

# Improving Reaction to Fire Properties of Thermoplastic Polyurethane with Intumescent Flame Retardants and MoS<sub>2</sub>

Leila Taghi-Akbari<sup>1</sup>, Mohammad Reza Naimi-Jamal<sup>1,\*</sup>, Shervin Ahmadi<sup>2</sup>

\* naimi@iust.ac.ir

<sup>1</sup> Research Laboratory of Green Organic Synthesis and Polymers, Department of Chemistry, Iran University of Science and Technology, 16846-13114, Tehran, Iran

<sup>2</sup> Iran Polymer and Petrochemical Institute (IPPI), 14965-115, Tehran, Iran

Received: September 2023

Revised: December 2023

Accepted: December 2023

DOI: 10.22068/ijmse.3387

**Abstract:** Two-dimensional molybdenum disulfide (MoS<sub>2</sub>) is used as a promising flame retardant and smoke suppressant nano additive in polymer composites due to its high thermal stability and layered structure. In this study, thermoplastic polyurethane (TPU) was melt-blended with MoS<sub>2</sub> (1 wt. %) and a halogen-free intumescent flame retardant (IFR) system. The IFR system consisted of ammonium polyphosphate (APP), Melamine polyphosphate (MPP), and pentaerythritol (PER), with a total amount of 25 wt.%. The TPU/IFR/MoS<sub>2</sub> composite exhibited outstanding flame-retardant properties, achieving a UL-94 V-0 rating and a limiting oxygen index (LOI) value of 34%. Reaction-to-fire performance of the TPU/IFR/MoS<sub>2</sub> composite was evaluated by cone calorimeter test (CCT). The CCT results indicated high flame-retardant efficiency and considerable smoke suppression performance, along with a significant decrease in the peak heat release rate (PHRR: 65.9%), peak smoke production rate (PSPR: 65.6%), and peak CO production (PCOP: 60.7%) compared to the neat TPU. The significant improvement in fire performance of TPU composite was mainly attributed to the effects of the physical barrier of MoS<sub>2</sub> and catalytic carbonization of the IFR system. These formed an intumescent compact carbonized layer during the combustion, effectively restricting dripping. FESEM revealed the continuous structure of the residual char. Thermogravimetric analysis (TGA) indicated improved thermal behavior of the TPU composite in high temperatures. This work provides an effective method to improve the reaction to fire of TPU composites by incorporating traditional IFRs and MoS<sub>2</sub>, resulting in enhanced fire safety.

**Keywords:** Reaction to fire, Intumescent flame retardant, MoS<sub>2</sub>, Thermoplastic polyurethane, Heat release rate.

## 1. INTRODUCTION

Flame retardancy, smoke suppression, and anti-dripping performances are principal considerations in the fire safety of flammable polymeric materials such as thermoplastic polyurethane (TPU). TPU, as a high-performance engineering plastic, is widely used in many industrial branches like cable and electric wiring, automotive, building, and medical devices due to its excellent properties such as outstanding abrasion resistance, high elastic properties, good processability, high chemical stability and mechanical performance [1-2]. These applications are limited due to the high flammability of TPU. Therefore, it is required to improve its fire reaction performance. TPU, like most polymeric materials, burns and generates high amounts of heat, smoke, and toxic gases with lots of dripping [3]. Hence, improving the fire behavior of TPU, while preserving its thermal and mechanical properties, is crucial. Nowadays, widespread research on developing effective flame retardants is performed to reduce fire

hazards [4-5]. Among them, intumescent flame retardant additives (IFRs), especially those containing both nitrogen (N) and phosphorus (P), are considered effective environmentally friendly halogen-free flame retardants (FRs) for improving the flame retardant properties of TPU. IFRs exhibit good flame retarded efficiency and low smoke and toxicity [6-8]. The IFR system is comprised of three components: an acid source, such as ammonium polyphosphate (APP), a charring agent, and a blowing agent, like pentaerythritol (PER) and melamine compounds that facilitate the formation of a protective char layer during combustion. According to the previously reported studies [9], a high loading amount of intumescent flame retardants is needed to achieve the desired flame retardant effect, which can deteriorate the physical properties. Hence, introducing synergistic agents can be responsible [10].

