6.56	22.5	7.5	0.46	0.92	3	100
FR-IFR-30-SP5	41.38	15.92	6.37	22.5	7.5	0.45	0.89	5	100
FR-IFR-25-SP3	45.84	17.63	7.05	18.75	6.25	0.49	0.99	3	100
FR-IFR-25-SP5	44.57	17.14	6.86	18.75	6.25	0.48	0.96	5	100

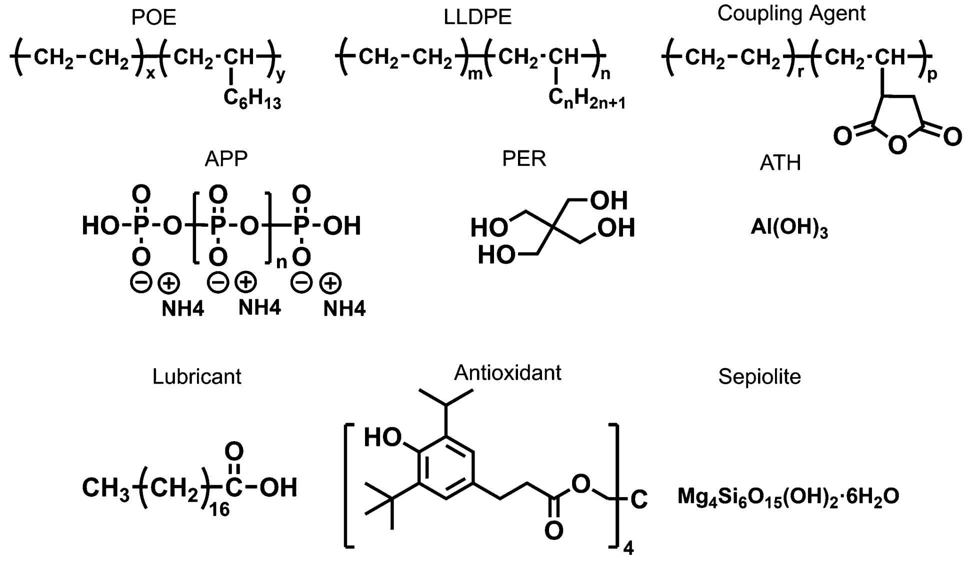
[a] *POE* polyolefin elastomers, *LLDPE* linear low-density polyethylene, *CA* coupling agent, *APP* ammonium polyphosphate, *PER* pentaerythritol, *AOx* antioxidant, *LUB* lubricant, *SP* sepiolite, *ATH* aluminum hydroxide

[b] APP/PER ratio: 3/1

[c] The ratio of all ingredients was % (by wt) and total of all compounds was equal to 100% (by wt)

[d] The reference sample contains Al $(OH)_3$ with 60% (by wt)

Scheme 1 Chemical structures of materials



Characterization methods

Mechanical tests and physical properties

Mechanical properties of the compounds such as tensile strength and elongation-at-break were tested according to IEC 60,811–501 and IEC 60,811–401 standards. These tests were performed with a Zwick Z050 Tensile Testing Machine (Germany) under different conditions before aging at ambient temperature and after aging for 7 days at 100 °C. Also, physical properties of the compounds such a density were measured appropriately with IEC 60,811–606 standard.

Flammability tests

LOI is an important parameter for evaluating the flame retardancy of compounds under the same conditions. In this study, LOI values of test samples prepared from the compounds with dimensions of $150 \times 10 \times 4$ mm^3 were measured using Fire Testing Technology Limiting Oxygen index analyzer instrument (Netzsch, Germany) according to the standard oxygen index test, ISO 4589–2.

The cone calorimeter (FTT, UK) is a standard apparatus in fire retardant tests (ISO 5660–1). The compound samples (each 100 × 100 × 1 mm^3) are placed horizontally on a balance and irradiated at a heat flux of 50 kW/m^2.

Thermal analysis

TGA tests of the compounds were carried out using a T500 Thermal Gravimetric Analyzer (USA) at a linear heating rate of 10 °C/min within the temperature range from ambient to 1000 °C. Nitrogen was used with a carrier gas flow of 60 mL/min during analysis. The weight of each sample was adjusted to be 9 ~ 10 mg.

