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Analysis of High-Performance Advanced Polymers Reinforced with Glass Fiber

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ABSTRACT

Rapid advancements in the automotive and electronics industries have required the adoption of high-performance engineering polymers with better strength and less weight. The current research compared and evaluated the mechanical behavior, volumetric shrinkage, and rheological properties of two high performance engineering polymers, 40% glass fiber reinforced and 30% glass fiber reinforced. Tensile rods and rectangular bar-type specimens were injected, under three process conditions, respectively. The values of tensile strength, strain (%), impact strength, volumetric shrinkage, melt flow index and density were obtained from the injection tests. The results exposed that the mechanical properties of 40 % glass fiber reinforced PPS polymer is superior than those of 30% glass fiber reinforced PEI polymer as a result of amount of glass fiber. Furthermore, due to the semi-crystalline form of the PPS polymer, the highest dimensional stability related with shrinkage has been obtained. Finally, this study has proven that glass fiber added high performance advanced polymers display great potential in engineering applications, and may provide a good potential for the development and application of electronics and automotive. Tensile stress values for PPS increased rapidly up to 1.50 % strain and then remained constant until 2.211%.

Cam Elyaf ile Güçlendirilmiş Yüksek Performanslı İleri Polimerlerin Analizi

ÖZ

Otomotiv ve elektronik endüstrilerindeki hızlı gelişmeler, daha iyi mukavemet ve daha az ağırlık ile yüksek performanslı mühendislik polimerlerinin benimsenmesini gerektirmiştir. Mevcut araştırma, %40 cam elyaf takviyeli ve %30 cam elyaf takviyeli iki yüksek performanslı mühendislik polimerinin mekanik davranışını, hacimsel büzülmesini ve reolojik özelliklerini karşılaştırdı ve değerlendirdi. Çekme çubukları ve dikdörtgen çubuk tipi numuneler sırasıyla üç işlem koşulu altında enjekte edildi. Enjeksiyon testlerinden çekme mukavemeti, gerinim (%), darbe mukavemeti, hacimsel büzülme, eriyik akış indeksi ve yoğunluk değerleri elde edilmiştir. Elde edilen sonuçlar, %40 cam elyaf takviyeli PPS polimerinin mekanik özelliklerinin, cam elyaf miktarının bir sonucu olarak %30 cam elyaf takviyeli PEI polimerinden daha üstün olduğunu ortaya koymuştur. Ayrıca PPS polimerinin yarı kristal yapısından dolayı büzülme ile ilgili en yüksek boyutsal kararlılık elde edilmiştir. Son olarak, bu çalışma, cam elyafı katkılı yüksek performanslı ileri polimerlerin mühendislik uygulamalarında büyük bir potansiyel sergilediğini ve elektronik ve otomotivin geliştirilmesi ve uygulanması için iyi bir potansiyel sağlayabileceğini kanıtlamıştır. PPS için çekme gerilimi değerleri, %1.50 gerinime kadar hızla artmış ve ardından %2.211'e kadar sabit kalmıştır.

Anahtar Kelimeler: Cam fiber, enjeksiyon testleri, mekanik davranış, hacimsel çekme, reolojik karakteristik

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1. INTRODUCTION

Advances in materials science have illustrated an important role in the production of polymer materials with properties such as high strength, low weight and ability to operate at high temperatures in critical regions [1, 2]. These polymers exhibit properties such as high strength, rigidity, high hardness, resistance to extreme chemicals, good thermal resistance, excellent chemical resistance and superior bending strength [3]. Due to the difficulty in forming high-performance advanced engineering polymers, a good polymer melting system, screw geometry providing a comfortable filling, and a well-designed cooling system are required [4]. The mold shrinkage of injection molding polymers is influenced by part wall thickness, runner type and dimensions, mold temperature, melt temperature, and injection pressure. These conditions affect to learn how and why the injection molding polymers shrink. There are very few studies in the literature on high-performance advanced polymers and there has not been enough research on the problems encountered in the industry. Especially, many studies have been carried out on mechanical, tribological, dimensional and melt flow characteristics on general purpose and engineering polymers [5, 6]. Some researchers have injected tensile rod and rectangular bar in plastic injection process with general purpose polymers such as Polypropylene under different process conditions. In their study, they investigated the mechanical, dimensional and flow properties of the injected plastic specimens. As a result, they stated that the injection conditions had an effect on all properties [7]. In other study, researchers have worked on determining the plastic injection process conditions in bottle production with Polyethylene Terephthalate (PET) type polymer. In this current study, the effect of injection process conditions on the volumetric shrinkage values in the direction parallel and perpendicular to the flow were investigated. From the research, they explained that the most effective process condition on volumetric shrinkage is the melt temperature [8]. Similarly, in another study, volumetric shrinkage and warpage of optical lenses in plastic injection process using Polymethyl Methacrylate (PMMA) polymer were investigated. They introduced that the packing pressure is an important factor on the dimensional quality of the process parameters [9].