In recent years, nanoscale fillers, as a promising generation of flame retardant and smoke suppressant synergist agents, have attracted wide attention in the field of fire safety. In Particular,

the use of two-dimensional (2D) nanomaterials, such as black phosphorus [11], molybdenum disulfide [12-14], graphene [15-16], Nano silica [17], and their derivatives, is increasing due to their ability to enhance thermal stability, flame retardant properties, and smoke suppression. It is achieved by forming a dense carbon structure as an effective thermal/physical barrier on the surface of the polymer. The most significant advantage of the synergistic agents is their low loading amounts due to their high aspect ratio [18-19]. One of the effective two-dimensional (2D) flame retardants is molybdenum disulfide ( $\text{MoS}_2$ ) which has high thermal stability and good smoke suppression performance.  $\text{MoS}_2$ , like graphene, has a hexagonal structure and falls into the category of layered nanomaterials [20]. The thermal conductivity of  $\text{MoS}_2$  is lower than that of graphene, which can delay thermal degradation by hindering the heat transfer within the polymer matrix [21].

According to the literature, incorporating  $\text{MoS}_2$  into the polymer composite promotes char-forming, thereby enhancing flame retardancy and smoke suppression characteristics in the polymer. According to Wang's study,  $\text{MoS}_2$  added to the waterborne polyurethane (WPU) improves the thermal and mechanical properties [22]. The effects of carbon microspheres (CMS) and  $\text{MoS}_2$  core-shell structure to enhance flame retardant properties of fireproof coating based on APP/MPP/PER in epoxy were studied by Chen et al. [23]. The findings showed excellent flame retardancy and smoke suppression performance. It has been reported that the combination of  $\text{MoS}_2$  with other flame retardants prevents the aggregation of  $\text{MoS}_2$  (due to van der Waals forces in the  $\text{MoS}_2$  alone) and enhances its flame retardant efficiency [24]. Qian et al. studied the incorporation of  $\text{MoS}_2$  into TPU and observed significant reductions in heat and smoke released and a decrease in toxic volatiles emitted during combustion. Recently, Feng et al. reported a synergistic effect of nickel phosphide ( $\text{Ni}_2\text{P}$ ) nanoparticles and molybdenum disulfide ( $\text{MoS}_2$ ) nanosheets on enhancing flame retardancy and smoke suppression of thermoplastic polyurethane (TPU) [25].

Nevertheless, our current knowledge indicates a lack of extensive research on the flame retardant application of  $\text{MoS}_2$  in improving the fire performance of TPU. The present study aims to

investigate the effects of the  $\text{MoS}_2$  and a traditional IFR system, consisting of APP, PER, and MPP with a mass ratio of 3:1:1, on flame retardancy and smoke suppression of TPU composite. This study is considered a novel addition to the existing literature since there has been no previous report on this topic.

## 2. EXPERIMENTAL PROCEDURES

### 2.1. Materials

A polyester-based thermoplastic polyurethane (TPU) (Estane® 58277) was obtained from Lubrizol. APP (Exolit® AP 422) was purchased from Clariant. Melamine polyphosphate (Melapur200) was obtained from BASF, and Pentaerythritol (PER) was provided by the MERCK group. Molybdenum disulfide ( $\text{MoS}_2$ ) powder was supplied by Sigma Aldrich with a density of  $5.06 \text{ g/cm}^3$ .

### 2.2. Sample Preparation

Before mixing, TPU was dried at  $80^\circ\text{C}$  for 12 h, and the IFR components (APP/MPP/PER) were dried at  $100^\circ\text{C}$  for 10 h in a vacuum oven. TPU composite was prepared by adding 15 wt.% APP, 5 wt.% PER, 5 wt.% MPP, and 1 wt.%  $\text{MoS}_2$  by melt mixing at  $170^\circ\text{C}$  for 5 min. The TPU sheets were prepared by a hot press machine. The thicknesses of the TPU samples were 3 mm.

### 2.3. Characterization

The limiting oxygen index (LOI) was performed according to ASTM D2863 on the samples with dimensions of  $(130 \times 6.5 \times 3.2) \text{ mm}^3$  by HC-2 oxygen index meter (China).

The UL 94 vertical burning test was performed according to the ASTM D3801 test method on the samples with dimensions of  $130 \text{ mm} \times 13 \text{ mm} \times 3.2 \text{ mm}$ .

Thermal stability was characterized by TGA analysis under a nitrogen/ $\text{O}_2$  atmosphere using a TGA-Mettler (Mettler Toledo, Switzerland) instrument. TPU samples were heated from room temperature to  $600^\circ\text{C}$  with a heating rate of  $20^\circ\text{C}/\text{min}$  under  $\text{N}_2$  atmosphere and up to  $800^\circ\text{C}$  in airflow.

