Recycling Polymer Blend made from Post-used Styrofoam and Polypropylene for Fuse Deposition Modelling

L J W William 1, S C Koay 1*, M Y Chan 2, M M Pang 1, T K Ong 2, K Y Tshai 3

1School of Computer Science and Engineering, Faculty of Innovation and Technology, Taylor’s University, No. 1, Jalan Taylor’s, 47500 Subang Jaya, Selangor, Malaysia.
2Faculty of Engineering and Technology, Tunku Abdul Rahman College University, 53300 Kuala Lumpur, Malaysia.
3Department of Mechanical, Materials and Manufacturing Engineering, The University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia.

*E-mail: seongchun.koay@taylors.edu.my

Abstract. Fuse deposition modelling (FDM) has become a revolutionary manufacturing technology as it offers numerous advantages, including freedom of fabrication, mass customisation, fast prototyping, and cost-effectiveness. Thermoplastic material is commonly used as feedstock for FDM process. The current state of material development, the recycled plastic material also can be used as printing material for FDM machine. Expanded polystyrene (EPS) has been extensively used as packaging materials for many industries but rarely be recycled, as its relatively large volume with minimal weight is conducive for transportation. This research aimed to utilize EPS waste and turn it into FDM feedstock. This research also aims to enhance the properties of recycled polystyrene (rPS) made from EPS waste by blending it with polypropylene (PP). Different ratios of rPS/PP blends were prepared and extruded into FDM filament using filament extruder. The formulated filaments were printed into specimen using FDM machine. This research found the filament made from rPS/PP blends can be printed into specimen with good printing quality if the nozzle temperature controlled at 240°C with 120% extrusion rate. With this printing parameter, the specimen printed with rPS/PP blend filament exhibit the greatest adhesion between the deposited layers without any visible voids or gaps. Besides, the printed specimen with rPS/PP blends possess lower tensile strength, but higher tensile modulus as compared to the printed specimen with neat rPS. The addition of more PP decreased both tensile strength and modulus of rPS/PP blends. On the other hand, the rPS/PP blends have higher thermal stability as the PP content increased. Overall, the rPS/PP blends filament shows a great potential as a feedstock material for FDM fabrication.

1. Introduction

Additive manufacturing (AM) is a fabrication process that applies material science and computer programming techniques to manufacture physical prototypes from computer-aided design (CAD) models, also known as 3-dimensional (3D) printing. AM technologies allow products with complex topology to be manufactured with great freedom but used way less time than traditional methods [1]. It has proved to be an effective substitute for the industries that utilize traditional manufacturing, which is comprised mainly of subtractive and forming processes that require the need for tooling and Design for Manufacturing (DFM) related imperatives to an enormous degree [2].
Fused deposition modelling (FDM) is the most common and widely used AM technique nowadays as it can print thermoplastic material into neat complex geometrical parts at the lowest cost. FDM is a process that heats thermoplastic filament into a semi-molten state and pushes it through the nozzle, while the nozzle moves in a pre-set printing path on the platform [3]. Thermoplastics are the most used feedstock for FDM process even included thermoplastic based composite [4]. Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) filaments are the frequently used thermoplastic for FDM process. In recent years, the approach of using recycled resin from plastic waste has been adopted for producing FDM feedstock, aiming to minimize the material cost, plastic waste, and carbon footprint [5]. Several researchers found the FDM fabricated parts made from recycled polymer were comparable to their respective virgin polymer in terms of mechanical performances. Vidakis et al. [6] reported that the mechanical strength of recycled ABS parts was generally comparable to the parts built with commercial ABS filament. Anderson [7] compared the mechanical properties of the parts printed using commercially available and recycled PLA filaments. The overall mechanical properties of both printed parts were similar. Besides, Zander et al. [8] discovered that the tensile strength of recycled PET printed parts was comparable with those printed with filament made from virgin PET pellets. The aim of utilizing recycled resin as FDM feedstock could potentially reduce the plastic waste that readily abundance. The use of recycled plastic as FDM feedstock also having less carbon dioxide (CO2) emission as compared to virgin plastic as the synthesis process of virgin plastic contributed to high amount of CO2 emission. Hence, this research highlighted the development of filaments using recycled polymers to ensure the sustainability of the feedstock for FDM process.