Scanning electron microscopy (SEM) analysis

SEM (Tescan, Czech Republic) analysis was used to investigate the char residue on the surface of compounds under study. The char residue on the surface was obtained from the cone calorimeter test. The accelerating voltage was set on 15.0 kV. The sample surface was sputter-coated with a gold layer by Cressington 108Auto (USA).

Table 2 Requirements of ST_8 in IEC 60,502–1

Tests performed	Symbol and unit	Specification value
Before aging		
Minimum tensile strength	TS_{min} (N/mm^2)	9
Minimum elongation-at-break	ε_{125} (%)	125
After aging (100 ± 2 °C, 168 h)		
Minimum tensile strength	TS_{min} (N/mm^2)	9
Maximum variation	MV_{40} (%)	± 40
Minimum elongation-at-break	ε_{100} (%)	100
Maximum variation	MV_{40} (%)	± 40

Results and discussion

Currently, there are many types of cables designed for applications ranging from communication to heavy industrial use. Each cable needs to be produced from specific formulations and must pass the rigorous mechanical, environmental and fire tests fully complied with certification requirements. For halogen-free flame-retardant cables, polymers such as POE, ethylene–vinyl acetate, LLDPE or thermoplastic polyurethane have been chosen as soft materials for compounding [21]. The outer jacketing material of these types of cables should meet the ST_8 in IEC 60,502–1 standard that exhibits restricted flame spread properties, low levels of smoke emission, and halogen-free gas emission when exposed to fire (Table 2) [22].

Mechanical and physical properties

Mechanical properties such as tensile strength and elongation-at-break, as well as the densities of the compounds are shown in Table 3. The dumb-bell samples were prepared from all compounds to measure their tensile strength and elongation-at-break values before and after aging. The reference compound, FR-ATH-60, met the mechanical requirements of ST_8 in IEC 60,502–1 with a minimum tensile strength of 12.45 and 12.23 N/mm^2 and a minimum elongation-at-break of 244 and 219% before/after aging. At high loading levels of IFRs, the FR-IFR-60 compound displayed a lower tensile strength value than the minimum requirements of ST_8 in IEC 60,502–1. Nonetheless, it was clear in the literature that the loading of IFR was not required as high as that of ATH to have similar flammability [23]. In general, the polymeric materials with LOI values greater than 26 can be considered to have flame retardant properties

Table 3 Mechanical tests on ST_8 in IEC 60,502–1, density and LOI values of compounds

	Before aging		After ageing					
No	TS_{min} (N/mm^2)	ε_{125} (%)	TS_{min} (N/mm^2)	MV_{40} (%)	ε_{100} (%)	MV_{40} (%)	ρ^d (g/cm^3)	LOI (%)
FR-ATH-60	12.45	244	12.23	− 1.8	219	− 10.2	1.43	28
FR-IFR-60	8.38	617	6.85	− 18.3	590	− 4.4	1.25	63
FR-IFR-40	12.82	645	13.40	4.50	631	− 2.2	1.10	31
FR-IFR-30	17.46	707	17.49	0.20	701	− 0.8	1.04	27
FR-IFR-25	22.33	728	14.88	− 33.3	661	− 9.2	1.01	26
FR-IFR-30-SP3	18.41	663	12.35	− 32.9	659	− 0.6	1.07	30
FR-IFR-30-SP5	15.84	698	12.44	− 21.5	620	− 11.2	1.07	29
FR-IFR-25-SP3	20.53	673	16.82	− 18.1	680	1.0	1.04	29
FR-IFR-25-SP5	19.56	730	14.81	− 24.3	646	− 11.5	1.04	27

[16, 24]. Therefore, a decrease of IFRs ratio from 40 to 25% not only improved tensile strength and elongation-at-break values for the requirements of ST_8 in IEC 60,502–1 but also provided the mandatory flammability requirements. The FR-IFR-40 compound containing 40% IFRs displayed 31% LOI value whereas the samples with less than 40% IFRs (FR-IFR-30 and FR-IFR-25) showed the lowest LOI values (27 and 26%). By adding 3 and 5% sepiolite clay as an anti-dripping agent to the compounds, the LOI values of FR-IFR-30 and FR-IFR-25 slightly increased between 27 and 30%, which was higher than those of flame retardants in the literature [16, 24–26]. At high SP clay content (5% loading), the LOI values of both FR-IFR-30 and FR-IFR-25 were slightly decreased due to the agglomeration of clay plates [14]. This reduction was also determined from tensile strength and elongation-at-break values of these compounds. Comparing the FR-ATH-60 reference sample with the FR-IFR-30 and FR-IFR-25 compounds, it was determined that although they had similar LOI values of around 28–30%, their concentrations were lower than that of reference sample. It was determined that 0.25 less compound would be consumed during cable production since they were approximately 26% lighter than the FR-ATH-60.