The reaction to fire performance was evaluated by an FTT Dual Cone Calorimeter apparatus (Fire Testing Technology, UK), according to ISO 5660-1 standard test method under a radiant heat flux of  $50 \text{ kW.m}^{-2}$ . The dimensions of the TPU samples were  $(100 \times 100 \times 3) \text{ mm}^3$ . The wrapped

specimen in aluminum foil was exposed to the heat flux horizontally.

Field emission scanning electron microscopy (FE-SEM) was used for the microstructure analysis using a FESEM TESCAN MIRA-III at 20 kV acceleration voltage.

### 3. RESULTS AND DISCUSSION

#### 3.1. Flammability

The flammability results are given in Table 1. As seen in Table 1, there is no rating for TPU in the UL 94 vertical burning test, while a V-0 rating was achieved for TPU/IFR/MoS<sub>2</sub> composite. It shows that TPU/IFR/MoS<sub>2</sub> effectively inhibits melt-dripping in TPU composite; in contrast, TPU burns fast with high dripping. LOI is an important index to evaluate flame retardancy. LOI value exhibits the minimum oxygen concentration in terms of volume percentage required to burn the material. TPU, with lots of melt-dripping during burning, reached an LOI value of 21%. The LOI value increased to 34% when the IFR/MoS<sub>2</sub> was added to TPU. It exhibited a high flame retardant efficiency in the TPU composite.

**Table 1.** Flame retardant properties of TPU samples

| Samples                  | LOI | UL 94     |
|--------------------------|-----|-----------|
| TPU                      | 21  | No rating |
| TPU/IFR/MoS <sub>2</sub> | 34  | V0        |

#### 3.2. Reaction to Fire and Flame Retardancy

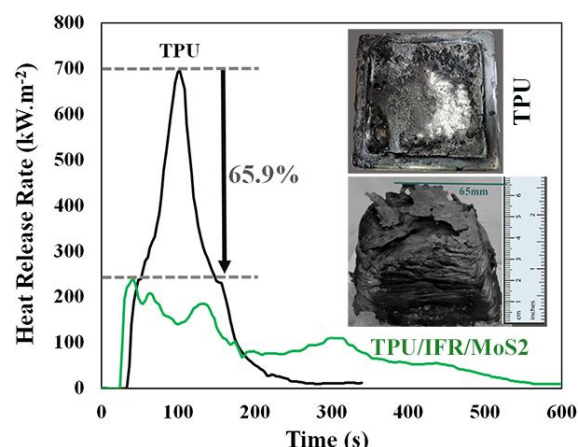
Cone calorimetry is one of the most effective methods for evaluating fire reaction performance and flame retardant properties of polymers. The heat release rate (HRR) measured by the cone calorimeter is the most critical parameter for fire hazard assessment [26-27].

The measured thermal, smoke, and toxicity parameters of reaction-to-fire, including time to ignition (TTI), peak HRR (PHRR), total heat release (THR), peak smoke production rate (PSPR), total smoke release (TSR), peak carbon monoxide production (PCOP) for the TPU

samples are listed in Table 2.

#### 3.3. Thermal Parameters

The curves of heat released during the combustion of TPU and TPU/IFR/MoS<sub>2</sub> were shown in Fig. 1. As seen in Fig. 1, a sharp peak appeared after ignition of TPU by PHRR value of 693 kW/m<sup>2</sup>, while the TPU composite showed a broad peak with a significant decrease in PHRR value of 237.5 kW/m<sup>2</sup>. Besides, ignition time (TTI) for TPU composite was shorter than TPU. It is attributed to the earlier decomposition of flame retardants in the TPU composite, promoting char formation and prohibiting the release of heat and pyrolysis gases during combustion [28]. This matter was confirmed by increased char residue after the cone calorimeter test, as shown in Fig. 1.



**Fig. 1.** HRR curves and char residues for TPU and TPU composite

The results indicated that the catalytic degradation of the IFR system and barrier effect of MoS<sub>2</sub> were effective in reducing heat released from the TPU composite. The other reason for the high efficiency of the IFR/MoS<sub>2</sub> is the increased residual mass after CCT. According to data in Table 2, the char residue that remained in the TPU composite significantly increased compared to the neat TPU. This result is supported by thermal analysis.