Higher strength and stiffness at elevated temperatures is obtained with glass or carbon fiber reinforcement. Numerous studies have been conducted on glass fiber reinforced general and engineering polymers. In these studies, mechanical properties such as strength and toughness of general purpose polymers were investigated by adding 10%, 20%, 30% and 40% glass fiber reinforcement [10]. In other study, hybrid composites were developed with the reinforcement of both glass fiber and carbon fiber. In studies, it has been explained that glass fiber and carbon fiber reinforcement increase tensile, bending and impact strength and decrease toughness [11-12]. As a different approach, they produced new materials in plastic injection method by mixing recycled PET fibers and original PET fibers. The mechanical and flow properties of the obtained polymer materials were evaluated. As a result, it was concluded that both reinforcement materials provided positive improvements [13]. In particular, high performance advanced engineering polymers such as PPS (Polypropylene Sulfide) and Polyetherimide (PEI) gain many advantages. Because of its high strength, low weight ratio, rigidity, thermal resistance, dimensional stability and good tribological properties, it has started to find rapid use in the fields of space, automobile, electronics and sports. A group of researchers investigated that the mechanical and tribological properties of polymer materials such as PA (Polyamide-PA), PPS and PPS/PA powder-granule mixture [14]. In similar study, researchers reported that it is important to show the effect of carbon fiber reinforcement on the mechanical behavior of PEEK (Polyether ether Ketone) polymer [15]. In the study, it has developed a composite material with PPS polymer matrix reinforced with e-glass. They claimed that as the glass reinforcement ratio increased, there was a visible increase in the mechanical, thermal and electrical properties of the developed composite [16]. Unlike the previously mentioned publications, the influence of cooling rate on PPS polymer and carbon fiber reinforced PPS polymer was investigated. From this research, the high crystallization caused by the slow cooling rate increased the modulus of elasticity and yield stress but the strength and toughness decreased [17].

In the mentioned studies are examined, it has been determined that there are some important points in the literature that are missing and waiting for a solution. For this reason, the purposed study has been carried out in order to both close the gap in the literature and support the developments in the industry. In particular, plastic injection tests were carried out by selecting two very important polymer materials such as PPS and PEI. Further, results have been obtained regarding the most outstanding properties of these polymers. At the end of the current study, the advantages and disadvantages of both polymers of PPS with 40 % glass fiber and PEI with 30 % glass fiber were compared and reliable results were obtained.

2. Material and Method

2.1 Plastic injection tests

In this study, using three process of two different high performance engineering polymers (PPS and PEI), a total of 18 tests were performed to the three-level orthogonal Taguchi design [19]. In the injection tests, the tensile strength, impact toughness, shrinkage, melt flow index and density were determined by using injection conditions such as melt temperature, injection pressure and runners (Table 1-2). In this study, three parameters are most effective parameters on mechanical, dimensional and rheological properties were selected from plastic manufacturer catalogue.

Table 1. Experiments plan for PPS polymer

Process Conditions	I. level	II. level	III. level
Melt temperature (°C)	320	330	340
Injection pressure(Bar)	80	100	120
Runners (A-B-C)	1	2	3

Table 2.Experiments plan for PEI polymer

Process Conditions	I. level	II. level	III. level
Melt temperature (°C)	350	360	370
Injection pressure(Bar)	80	100	120
Runners (A-B-C)	1	2	3

2.2. Experimental procedure

In this study, PPS and PEI polymers were used to realize ENGEL-Factory injection machine. PPS and PEI polymers were tested in condition of the injection time 3 s, packing time is 6 s, cooling time is 10 s, mold open-close time and total cycle time is 20 s. The injection machine specifications are given in Table 3. Plastic mold in situ are shown in Fig.1 and plastic samples are displayed in Figure 2 and 3.