Thermogravimetric analyses

The TGA and derivative thermogravimetry (DTG) curves of the initial materials and designed compounds are shown in Figs. 1 and 2. To further investigate the thermal degradation mechanism, the $T_{5\%}$, $T_{50\%}$, and T_{max} were noted in Table 4 as temperatures at 5% weight loss, 50% weight loss, and maximum degradation rate temperatures, respectively. The $T_{5\%}$ gave information of the temperature at which the initial weight loss of the compounds reached 5%, where for neat POE and LLDPE 405.9 and 408.3 °C were estimated. The neat POE and LLDPE also displayed single thermal degradation step between 400 and 500 °C with 475.8 and 468.5 °C as T_{max}. After adding 60% by weight of both ATH and IFR to the POE/LLDPE compounds, the $T_{5\%}$ of FR-ATH-60 and FR-IFR-60 compounds were gradually decreased to 312.3 oC and 209.7 °C. Still, T_{max} values of these compounds were significantly improved to 493.3 and 495.4 °C. Initial thermal degradations of FR-ATH-60 and FR-IFR-60 could be due to the chemical structure of the flame-retardant additives (ATH and APP/PER).

The effect of IFR concentration on the thermal stability of the prepared compounds was also investigated by TGA test in obtaining $T_{5\%}$, $T_{50\%}$, and T_{max} values. The $T_{5\%}$ values of FR-IFR-30 and FR-IFR-25 were gradually increased with decreasing concentration of IFR from 60 to 25%. Nevertheless, the $T_{50\%}$ and T_{max} values of FR-IFR-30 and FR-IFR-25 were slightly decreased from 495.4 to 493.9 °C. On the other hand, the addition of 3% (by wt) SP clay into the compounds decreased the $T_{50\%}$, and T_{max} values of FR-IFR-30 and FR-IFR-25 compounds. A decrease in $T_{5\%}$ indicated that the presence of IFR accelerated the thermal decomposition of the designed compounds [27]. The higher $T_{50\%}$ and T_{max} values were attributed to the char layer formed during the thermal degradation of the compounds, which protected the cable from decomposition and the backbone thermal degradation [7]. Moreover, a similar situation was also valid for FR-ATH-60 as reference compound, since the endothermic decomposition of ATH was at relatively low temperature (200–350 ºC), forming water and residual alumina, absorbing heat from the surroundings and retarding the flame spread or resisting an initial ignition [28].