**Table 2.** Thermal parameters obtained from cone calorimeter

| Samples                  | Thermal parameters |                            |                           | Smoke/Toxicity parameters               |                                        |                           | Char residue (%) |
|--------------------------|--------------------|----------------------------|---------------------------|-----------------------------------------|----------------------------------------|---------------------------|------------------|
|                          | TTI (s)            | PHRR (kW.m <sup>-2</sup> ) | THR (MJ.m <sup>-2</sup> ) | PSPR (m <sup>2</sup> .s <sup>-1</sup> ) | TSR (m <sup>2</sup> .m <sup>-2</sup> ) | PCOP (g.s <sup>-1</sup> ) |                  |
| TPU                      | 37                 | 696.30                     | 51.5                      | 0.096                                   | 952.1                                  | 0.015                     | 6.3              |
| TPU/IFR/MoS <sub>2</sub> | 28                 | 237.5                      | 45.7                      | 0.033                                   | 624.8                                  | 0.006                     | 31.6             |

The curves of mass loss during the combustion of TPU and TPU/IFR/MoS<sub>2</sub> are shown in Fig. 2. It can be seen from Fig. 2 that lower mass loss is observed due to the char formed on the surface of TPU. It shows the combustion of the TPU/IFR/MoS<sub>2</sub> composite results in a significantly higher residual mass compared to the neat TPU. According to the findings presented in Figure 2, the TPU composite exhibits a residue of 49.9% at 300°C, whereas the neat TPU only has a residue of 8.1%. It indicates that MoS<sub>2</sub> acts as a physical barrier during the combustion, protecting the under-layer TPU composite and facilitating the catalytic carbonization of the IFR. As a result, the overall mass loss is reduced.

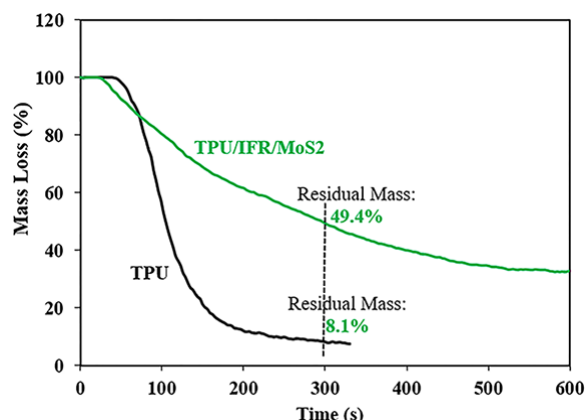


Fig. 2. Mass loss curves for TPU and TPU composite

### 3.4. Smoke/Toxicity Parameters

According to data in Table 2, the high value of TSR for TPU (952.1 m<sup>2</sup>.m<sup>-2</sup>) showed that lots of smoke is generated during the combustion of TPU. When the IFR/MoS<sub>2</sub> was added to the TPU, the TSR value was reduced by 34.4% (624.8 m<sup>2</sup>.m<sup>-2</sup>). The decomposition of the IFR system forms the acidic components reacting with TPU to create an intumescent char. This issue was studied by Liu et al. [29], who investigated smoke suppression in TPU composite with APP/carbon black. Further, MoS<sub>2</sub> creates a protective shield by the physical barrier effect, which helps to strengthen the char structure with integrity and densification. By forming the integrated carbonized layer on the polymer surface, the release of heat and smoke is effectively inhibited, and dripping is highly restricted consequently. This trend was also observed for peak SPR in TPU and TPU composite, so PSPR decreased by 65.6% in TPU/IFR/MoS<sub>2</sub> compared to TPU. Fig. 3 shows

The SPR curves for TPU samples. As seen in Fig 2, the SPR curve of TPU composite remarkably dropped compared to the SPR curve of TPU.