Table 3. Injection machine specifications

Setups	Value
Max injection pressure	140 bar
Max clamp force	60 t
Max screw stroke	100 mm
Screw diameter	30 mm
Max injection flow	85 cm3/s

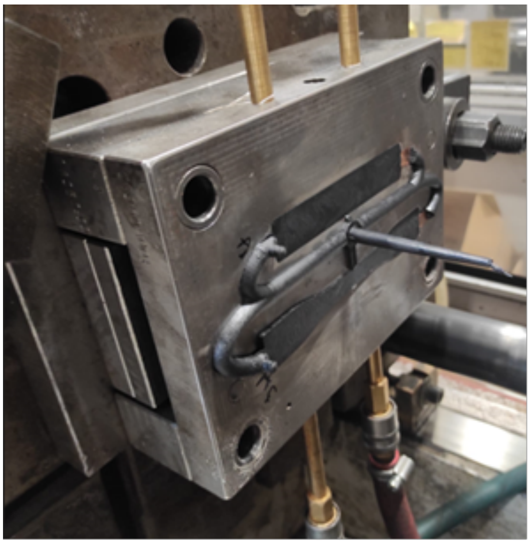


Figure 1. The finished of Plastic molds for plastic specimens

Figure 2. Tensile test specimens for PPS

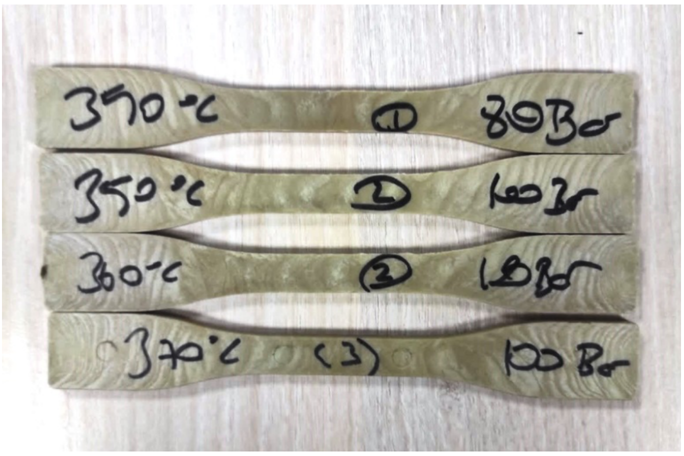
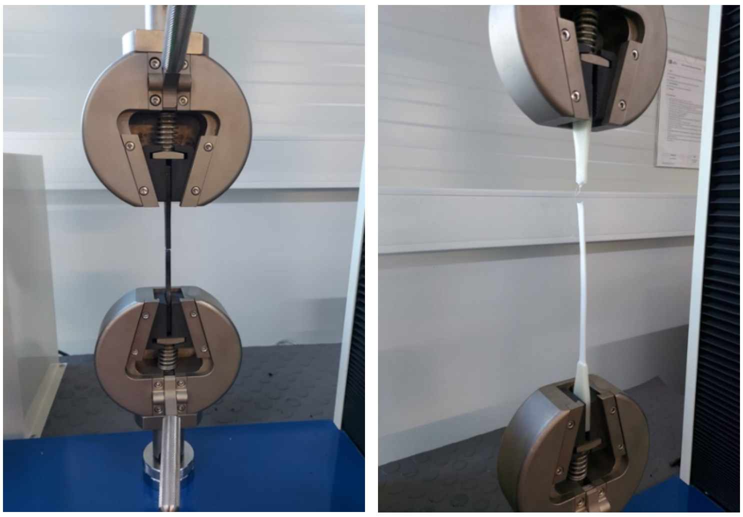


Figure 3. Tensile test specimens for PEI

3. Testing and Measurement Methods

Total of 18 tensile tests were conducted to obtain the values of tensile strength (MPa) and strain (%) in accordance with ASTM D-638 [20]. The testing speed was 100 mm/min at least three times 3 specimens were tested in a MACRONA model instrument as shown in Figure 4.



(a) PPS **(b) PEI**

Figure 4. The tensile tests of polymers

Izod impact tests (totally 18) of PPS and PEI specimens were carried out to collect the values of impact strength (KJ/m2) accordance with ASTM D-256 [26]. The izod notched (V) method in impact tests were performed by using an INSTRON instrument Ceast 9050 model as shown in Figure 5. Hammer energy of 5.5 J was used and the striking velocity was 3.80 m/s. For the specimens, notch izod impact test was made using a motion cutting machine.