Polystyrene (PS) is a petroleum-based thermoplastic that is naturally transparent. It can be either a solid plastic or rigid foam material that is known as expanded polystyrene (EPS). EPS is low in density and cost, as well as having good insulation properties which makes it highly used as packaging materials that are often be utilized for single use only. However, the Environmental Protection Agency (EPA) reported that the disposal of EPS waste has created million tons of municipal solid waste worldwide every year [9]. EPS waste is rarely recycled because it is made of 98% of air and 2% of resin which is high cost on transportation of EPS waste to the recycling plant. This is because the EPS waste is bulky and high occupancy of space with minimal weight [10–11]. Recently, the attention was given to recycling and transforming EPS waste into FDM feedstock as it has multiple desired properties, including high stiffness, great dimensional stability, and its readily abundance [12-13]. According to Ng et al. [10], the FDM filament made from EPS waste was found higher stiffness than commercial filament made from high impact polystyrene (HIPS), but it was relatively brittle, and the filament was easily broken during the printing. Thus, the research aimed to further improve the properties of recycled polystyrene (rPS) filament made from EPS waste for FDM fabrication.

In order to enhance the ductility of rPS filament that easily break during the printing, the rPS could blend with a more ductile plastic resin such as polypropylene (PP). The blending of polymers is common as it provides an efficient and economical way to develop new materials. The properties of a single polymer can be improved while keeping a few of its original properties by blending with another type of polymer. According to Aravind et al. [14], they blended the virgin PS pellets with PP resin via melt-blending with 50/50 blend ratio and the ductility of the blend was significantly higher than the virgin PS. Also, Samsuddin et al. [15] found the addition of PP improved the ductility of PS but compromised the tensile strength of the blend. Ideally, the blending of PS resin with PP resin can improve the ductility of virgin PS. However, the research related to the use of rPS/PP blends as FDM feedstock is not available in any open-source literature. Therefore, this research was underway to produce FDM filaments from rPS/PP blend.

In short, the goal of this research is to enhance the properties of rPS filament made from EPS waste by turning it into a polymer blend. In this research, different blend ratios of rPS/PP blend filament were produced, and the filament was 3D printed in specimens. The printability of these materials with different printing temperature and extrusion rate were studied to identify their optimum printing parameters. Then, the mechanical strengths of the 3D printed specimens with these materials were
assessed through the tensile test. Also, the thermal properties of the filament made from various blend ratio of rPS/PP blend was studied in this research as well.

2. Methodology

2.1. Raw Material
The post-consumer Styrofoam (EPS) wastes were collected from a local electronics and home appliances store located around Subang Jaya, Selangor. The EPS wastes usually were used as protective covers for the electrical appliances. Besides, homopolymer PP (grade: PM200SB) pellets were obtained from Lotte Chemical Titan (M) Sdn. Bhd.

2.2. Preparation of rPS from Styrofoam Waste
The preparation of rPS from EPS wastes was referred to the method used by Ling et al. [16]. It is because the method reported by Ling et al. [16] has successfully converted EPS waste into rPS resin. The collected EPS was first thoroughly washed with soap to remove any visible contaminants and left to air-dry at room temperature until completely dried. The cleaned EPS was manually cut into smaller sizes ranging from 2 to 4 cm, then the EPS pieces were placed in an air circulated oven at 140 °C for 15 minutes. After 15 minutes, then the EPS foams shrank approximately 95 % from their original size and became rigid, which signified the removal of entrapped air from the foams. The shrunken foams can consider as rPS crumbs after removing the entrapped air. Next, the rPS crumbs were further ground using a conical burr grinder (Model: DFJ-BL) and sieved through a 5 mm mesh size sieve to obtain a uniform size of rPS grains. Lastly, rPS was stored in an air-tight container and ready to be used for filament extrusion. The overall preparation of rPS from EPS waste is illustrated in Figure 1.