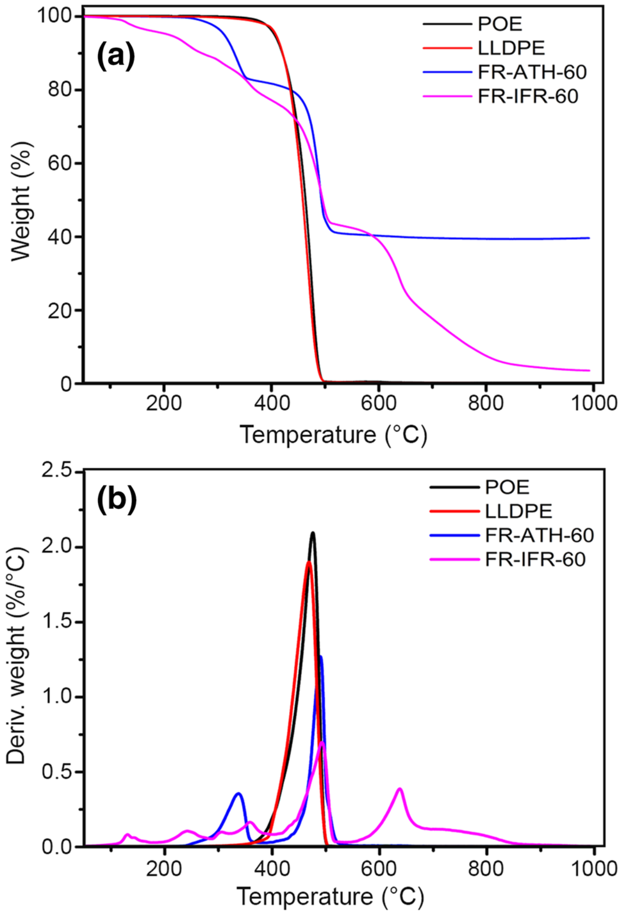


Fig. 1 TGA **a** and DTG **b** curves of POE, LLDPE, FR-ATH-60 and FR-IFR-60

The addition of flame-retardant additives quantitatively increased the char yield from 0.5% to 40.3% due to the carbonization reactions of polymers with the ATH or IFR system [29]. It was also noted that the char yields of FR-IFR-30 and FR-IFR-25 compounds were decreased

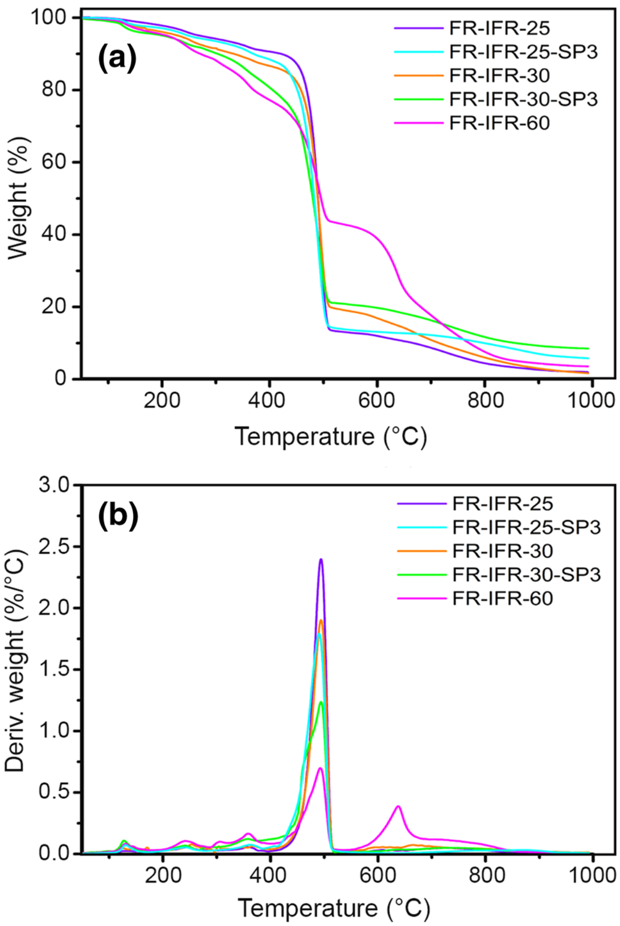


Fig. 2 TGA **a** and DTG **b** curves of FR-IFR-60, FR-IFR-25, FR-IFR-25-SP3, FR-IFR-30 and FR-IFR-30-SP3

Table 4 TGA data of the compounds

No	$T_{5\%}$[a] (°C)	$T_{50\%}$[b] (°C)	T_{max}[c] (°C)	Char yield[d] (%)
POE	405.9	463.6	475.8	0.5
LLDPE	408.3	458.5	468.5	0.3
FR-ATH-60	312.3	489.8	493.3	40.3
FR-IFR-60	209.7	492.5	495.4	38.9
FR-IFR-30	230.2	489.4	493.9	16.9
FR-IFR-25	270.8	489.9	493.9	12.0
FR-IFR-30-SP3	203.5	480.2	493.8	19.8
FR-IFR-25-SP3	249.8	482.8	490.2	13.1

[a] Temperature at 5% weight loss

[b] Temperature at 50% weight loss

[c] The maximum rate degradation temperature

[d] Char yield at 600 °C

in parallel with the decreasing concentration of IFR. Furthermore, the inclusion of 3% (by wt) SP clays clearly improved the char yields of FR-IFR-30-SP3 and FR-IFR-25-SP3 compounds (Table 4).