Figure 5. The tensile tests of polymers

Dimensional measurements were performed to obtain the values of shrinkage (%) in flow and transverse directions in accordance with ASTM D-638 [21]. The bar specimens of PPS and PEI polymers were measured by the digital caliper with accuracy of 0.01 at least three times as shown in Figure 6.

(a) PPS **(b) PEI**

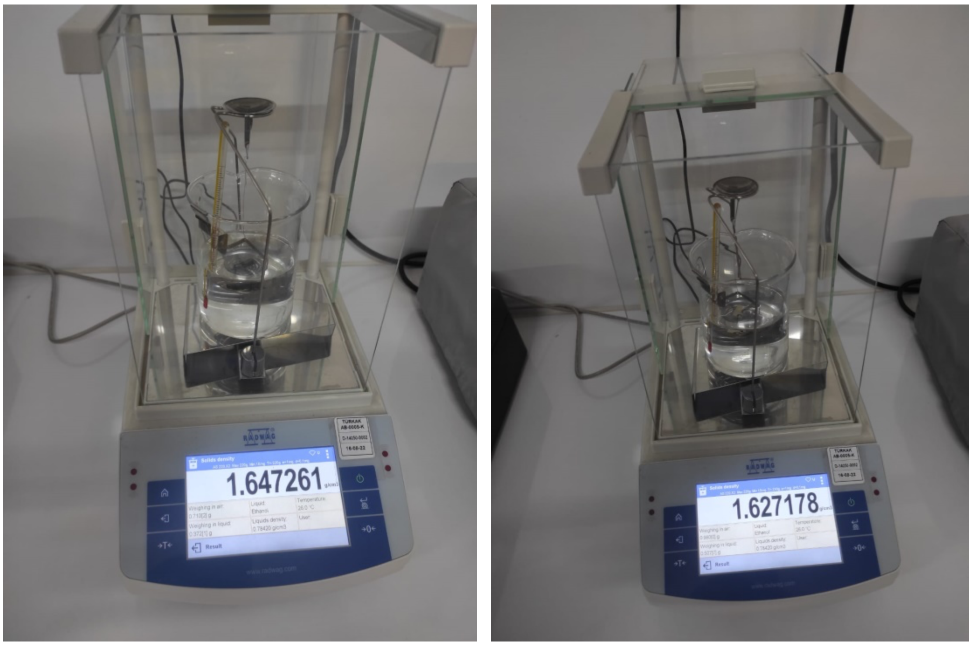
(c) PPS **d) PEI**

Figure 6. Measurement of shrinkage calculations in flow and transverse

Melt flow index test accordance with ASTM 1238-D [22] was carried out in an INPROS model instrument in Figure 7. Test conditions are 5 kg of mass, of displacement of 30 mm, temperatures of 310 °C, 240 °C and 345 °C for polymers of PPS and PEI, respectively.

Figure 7. Melt flow index test of polymers

In order to determine the solid density of polymer materials of PPS and PEI, a series of measurements were carried out using a RADWAG brand AS 220 X 2 model devices with 0.2 mg sensitivity. Density measurements applied to the polymers are shown in Figure 8, respectively.



(a) PPS (b) PEI

Figure 8. Measurement of solid density for PPS and PEI

4. Results and Discussion

In this section, the experimental results obtained from tensile test, impact test, volumetric shrinkage, melt flow analysis and density measurements of PPS and PEI polymer specimens, discussions and their relation with the literature are discussed.

Figures 9 and 10 show the Force (N)-Elongation (mm) graphs of both polymers during the tensile test. As seen from Figure 9, it can be seen that the PPS polymer exhibits a rapid elongation (3.4 mm) behavior up to a load of 3400 N, and then falls rapidly after this point. From Figure 10, it can be seen that the PEI polymer exhibits a rapid elongation (5 mm) up to 2400 N load, and it decreases rapidly after this point. Comparing both polymers, PPS has tighter bonds, carrying higher load and showing less strain, while PEI has weaker bonds, causing it to carry less load and show more strain [3, 23].