![Figure 1. Preparation of rPS from EPS waste.](image-url)
2.3. Preparation of filaments
At first, PP resin was dried in an air circulated oven at 60 °C for 5 hours to remove entrapped moisture. The moisture in PP resin could cause bubbles and holes in the extruded filament. Next, the PP resin was pre-mixed with rPS following the rPS/PP ratio of 90/10, 80/20, 70/30, 60/40, and 50/50. For filament extrusion, the mixture was then fed into a Single-Screw Desktop Filament Extruder Line II with a processing temperature and extrusion speed of 190 °C and 40 rpm, respectively. This extruder did not equip with an auto-calibration spooling system for controlling the diameter of filament to achieve high dimension accuracy. In order to overcome this challenge, the filament spool winding speed was manually adjusted to ensure the diameter of the extruded filament was in the range of 1.55 to 1.75 mm. The process flow of producing rPS/PP blend filament is shown in Figure 2. The preparation of filament was followed method reported by Ariel Leong et al. [1].

![Pre-mixed rPS/PP](image1)
![Filament extrusion using Single-Screw Desktop Filament Extruder Line II](image2)
![Extruded rPS/PP blend filament](image3)

**Figure 2.** Process of filament extrusion for rPS/PP blend.

2.4. 3D Printing
The steps of 3D printing the test specimens are illustrated in Figure 3. The 3D model of two different specimens was first drawn in SolidWorks 2020, such as a specimen with size of 20 mm × 20 mm × 2 mm, and dumbell specimen with dimension following ASTM D638 Type V. Both 3D models were saved as STL format files and converted into g-code using Ultimate Cura version 4.8.0. The Creality Ender-3 V2 3D printer with a nozzle inner diameter of 4 mm used to print the test specimens. To study the printability of these rPS/PP blend filaments, the specimens were printed using rPS/PP blend filaments with different blend ratios, nozzle temperatures and extrusion rates as listed in Table 1. While the bed temperature was set constant at 110 °C to avoid the warpage of specimen during the printing. The test specimens were printed horizontally with the dimension of 20 mm × 20 mm × 2 mm, with 100 % infill density and the raster angles of 45°/135° or in crisscross raster orientation. The layer height of the printer was set at 0.2 mm. For the tensile specimen, the nozzle temperature and extrusion rate were set at 240 °C and 120 %, respectively. A good printing layer adhesion can be observed from visual observation if using these parameters, whereas the other printing parameters remain the same.

**Table 1.** 3D printing parameters.

| Blend ratio (rPS/PP) | Nozzle Temperature (°C) | Extrusion Rate (%) |
|---------------------|-------------------------|--------------------|
| 90/10, 80/20, 70/30, 60/40, 50/50 | 220, 230, 240 | 100 |
|                      | 240                     | 100, 110, 120      |
2.5. **Visual Observation**

The printed specimens with the dimension of 20 mm × 20 mm × 2 mm at different printing parameters were taken to examine their print quality. An optical microscope (model: Swift M10) was used to inspect the adhesion between deposited layers in the specimen and the micrographs were captured with software Motic Images Plus 3.0. The observation of micrograph was captured on two specific locations on the specimen, where the location was printed with parallel layer (spot A) and crisscross layer (spot B) as displayed in Figure 4. The magnification used in the microscope was 4×.