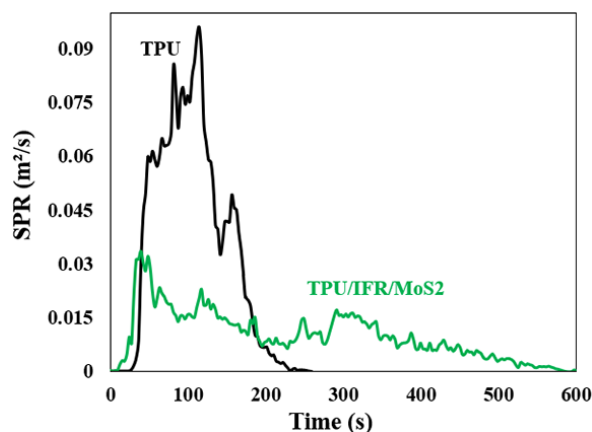


Fig. 3. SPR curves for TPU samples

The reduced smoke production is a critical factor in fire accidents because the inhalation of toxic smoke affects people's survival and the rescue performance of fire brigades. Moreover, smoke and toxic gas inhalation are two crucial factors in fire deaths [30]. CO toxic gas has been known as the most hazardous gas in fires. The COP curves for TPU samples are shown in Fig. 4. The IFR/MoS<sub>2</sub> exhibited high performance in toxicity suppression by the reduced PCOP of 60.7%.

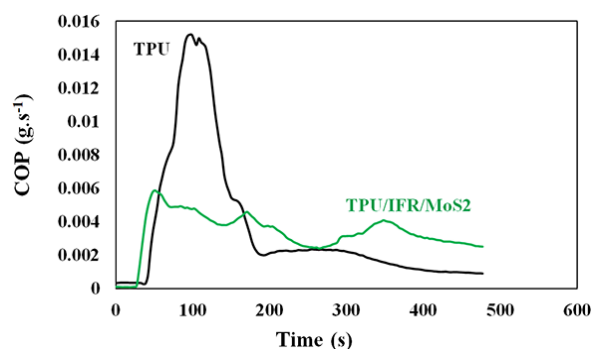


Fig. 4. COP curves for TPU samples

### 3.5. Char Morphology

The microstructure of the residual chars that remained in the TPU samples was investigated by the FESEM. Fig. 5 shows the FESEM images of the residual chars. It can be seen from Fig. 4 that pure TPU forms little char residue with many cracks and holes and a loose structure. Adding 25 wt.% IFR and 1 wt.% MoS<sub>2</sub> leading to an intumescent compact residual char with significantly reduced surface cracks and holes.

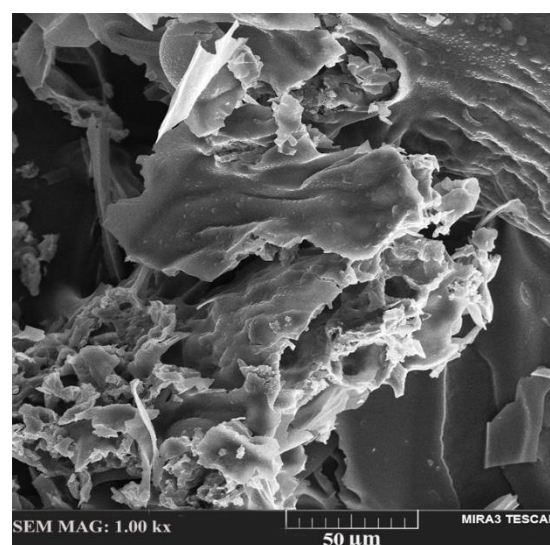
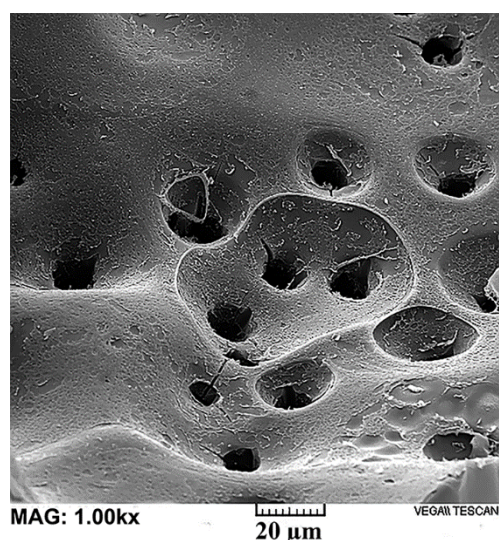


Fig. 5. The microstructure of the residual chars for the TPU samples

### 3.6. Thermal Stability

The thermal degradation of TPU and TPU/IFR/MoS<sub>2</sub> were investigated by TGA analysis. Fig. 6 and Fig. 7 show the TGA/DTG curves of the TPU samples. According to the curves, there are two degradation steps in the chain of TPU starting at 311.7°C. The first step corresponds to the breakage of the hard segment of the main chains of TPU and the elimination of the volatile compounds. The second step at 396°C is attributed to the further degradation of C-C and C-O bonds in soft segments [7].