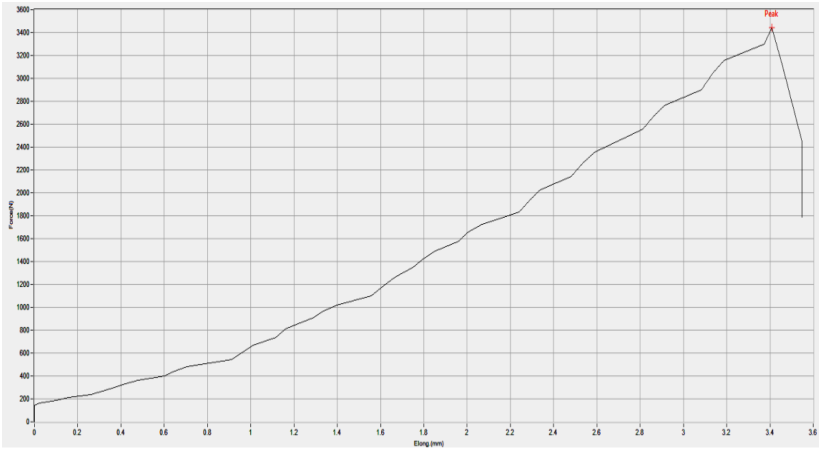


Figure 9. Tensile test of PPS (Force in X axis-elongation in Y axis)

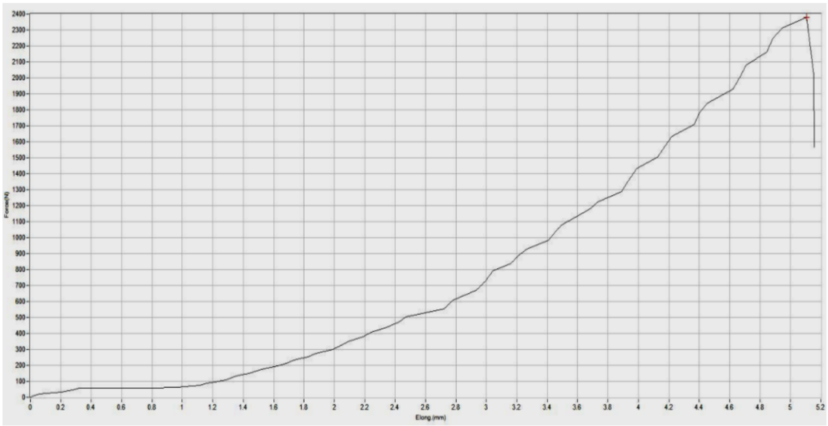


Figure 10. Tensile test of PEI (Force in X axis-elongation in Y axis)

Figure 11 indicates the variation of stress-strain of PPS and PEI polymer. From Figure 11, it can be observed that the tensile stress increases with increasing strain values for both two polymers. Tensile stress values for PPS increased rapidly up to 1.50 % strain and then remained constant until 2.211%. After this point, it continued steadily with a slight increase. As a result, the PPS polymer broke when the tensile stress was 180 MPa and the strain was 3.66 %. On the other hand, the tensile stress of PEI increased rapidly up to a strain of 3.33 % and then continued at a strain of 4.413% with small increases-decreases. From this point, PEI polymer broke at tensile stress of 60 MPa and the strain of 4.33 %. Comparing both polymers, it is seen that PPS material exhibits better mechanical properties than PEI. This is why, better interfacial bonding between fiber and matrix in PPS polymer, better tensile properties of PPS [3, 4, 24]. Figure 12 shows a tensile strength-strain graph obtained from a single injection condition both for PPS and PEI among nine injection conditions in Table 1 and 2.

The most effective method to determine the impact toughness of a polymer material is to perform impact notch testing. Table 4 indicates the impact strength values and the differences between those for polymer materials measured from the V-notched izod impact test. From Table 4, it can be seen that the impact strength values of the PPS polymer are generally higher than the values of the PEI polymer. As seen from Table 4, it has been determined that the most important injection condition affecting the change in impact strength for both PPS and PEI polymer materials is the runner type. The highest impact strength value is 14.88 KJ/m^2, while the smallest impact strength value is 7.28 KJ/m^2 [18]. Since the glass fiber additive ratio in each polymer material is close to each other, great differences in impact resistance values were not observed [18].