![Figure 3. Preparation of 3D printed test specimens.](image)

![Figure 4. Locations for visual observation.](image)

2.6. **Tensile Test**

The tensile properties of printed specimens with rPS/PP blend filaments were determined using an Instron Universal Testing Machine (Model 5569). The load cell and the crosshead speed used in this test were set at 15 kN and 5 mm/min, respectively. For each blend ratio, at least 5 specimens were tested and retrieved their average values for the tensile strengths and modulus. Also, one-way analysis of variance (ANOVA) was applied to analyze the statistical uncertainty of these tensile results.
2.7. Thermal Analysis
Thermogravimetric analysis (TGA) was conducted using PerkinElmer Pyris Diamond TGA 8000 to determine the thermal stability of rPS/PP blends. The filaments were first cut into small pieces weighing from 5 to 8 mg and placing each of them on an alumina pan. Next, the specimen was attached to the weighing hook in the TGA machine and heated from 30 °C to 700 °C with a heating rate of 10 °C/min. This process was conducted under a nitrogen atmosphere with 20 mL/min nitrogen gas flow rate. The graph of weight loss against the temperature was generated from the TGA result, the onset thermal degradation temperature ($T_{onset}$) of specimen was extracted from the graph.

3. Results and Discussion

3.1. Microscopy Analysis
Figure 5 illustrates the micrograph of rPS/PP specimens with different blend ratio printed at different nozzle temperature. From the micrographs, there were many tiny black dots can be observed in the printed specimens. The tiny black dots were the contamination from rPS. This similar observation also reported by Ng. et al. [10]. At the temperature of 220 °C, the gaps were obviously observed between the printed layers in all rPS/PP blends. As the nozzle temperature increase, the gaps between the printed layers were getting narrow or absence in specimens. Generally, the printing temperature highly influenced the melt viscosity of the thermoplastic, as the increase of temperature would reduce the melt viscosity and improve the wetting of the thermoplastic [17]. The melt viscosity of thermoplastic indicates how the fast material can be extrude out nozzle during the printing process [18].

| rPS/PP blend ratio | Printing Temperature |
|--------------------|----------------------|
| 90/10              | 220 °C               |
| 80/20              | 230 °C               |
| 70/30              | 240 °C               |
| 60/40              |                      |
| 50/50              |                      |

Figure 5. Micrograph of rPS/PP specimens printed at difference printing temperature.

The increase in printing temperature causes the deposited layers to remain in the molten state for a longer period, which results in more interlayer and inter-stand coalescence within the deposited layers.
Furthermore, the increase of printing temperature also promoted the intermolecular diffusion and stronger interfacial bonds between the deposited layers [19–20]. Thus, the adhesion between the deposited layers and the overall printing quality of the part was improved when using a higher printing temperature. Also, the addition of more PP in the blends with rPS/PP ratio above 20 wt % showed smaller gaps and better coalescence within the layers at all three printing temperatures. According to Adewole et al. [21], PP polymer matrix could experience a more structural and morphological breakdown due to the severe mixing screw in filament extruder, resulting in a decrement in its intrinsic viscosity. The increase in PP further decreases the melt viscosity of rPS/PP and hence, provide a better adhesion between the layers in the printed parts. However, not all specimens printed with a completely adhered deposited layers at printing temperature of 240 ° C. The gaps between printed layers still visible for specimen printed with rPS/PP blend filaments with blend ratio beyond 80/20. The possible cause of these internal defects could be the low tolerance in the diameter of rPS/PP filaments. The diameter tolerance of filament describes the variation in diameter the filament possesses, and the industry’s gold standard for diameter tolerance is 0.05 mm. The low tolerance in the diameter of the filament can cause the filament unable to fit into the feeder and hot end opening if they are undersized or oversized to be held by the extruder motor [22]. The absence of an auto-calibrated spooling in the extruder has compromised the diameter tolerance to allow the diameter of rPS/PP filaments to lies in the range of 1.55 to 1.75 mm. This range of diameter of filament was allow the extruder motor to fit the filament into the hot end chamber without any issue.