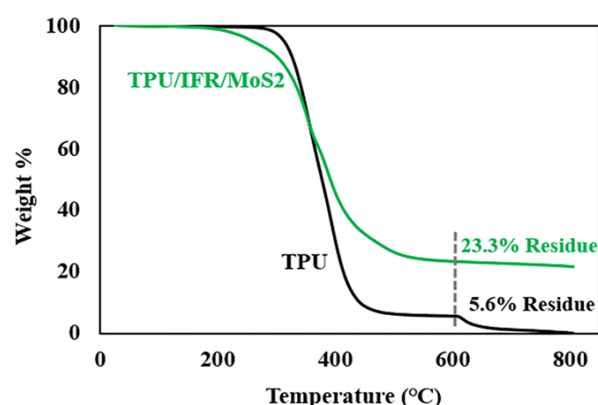


Fig. 6. TGA curves for TPU samples

In the TPU/IFR/MoS<sub>2</sub> composite, the first degradation step started at 257.0°C, which is lower than that of TPU due to the earlier decomposition of the IFR. Three thermal degradation peaks appeared at 354.3°C, 411.7°C, and 498.3°C, respectively. The enhanced thermal stability of the TPU composite can be attributed

to the intumescent protective char layer formed by the IFR and strengthened by MoS<sub>2</sub>. The residues at 600°C in Fig. 5 confirm the effective role of IFR/MoS<sub>2</sub> in promoting char formation, as seen in the CCT results (Table 2). The protective char layer inhibits the further degradation of TPU, and improved thermal behavior is achieved.

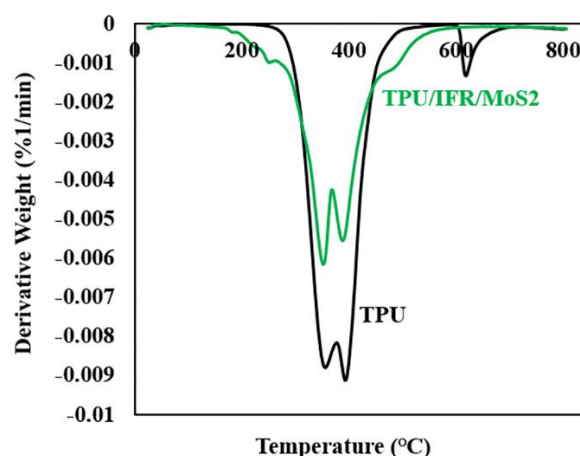


Fig. 7. DTG curves for TPU samples

### 4. CONCLUSIONS

The combination of MoS<sub>2</sub> (1 wt.%) and a halogen-free intumescent flame retardant (IFR) system consisting of APP/PER/ MPP with a ratio of 3:1:1 and a total amount of 25 wt.% was used to improve the reaction to fire performance of TPU. The TPU/IFR/MoS<sub>2</sub> composite showed excellent flame-retardant properties with an increased LOI of 34% and UL 94 V-0. The measured reaction-to-fire properties by cone

calorimeter indicated high efficiencies in flame retardancy and smoke/toxic gas suppression with reduced PHRR by 65.9%, PSPR by 65.6%, and PCOP by 60.7%, respectively, compared with the neat TPU. FESEM revealed a high-quality char with an integrated structure. The catalytic degradation of the IFRs and the barrier effect of MoS<sub>2</sub> resulted in protecting the underlayer polymer by creating a highly intumescent continuous char residue. The TGA results confirmed the high charring ability of TPU/IFR/MoS<sub>2</sub> and the enhanced thermal stability in high temperatures. The results indicated that incorporating MoS<sub>2</sub> nano additive and traditional IFRs into TPU can significantly improve fire reaction properties, leading to enhanced fire safety.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge Road, Housing & Urban Development Research Center (BHRC) for providing the fire test facilities, and Iran Polymer and Petrochemical Institute (IPPI) for the workspace and facilities for the sample preparation, and Iran University of Science and Technology (IUST) for partial support for the completion of this work.