Cone calorimeter study

For the quantitative analysis of material flammability, the cone calorimeter has gained wider acceptance for testing various fire reactions and parameters including heat release rate (HRR) and total heat release (THR), time to ignition (TTI), smoke production rate (SPR) and total smoke production (TSP) [6]. The results from the cone calorimeter are shown in Fig. 3 and the data are summarized in Table 5. Like other olefinic polymers, pure POE burned rapidly after ignition, resulting in a single sharp peak at 1025.3 kW/m^2 HRR and 49.0 MJ/m^2 THR values [13]. The HRR and THR values of FR-ATH-60 were determined as 317.8 kW/m^2 and 34.2 MJ/m^2, considerably lower than POE's values. With the addition of IFRs, HRR and THR values of both FR-IFR-25 and FR-IFR-30 considerably decreased to 630.0 and 545.8 kW/m^2, and 36.7 and 35.4 MJ/m^2, respectively. The incorporation of IFRs into the POE/LLDPE system effectively enhanced the flame retardancy of the compounds by reducing HRR and THR values of FR-IFR-30 and FR-IFR-25 [29]. During the combustion of FR-IFR-30 and FR-IFR-25, the char layer formed from the intumescent coating preventing the transfer of heat and oxygen to the inner parts of the matrix and acting as a thermal insulation for the materials [7]. The HRR and THR values also improved to 441.8 and 460.2 kW/m^2, and 34.7 and 35.0 MJ/m^2 by the addition of 3% (by wt) SP clay to the FR-IFR-30 and FR-IFR-25 compounds. These results implied that SP clay generated a synergistic effect on combustion with IFRs. Additionally, the TTI of FR-ATH-60 was significantly improved from 29 to 44 s compared to that of POE. Notably, the TTIs of FR-IFR-30 and FR-IFR-25 were determined as 20 s and 22 s that were surprisingly lower than TTI of POE. Addition of SP clay to these compounds increased the TTI values from 20 to 24 and from 22 to 23 s, which were still lower than the TTI of neat POE. The reduction of TTI implied that the inclusion of flame-retardant additives led to a rapid increase in the surface temperature of the sample due to the formation of a char layer, which then caused rapid decomposition of the polyolefins as previously reported [30]. The incorporation of IFRs in compounds also significantly increased the SPR and TSP values, as other important parameters for the flame-retardant materials. This could be due to the decomposition of intermediates in the compounds leading to increase smoke yields. However, the addition of SP clay remarkably reduced the smoke emission as well as the SPR and TSP values [15].