![Figure 6. Micrograph of rPS/PP specimens printed with different extrusion percentage.](image)

To compensate for the under extrusion due to the inconsistency of filament diameter, the extrusion rate of the 3D printer was increased from its originals, 100 % to 110 and 120 %. The micrographs of rPS/PP specimens printed at different extrusion rates are shown in Figure 6. The adhesion of printed layer of all specimens were obviously improved as the extrusion rate increases. Based on the findings
of Tay et al. [23], a larger filament surface was found at the nozzle outlet with higher extrusion rate as more material was extruded than expected. This excess material deposited on the layer provides a larger contact surface for interlayer bonding, and therefore leading to a better overall print quality of the printed parts. There were no visible gaps between the deposited parallel and crisscross layers in the specimens printed at 120 % extrusion. For this reason, the rPS/PP specimens printed at 240 °C with the extrusion rate of 120 % exhibit a consistent print quality. Thus, the dumbbell specimen for this research was printed with this parameter. The effect of both printing temperature and extrusion rate on the overall print quality of specimen is illustrated in Figure 7.

![Figure 7. The influence of printing temperature and extrusion rate on the print quality of specimen.](image)

3.2. Mechanical Testing

For one-way ANOVA analysis, the significance level (α) used was 0.05, this means any factor with a P-value of 0.05 or less is considered to have a significant effect on the responses. The result shows the tensile strength and modulus have a P-value of 0.005 and 0.0003, respectively. The P-value was lower than 0.05, which indicates the rPS/PP blend ratio have significant effect on the tensile strength and modulus.

Figure 8(a) displays the tensile strength of printed specimens with neat rPS and rPS/PP blend filaments. The results reveal that the increase of the PP content decreased the tensile strength of the printed specimens with rPS/PP blend filament. Also, rPS/PP blend is an immiscible polymer blend, thus, the overall printed specimen with rPS/PP blend filament exhibited an average reduction of 20.5 % in tensile strength as compared to one of neat rPS [10]. The rPS/PP blend is considered immiscible because of their different states of intermixing encountered. The blending of rPS, an amorphous polymer, with PP, a semicrystalline polymer, both unidentical phases in terms of crystallization results in poor interfacial adhesion between the polymer phases and leads to poor mechanical properties of the blends [24]. Rather, Seier et al. [25] stated that the inherent nature of a compatible system was revealed by the modulus behavior. Besides, the results regarding the decrement in tensile strength are in agreement with a finding related to rPS or PS/PP blend from Xie et al. [26] and Brostow et al. [27]. They agreed that the addition or more PP content would lower the tensile strength of PS/PP blend. Moreover, PP used in this research has a tensile strength of 29 MPa due to its high strain to failure profile which leads to the decrement in the tensile strength of rPS/PP blends [28]. Thus, rPS/PP shows a decrement in tensile strength when more PP was added to the blends.

Figure 8(b) shows the tensile modulus of printed specimens with neat rPS and rPS/PP blend filaments. As compared the tensile modulus of printed specimen with neat rPS reported by Ng et al. [10], its tensile modulus is the lowest among all specimens. According to the literature, neat rPS supposed to exhibit the highest tensile modulus and reduce subsequently as the PP content increased in rPS/PP blends [26, 29]. For this case, the increase in stiffness of rPS/PP blends from neat rPS attributes to the relatively large increment in their brittleness that results in premature failure of the specimens. The incompatibility between rPS and PP probably affected the brittleness of the material due to weak adhesion between printed layers because of the poor interfacial adhesion between the molecules as mentioned. Refers to Figure 9, the rPS/PP tensile specimen was initially fracture at the centre region where, then the fracture was propagated along the parallel printed layers causing the
delamination. Lastly, the fracture across the printed layers by layers. The absence of physical chains entanglement between rPS and PP matrices leads to the uneven distribution of PP dispersed phase in rPS continuous phase in the blends. Thus, it weakens the adhesion between the layers of rPS/PP specimens. The addition of more PP in rPS/PP blends decreases the tensile modulus of printed specimen as the fully brittle nature of neat rPS is altered by PP that exhibits high ductility. In short, the despite rPS/PP blends show a reduction in stiffness as the PP content increases, the blends are still exhibit a higher stiffness than neat rPS due to the incompatibility of rPS and PP.