## REFERENCES

- [1]. Shi, Y., Fu, L., Chen, X., Guo, J., Yang, F., Wang, J., Zheng, Y. and Hu, Y., "Hypophosphite/graphitic carbon nitride hybrids: Preparation and flame-retardant application in thermoplastic polyurethane". *Nanomaterials.*, 2017, 7, 259.
- [2]. Choi, J., Jang, J. U., Yin, W. B., Lee, B. and Lee, K.J., "Synthesis of highly functionalized thermoplastic polyurethanes and their potential applications". *Polymer.*, 2017, 116, 287–294.
- [3]. Wang, J., Zhang, D., Zhang, Y., Cai, W., Yao, C., Hu, Y. and Hu, W. "Construction of multifunctional boron nitride nanosheet towards reducing toxic volatiles (CO and HCN) generation and fire hazard of thermoplastic polyurethane". *J. Hazard. Mater.*, 2019, 362, 482–4.
- [4]. Vaithyalingam, R., Ansari, M.N.M. and Shanks, R.A., "Recent advances in polyurethane-based nanocomposites: a review". *Polym. Plast. Technol. Eng.*, 2017, 56 (14), 1528-1541.
- [5]. Sanusi, O.M., Benelfellah, A. and Hocine, N.A., "Clays and carbon nanotubes as hybrid nanofillers in thermoplastic-based nanocomposites—A review". *Appl. Clay Sci.*, 2020, 185, 105408.
- [6]. Thirumal, M., Khastgir, D., Nando, G.B., Naik, Y.P. and Singha, N.K., "Halogen-free flame retardant PUF: Effect of melamine compounds on mechanical, thermal and flame retardant properties". *Polym. Degrad. Stab.*, 2010, 95(6), 1138-1145.
- [7]. Lin, M., Li, B., Li, Q.F., Li, S. and Zhang, S.Q., "Synergistic effect of metal oxides on the flame retardancy and thermal degradation of novel intumescent flame-retardant thermoplastic polyurethanes". *J. Appl. Polym. Sci.*, 2011, 121, 951–960.
- [8]. Liu, X., Sun, J, Zhang, S, Guo, J, Tang, W, Li, H. and Gu, X., "Effects of carboxymethyl chitosan microencapsulated melamine polyphosphate on the flame retardancy and water resistance of thermoplastic polyurethane". *Polym. Degrad. Stab.*, 2019, 160, 168–76.
- [9]. Zhou, Q., Gong, K., Zhou, K., Zhao, S. and Shi, C., "Synergistic effect between phosphorus tailings and aluminum hypophosphite in flame-retardant thermoplastic polyurethane composites". *Polym. Adv. Technol.*, 2019, 30(9), 2480-2487.
- [10]. Khanal, S., Lu, Y., Ahmed, S., Ali, M. and Xu, S., "Synergistic effect of zeolite 4A on thermal, mechanical and flame retardant properties of intumescent flame retardant HDPE composites". *Polym. Test.*, 2020, 81, 106177.
- [11]. Velencoso, M.M., Battig, A., Markwart, J.C., Schartel, B. and Wurm, F.R., "Molecular firefighting—how modern phosphorus chemistry can help solve the challenge of flame retardancy". *Angew. Chem. Int. Ed. Engl.*, 2018, 57(33), 10450-10467.
- [12]. Wang, D., Song, L., Zhou, K., Yu, X., Hu, Y. and Wang, J., "Anomalous nano-barrier effects of ultrathin molybdenum disulfide nanosheets for improving the flame retardance of polymer nanocomposites". *J. Mater. Chem. A. Mater.*, 2015, 3(27),