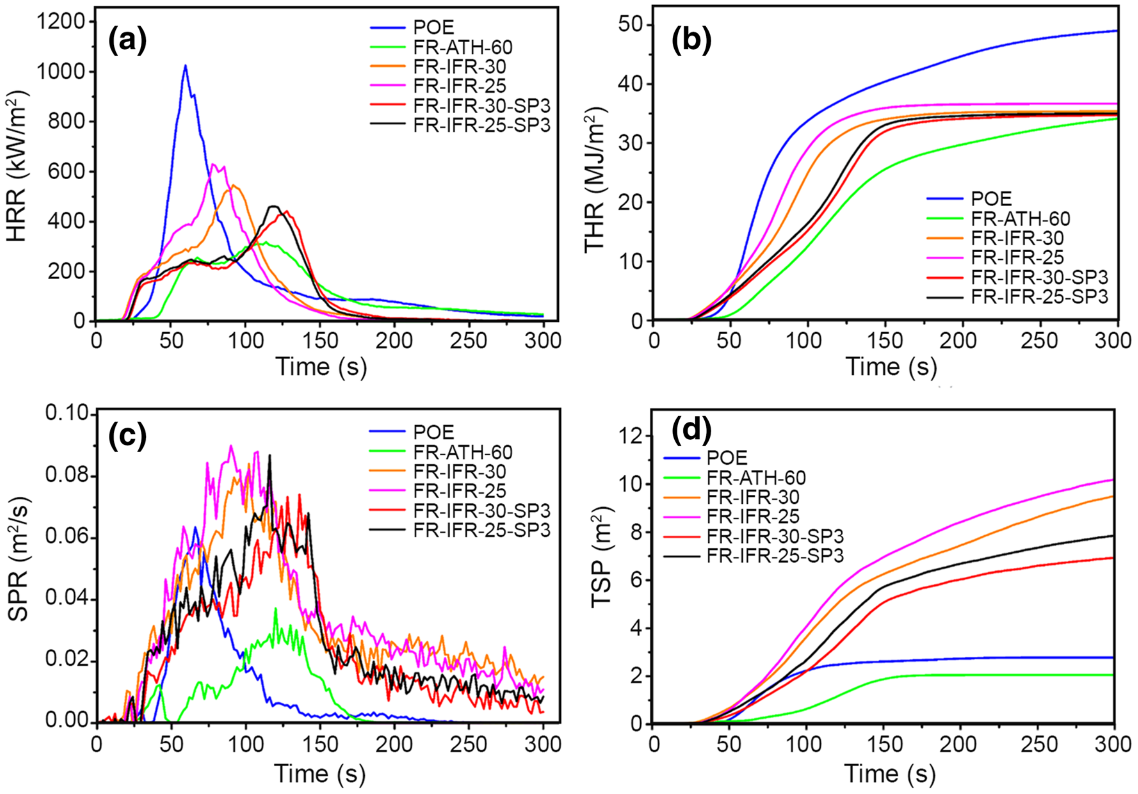


Fig. 3 HRR **a**, THR **b**, SPR **c,** and TSP **d** curves of the POE, FR-ATH-60, FR-IFR-60, FR-IFR-25, FR-IFR-25-SP3, FR-IFR-30 and FR-IFR-30-SP3

Table 5 Cone calorimeter data of selected compounds

No	TTI (s)	Maximum HRR (Kw/m^2)	THR (MJ/m^2)	SPR (m^2/s)	TSP (m^2)
POE	29	1025.3	49.0	0.0102	2.7
FR-ATH-60	44	317.8	34.2	0.0043	2.1
FR-IFR-30	20	545.8	35.4	0.0339	9.5
FR-IFR-25	22	630.0	36.7	0.0366	10.2
FR-IFR-30-SP3	24	441.8	34.7	0.0249	6.9
FR-IFR-25-SP3	23	460.2	35.0	0.0283	7.9

Residue morphology

The morphology of the char residues of FR-ATH-60, FR-IFR-30 and FR-IFR-30-SP3 after cone calorimeter tests was further investigated and digital photographs of the residual chars are presented in Fig. 4. The type of flame retardant additives directly affected the residues clearly visible in the digital images of the samples. The FR-ATH-60 sample formed an effective inorganic barrier with significant charring as indicated by the white color of the fluffy residue. On the other hand, the FR-IFR-30 residue presented an expanded honeycomb-like structure with various cracks and holes on its surface. At high temperatures, the resulting char layers were not compact and had less strength to act as a thermal insulation barrier [27]. To overcome this problem, the SP clay was included in the formulations as an anti-dripping agent. Compared to FR-IFR-30, the FR-IFR-30-SP3 sample demonstrated a smoother and more compact carbonaceous residue with less cracks and holes on their surface. This could be explained by the fact that the addition of SP clay reduced the burning rate, limited the heat and mass transfer to the surface, and provided higher thermal stability for the material.