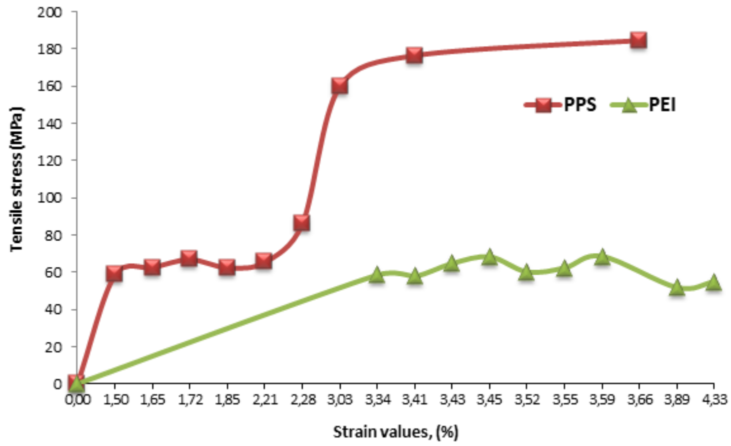


Figure 11. Tensile stress-strain curves for PPS and PEI

Table 4. Impact Strength values of PPS and PEI

	Polymer materials		***Differences***
	PPS	**PEI**	
	11.55	10.94	0.62
	10.96	10.71	0.25
	14.88	10.02	4.86
	11.69	9.89	1.80
	9.89	12.64	2.75
Impact Strength	11.63	12.02	0.39
(Izod Notched)	11.17	10.82	0.35
(KJ/m^2)	9.24	7.28	1.96
	9.60	11.8	2.20

Table 5. Shrinkage results for PPS and PEI

Polymer materials	**Shrinkage (%) (flow direction)**	**Shrinkage (%) (transverse)**	**Melt flow index (cm^3/10min)**
	0.164	1.00	**30.6**
	0.191	0.90	
	0.364	0.40	
	0.318	0.65	
PPS	0.182	0.90	
	0.245	1.05	
	0.201	0.85	
	0.382	0.35	
	0.218	0.95	
	0.182	0.75	**8.94**
	0.255	0.60	
	0.345	0.55	
	0.373	0.50	
PEI	0.100	0.95	
	0.218	0.60	
	0.236	0.50	
	0.391	0.65	
	0.200	0.80	

Dimensional change can be determined with the volumetric shrinkage. Table 5 gives the values of shrinkage at directions of melt flow, transverse and depth for PPS and PEI polymers. In Table 5, it can be seen that the lowest shrinkage values for both PPS and PEI are obtained in the flow direction whereas the highest values are measured in transverse direction for PPS. The amount of crystallinity of polymer materials affects the shrinkage indirectly; therefore, it can be assumed by the semi-crystalline materials (PPS) have higher shrinkage rates than amorphous materials (PEI) [25].

Melt flow index of PPS and PEI vary from 30.4 g/cm^3 to 8.94 g/cm^3 in Table 5. From this Table, it can be stated that the flowability of PPS polymer are faster than the polymers of PEI. Therefore, this polymer has been preferred in many applications. Additionally, solid density of PPS and PEI were found in 1.647 g/cm^3 and 1.627 g/cm^3, respectively.

5. Conclusions

This paper focused on the performance of high performance advanced polymers of PPS and PEI by evaluating the mechanical behavior, rheological characteristic and dimensional property. The obtained results can be expressed in the following:

• The plastic injection tests for both PPS and PEI polymers were conducted to reduce the time of experiments based on Taguchi design.
• From tensile tests, it can be understood that the tensile strength values of the PPS polymer are higher than that of the PEI polymer. In contrast, the strain values of PPS polymer are smaller than those of PEI.
• It can be found that the most effective parameter on the tensile strength is the type of runner type among the three injection conditions. In similar way, the conditions of temperature and the type of runner are very significant on the shrinkage.
• The tensile strength of PPS increases with the increase the content of glass fiber, but strain values indicates decreasing trend with increasing of glass fiber content. This result indicates that the mechanical behavior of PPS is better than that of PEI.
• The best impact toughness was achieved with PPS polymer material while low impact toughness was obtained from PEI polymer. This result was associated with the injection conditions of melt temperature, injection pressure and runner type.
• The volumetric shrinkage of PPS and PEI polymer is between international standards. Additionally, it can be concluded that the best shrinkage values for both PPS and PEI are obtained in the melt flow direction whereas the higher values are measured in transverse direction for PPS. It can be assumed that the content of glass fiber affects the dimensional stability of PPS specimens.
• The addition of glass fiber has no important effect on the melt flow characteristic of the polymers but also PPS of the melt flow index is higher than that of PEI. In addition to this, the solid density value of both polymers is very close to each other.
• As a result, this current study shows that high performance advanced polymers such as PPS and PEI can be used effectively and safely in the automotive, aerospace, electronics and sports industries due to their properties such as high strength, medium toughness and good dimensional stability.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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