- 14307-14317.
- [13]. Pan, H., Shen, Q., Zhang, Z., Yu, B. and Lu, Y., "MoS<sub>2</sub>-filled coating on flexible polyurethane foam via layer-by-layer assembly technique: flame-retardant and smoke suppression properties". *J. Mater. Sci.*, 2018, 53(12), 9340-9349.
  - [14]. Zhou, K., Zhang, Q., Liu, J., Wang, B., Jiang, S., Shi, Y., Hu, Y. and Gui, Z., "Synergetic effect of ferrocene and MoS<sub>2</sub> in polystyrene composites with enhanced thermal stability, flame retardant and smoke suppression properties". *RSC Adv.*, 2014, 4(26), 13205-13214.
  - [15]. Zhou, K., Gui, Z. and Hu, Y., "The influence of graphene-based smoke suppression agents on reduced fire hazards of polystyrene composites". *Compos. Part A. Appl. Sci. Manuf.*, 2016, 80, 217-227.
  - [16]. Xu, W., Zhang, B., Xu, B., and Li, A., "The Flame retardancy and smoke suppression effect of heptamolybdate modified reduced graphene oxide/layered double hydroxide hybrids on polyurethane elastomer," *Compos. Part A. Appl. Sci. Manuf.*, 2016, 91(1), 30-40.
  - [17]. Taghi-Akbari, L., Naimi-Jamal, M.R. and Ahmadi, S., "Flammability, smoke production, and mechanical properties of thermoplastic polyurethane composites with an intumescent flame-retardant system and nano-silica". *Iran Polym. J.*, 2023, 32, 1165-1178
  - [18]. Yuan, B., Fan, A., Yang, M., Chen, X., Hu, Y., Bao, C., Jiang, S., Niu, Y., Zhang, Y., He, S. and Dai, H., "The effects of graphene on the flammability and fire behavior of intumescent flame retardant polypropylene composites at different flame scenarios". 2017, *Polym. Degrad. Stab.*, 143, 42-56.
  - [19]. Liu, X., Guo, J., Tang, W., Li, H., Gu, X., Sun, J. and Zhang, S., "Enhancing the flame retardancy of thermoplastic polyurethane by introducing montmorillonite nanosheets modified with phosphorylated chitosan". *Compos. Part A. Appl. Sci. Manuf.*, 2019, 119, 291-298.
  - [20]. Cai, W., Zhan, J., Feng, X., Yuan, B., Liu, J., Hu, W., & Hu, Y., "Facile construction of flame-retardant-wrapped molybdenum disulfide nanosheets for properties enhancement of thermoplastic polyurethane". *J. Ind. Eng. Chem.*, 2017, 56(25), 7229-7238.
  - [21]. Jiang, J. W., "Graphene versus MoS<sub>2</sub>: A short review". *Front. Phys.*, 2015, 10(3), 287-302.
  - [22]. Wang, X., Xing, W., Feng, X., Yu, B., Song, L., Yeoh, G.H. and Hu, Y., "Enhanced mechanical and barrier properties of polyurethane nanocomposite films with randomly distributed molybdenum disulfide nanosheets". *Compos. Sci. Technol.*, 2016, 127, 142-148.
  - [23]. Chen, C., Xiao, G., Dong, S., Zhong, F., Yang, Z., Chen, C., Wang, M. and Zou, R., "Construction of CMS@ MoS<sub>2</sub> core-shell structure to enhance flame retardancy and smoke suppression performance of waterborne epoxy fireproof coatings for steel structures". *Colloids Surf. A: Physicochem. Eng. Asp.*, 2022, 633, 127836.
  - [24]. Qian, Y., Su, W., Li, L., Fu, H., Li, J. and Zhang, Y., "Synthesis of 3D hollow layered double hydroxide-molybdenum disulfide hybrid materials and their application in flame retardant thermoplastic polyurethane". *Polymers*, 2022, 14(8), 1506.
  - [25]. Feng, X., and Yang, H., "Boosting flame retardancy of thermoplastic polyurethane: Synergistic effect of nickel phosphide nanoparticles and molybdenum disulfide nanosheets". *J. Vinyl Addit. Technol.*, 2023.
  - [26]. Babrauskas, V., Peacock, R., "Heat release rate: the single most important variable in fire hazard". *Fire Retardant Chemicals Association (FRCA)*, 1990.
  - [27]. Zhu, J., Cheng, Y.P., Han, S.S. and Chow, W.K., "A feasible heat release rate estimation approach for fire hazard assessment in green design". *J. Build. Eng.*, 2023, 79, 107907.
  - [28]. Liu, L., Xu, Y., He, Y., Xu, M., Shi, Z., Hu, H., Yang, Z. and Li, B., "An Effective Mono-Component Intumescent Flame Retardant for the Enhancement of Water Resistance and Fire Safety of Thermoplastic Polyurethane Composites". *Polym. Degrad. Stab.*, 2019, 167, 146-56.
  - [29]. Liu, L., Zhao, X., Ma, C., Chen, X., Li, S.

- and Jiao, C., “Smoke suppression properties of carbon black on flame retardant thermoplastic polyurethane based on ammonium polyphosphate”. *J. Therm. Anal. Calorim.*, 2016, 126, 1821–1830.
- [30]. Hu, W., Yu, B., Jiang, S.D., Song, L., Hu, Y., Wang, B., “Hyper-branched polymer grafting graphene oxide as an effective flame retardant and smoke suppressant for polystyrene”. *J. Hazard. Mater.*, 2015, 300: 58-66.