![Figure 8](image1.png)

**Figure 8.** (a) Tensile strength, (b) tensile modulus of 3D printed rPS/PP specimens

![Figure 9](image2.png)

**Figure 9.** Fracture tensile specimen.

3.3. Thermal Analysis

Figure 10 shows the TGA curves of neat rPS and PP, and rPS/PP blends. All materials show only a single stage of degradation. The $T_{\text{onset}}$ of all materials are summarized in Table 2. The neat rPS exhibited lower $T_{\text{onset}}$ than neat PP, this indicated the neat rPS has lower thermal stability. PP resin is a semi-crystalline polymer which can withstand higher temperature before being thermally degraded as it requires more energy to break down the strong molecular bonds and tightly packed molecular chains as compared to rPS, an amorphous polymer. Thus, neat PP exhibits greater thermal stability than neat rPS. Besides, the increase in PP content increased the $T_{\text{onset}}$ of rPS/PP blends, in which PP plays an important role in contributing thermal stability for the blends. Similar observation also found by Chen et al. [29]. They reported the decrease of rPS content in the blends could also decrease the mean size and the size concentration of rPS droplets, which demoted the heat transfer between rPS droplets and PP matrix. The rPS/PP blends with high thermal stability could bring significant advantages to 3D
printing blends, such as the printed part with this high thermal stability material is applicable for applications that are conducted under elevated temperature [1].

**Table 2.** TGA results of neat rPS and PP, and rPS/PP blends.

| Materials         | Onset Temperature, $T_{onset}$ (°C) |
|-------------------|-------------------------------------|
| Neat rPS          | 412.5                               |
| Neat PP           | 453.3                               |
| rPS/PP: 90/10     | 426.0                               |
| rPS/PP: 80/20     | 426.6                               |
| rPS/PP: 70/30     | 426.9                               |
| rPS/PP: 60/40     | 427.5                               |
| rPS/PP: 50/50     | 431.4                               |

**Figure 10.** Thermogravimetric (TGA) curves of neat rPS and PP, and rPS/PP blends.

4. **Conclusion**

This research has been produced from FDM filament from rPS/PP blend that initially produced EPS waste. The optimum printing parameters, including printing temperature and extrusion rate, were studied to ensure a printing quality is good can be achievable using rPS/PP blend filaments. The result showed that the rPS/PP specimens printed at 240 °C have the best coalescence between the deposited layers with reduced pore and gap sizes. The drawbacks of under-extruded rPS/PP specimens printed at 240 °C were compensated by the adjustment of extrusion rate to 120 %. Besides, the printed specimen with rPS/PP blends have a lower tensile strength, but higher tensile modulus as compared to printed specimen with neat rPS. The incompatibility between rPS and PP has led to a relatively large increment in the brittleness of the blends as it showed a higher tensile modulus compared to printed specimen with neat rPS. The addition of more PP decreased both tensile strength and modulus of the rPP/PP blends. However, the increase of PP content in the rPS/PP blend filament enhanced the ductility of the printed specimen. Moreover, the blending of rPS with PP improved the thermal stability of neat rPS due to the incorporation of strong and tightly packed molecular chains in PP. The rPS/PP blend filament with higher content of PP having a higher thermal stability. Overall, this
research has demonstrated the potential of rPS/PP blend filaments use in FDM process. However, the incompatibility between rPS and PP remains main challenge for this research. In future, the addition of compatibilizer probably can overcome the issue related to incompatibility. For FDM, filaments made from recycling plastic could be an alternate as its poses many advantages over filament made from virgin plastic.