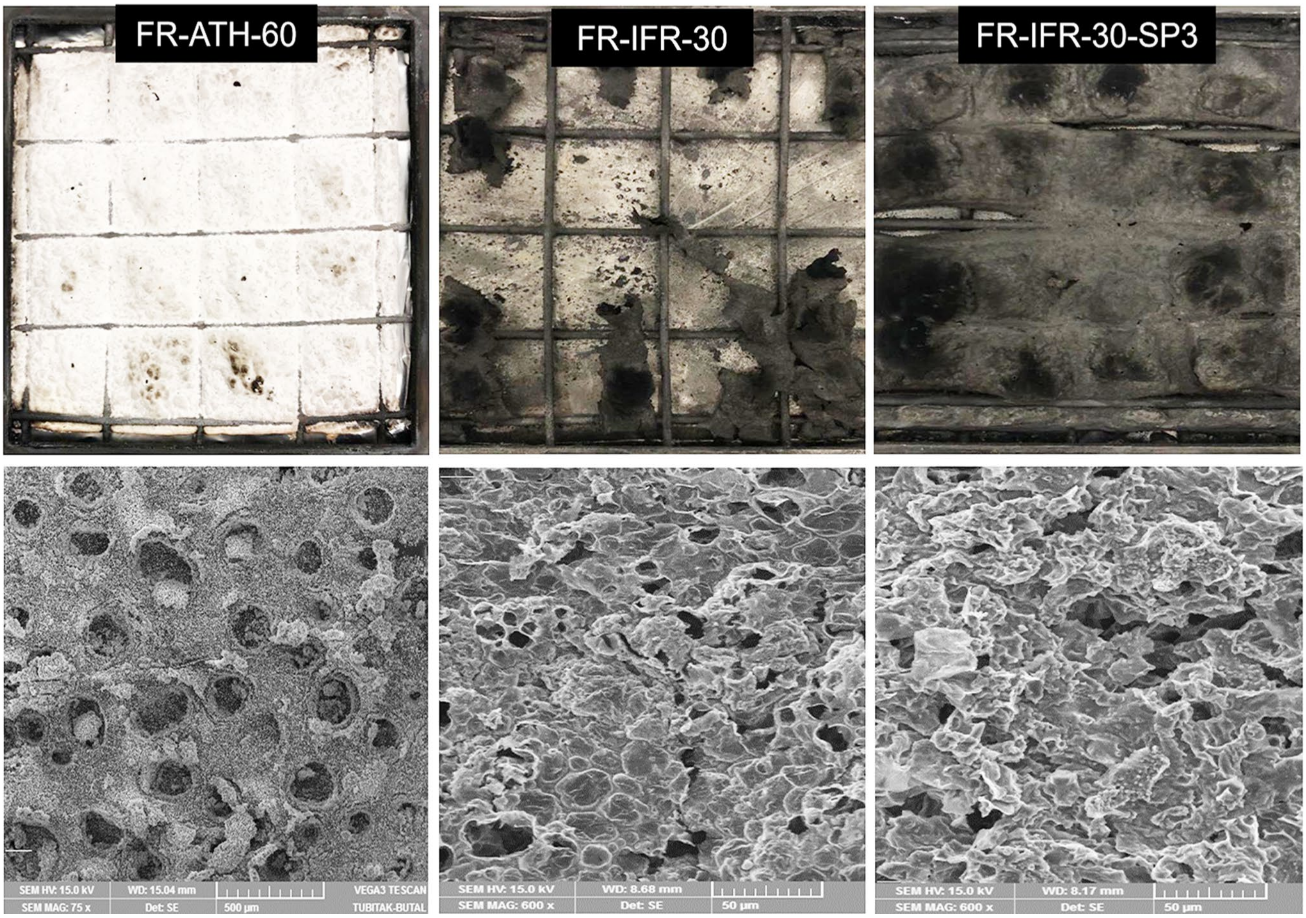


Fig. 4 Digital and SEM images of the charred residues generated by FR-ATH-60, FR-IFR-30 and FR-IFR-30-SP3 after cone calorimetry

Conclusion

The influence of SP nanoclay and APP/PER as IFR additives on the mechanical, thermal, flame-retardant, and morphological properties of POE/LLDPE based compounds was systematically investigated. The physical properties of the obtained compounds with different SP and IFR loadings were compared with the reference sample containing 60% (by wt) ATH as a flame-retardant additive. Although reducing the amount of IFRs from 40 to 25% decreased the LOI values of the compounds from 31 to 26%, their mechanical properties met the requirements of the ST_8 type cable standard. Furthermore, the addition of organomodified SP nanoclay as an anti-dripping agent with 3% loading enhanced not only the LOI values but also mechanical properties of the obtained compounds. Due to the agglomeration of clay plates, LOI and mechanical properties of the resulting compounds were decreased at high SP nanoclay with 5% loading. By increasing IFR concentration, the obtained compounds displayed slightly better thermal properties including $T_{5\%}$, $T_{50\%}$, and $T_{\max}$ values, and char yields in the absence or presence of SP nanoclay. The heat release rate and total heat release values were significantly improved by adding both IFR and SP, whereas the TTI, SPR and TSP values of the compounds were deteriorated compared to pure POE. These results were confirmed by previous literature and explained as the earlier decomposition of the flame-retardant additives caused a rapid increase in the surface temperature of the sample. The addition of SP nanoclay not only has improved the TTI, SPR and TSP values it has still limited the heat and mass transfer on the surface of the compounds by reducing the burning rate that confirmed by SEM analysis with a smoother and more compact carbonaceous residue with fewer cracks and holes on their surfaces. Overall, an additional synergetic effect of organomodified SP nanoclay in combination with IFR additives will simply be applied in the production of the outer sheath compounds of halogen free flame-retardant cables.

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Declaration

Data availability Data available on request from the authors.

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