References

[1] Ariel Leong J J, Koay S C, Chan M Y, Choo H L, Tshai K Y, and Ong T K 2021 J. Nat. Fibres In Press doi: 10.1080/15440478.2021.1941488
[2] Juarez C Z J, Koay S C, Chan M Y, Choo H L, Pang M M and Ong T K 2021 MATEC Web Conf. 335 03007
[3] Jiang J, Xu X and Stringer J 2019 Virtual Phys. Prototyp. 14 219
[4] Sulaiman M S M, Koay S C, Chan M Y, Choo H L, Pang M M and Ong T K 2021 MATEC Web Conf. 335 03011
[5] Cruz Sanchez F A, Boudaoud H, Hoppe S and Camargo M 2017 Addit. Manuf. 17 87
[6] Vidakis N, Petousis M, Maniadi A, Koudoumas E, Vairis A and Kechagias J 2020 Sustainability 12 3568
[7] Anderson I 2017 3D Print Addit. Manuf. 4 110
[8] Zander N E, Gillan M and Lambeth R H 2018 Addit. Manuf. 21 174
[9] Geyer R, Jambeck J R and Law K L 2017 Sci. Adv. 3 25
[10] Ng T Y, Koay S C, Chan M Y, Choo H L and Ong T K 2020 AIP Conf. Proc. 2233 020022
[11] Chun K S, Subramaniam V, Yeng C M, Meng P M, Ratnam C T, Yeow T K and How C K 2019 J. Thermoplast. Compos. Mater. 32 1455
[12] Chun K S, Fahamy N M Y, Yeng C Y, Choo H L, Pang M M and Tshai K Y 2018 J. Eng. Sci. Technol. 13 3445
[13] Koay S C, Subramanian V, Chan M Y, Pang M M, Tshai K Y and Cheah K H 2018 MATEC Web Conf. 152 02019
[14] Birudugadda A K, Madhav C V and Bhukya R 2016 Int. J. Metall. Mater. Chem. Eng. 5 61
[15] Samsudin S A, Hassan A and Mokhtar M 2006 Malaysian Polym. J. 1 11
[16] Ling S L, Koay S C, Chan M Y, Tshai K Y, Chantara T R and Pang M M 2020 Polym. Eng. Sci. 60 202
[17] Koay S C, Husseinsyah S and Yeng C M 2017 J. Thermoplast. Compos. Mater. 30 1217
[18] Ibrahim M, Isa N M A, Sa'ude N and Ibrahim M I 2016 J. Eng. Appl. Sci. 11 6556
[19] Aliheidari N, Christ J, Tripuraneni R, Nadimpalli S and Ameli A 2018 Mater. Des. 156 351
[20] Hashemi Sanatgar R, Campagne C and Nierstrasz V 2017 Appl. Surf. Sci. 403 551
[21] Adewole A A, DeNicola A, Gogos C G and Mascia L 2013 Plast. Rubber Compos. Process. Appl. 29 70
[22] Iunolainen E 2017 Theseus I 1
[23] Tay Y W D, Li M Y and Tan M J 2019 J. Mater. Process. Technol. 271 261
[24] Nofar M, Sacligil D, Carreau P J, Karnal M R and Heuzey M C 2019 Int. J. Biol. Macromol. 125 307
[25] Seier M, Stanic S, Koch T and Archodoulaki V M 2020 Polym. 12 1
[26] Xie Z, Sheng J and Wan Z M 2013 J. Macromol. Sci. Part B Phys. 52 716
[27] Brostow W, Grguric T H, Olea-Mejia O, Rek V and Unni J 2008 E-Polymers 8 1
[28] Hisham A, Maddah 2016 Am. J. Polym. Sci. 6 1
[29] Chen R, Liu X, Han L, Zhang Z and Li Y 2020 Polym. Adv. Technol. 31 2722