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Research Article

Practical Technology of Toughening Epoxy Resin (II): Modification Effects of Special Engineering Plastics on Epoxy Resin

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Abstract

The effects of Special engineering plastics (SEP) such as polyether ether ketone (PEEK), polyimide (PI), thermoplastic polyimide (TPI), polyphenylene sulfide (PPS), polysulfone (PSF), liquid crystal polymer (LCP), polyaromatic (PAR) on the mechanical, thermal and electrical properties of epoxy resins were studied in this paper. The engineering plastics with rigid and active elements produce differential phase in the epoxy curing process, which can absorb energy under stress, prevent micro-crack diffusion, and improve the mechanical properties of epoxy resin, including tensile, compression and impact strength. SEP with better heat resistance than epoxy resins are beneficial for improving the heat resistance of epoxy resins. During the epoxy curing process, strong intermolecular forces are generated between SEP and epoxy resin, which further enhances the heat resistance of modified epoxy resins. Better insulation of epoxy resin are achieved by adding engineering plastics with fine insulation equipment. PSF with poor dispersion aggregates to form a weak interface layer, which first fails under stress, and its main mechanical properties slightly decrease. The dispersion of pulp like LCP in epoxy resin is poor, and there is no significant improvement in the mechanical properties of epoxy resin. PAR are difficult to form a homogeneous phase in epoxy resin and cannot be used for epoxy resin modification research.

Keywords

Epoxy Resin, Mechanical Properties, Special Engineering Plastics, Thermal Performance, Electrical Performance

1. Introduction

Epoxy resin is a commonly used thermosetting resin with excellent mechanical properties, low shrinkage, chemical resistance, electrical insulation, and other advantages [1, 2]. It has been applied in many fields such as electronics and electrical, mechanical, construction, and even aerospace. Due to its high cross-linking density, unmodified epoxy resins have drawbacks such as brittleness, poor fatigue resistance, and impact toughness; In addition, conventional epoxy resins usually have low heat resistance, making it difficult to meet increasingly high engineering and technical requirements, and their applications are limited to some extent. Therefore, toughening and heat resistance modification of epoxy resin has always been a hot research direction for epoxy researchers [3]. The epoxy resin widely used for electronic material

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bonding or packaging nowadays has increasingly high requirements for electrical performance, so improving the insulation performance of epoxy resin is also receiving attention [4-6].

In order to improve mechanical properties [7-9], the use of ductile polymer toughening epoxy resin is a common method. For example, Saberian [10] studied the properties of epoxy/graphene sheets/carboxyl nitrile rubber ternary nanocomposites. Adding 10% carboxyl nitrile rubber significantly improved the tensile strength of the epoxy system, and the elongation at break increased by 49%. Tan [11] adopted the end epoxide polyurethane toughening system to improve the impact strength of epoxy resin. In addition, there are also core-shell polymer toughening and graphene toughening modifications. These modification methods usually improve the mechanical properties of epoxy resins, but generally do not improve or slightly decrease their heat resistance. The toughening effects of CTPE, CTPF, CTBN, RNBR, CSM and other toughening agents on epoxy resin are discussed in our paper [12] "Practical Technology of Toughening Epoxy Resin: Influence of Toughening Agents on Mechanical and Heat Properties". The price of these toughening agents is relatively cheap, and they have a certain effect on epoxy toughening, but the heat resistance and electrical properties are usually slightly decreased or not significantly improved.

In order to improve the heat resistance of epoxy resin, Liu [13] used phenolic epoxy instead of bisphenol epoxy to obtain a heat-resistant 150 ℃ container coating. Of course, the use of multi-functional epoxy is also an effective way, such as the use of four-functional epoxy resin in the system by Li [14]. The glass transition temperature increased by 65.7% compared with the pre-modification. In terms of improving the electrical properties of epoxy resin, the composite material of nano-Al_2O_3 and BN was used as a significant additive. When the addition amounts of Al_2O_3 and BN were 2% and 1%, respectively, the electrical insulation parameters were significantly improved, while the thermal properties were also significantly improved [15]; Under the premise of a large number of experiments, Chen [16] believe that the use of hexagonal boron nitride in epoxy resin system can improve the thermal, electrical, mechanical and anti-corrosion properties.

The use of thermoplastics to modify epoxy resin is an important way, and the main consideration for plastic classification is the heat resistance of the product. Generally, it is attributed to general plastics according to the long-term use temperature below 100 ℃, the long-term use temperature is lower than 150 ℃ and is attributed to engineering plastics, and the long-term use temperature above 150 ℃ is attributed to special engineering plastics (SEP). In terms of SEP modified epoxy resin properties, Yang [17] modified epoxy composite materials with LCP, which improved the tensile and bending properties. Li [18] modified epoxy with thermotropic liquid crystal, which significantly improved the impact strength. The study of Hu [19] showed that PEEK had a good toughening effect on epoxy resin, but the heat resistance of the material was not affected. Rehman [20] showed that the glass transition temperature could be significantly increased by using PEEK in epoxy composites. Wang [21] modified epoxy with PI, and the mechanical properties of the material first increased and then decreased, and the heat resistance remained good.

SEP with heat resistance above 150 ℃ mainly include polyarylate (PAR), polyphenylene sulfide (PPS), polyimide (PI) [22], polyetheretherketone (PEEK), liquid crystal polymer (LCP), and polysulfone (PSF). Because of its unique and excellent physical properties, they are mainly used in high-end demand in special high-tech fields such as electronics, electronics, aerospace, etc. Thermoplastic Polyimide (TPI) is a derivative category of PI with similar properties, which are also grouped together for comparison and discussion in this paper.

In this paper, the transverse comparison of several SEP modified epoxies and experiments show that SEP modified epoxy resins generally improve their mechanical properties and electrical properties without reducing or even improving their heat resistance. Although some varieties of these SEPs are relatively expensive, they are used for epoxy toughening with simple usage methods, good toughening effects on epoxy resins, significant improvements in heat resistance and electrical properties. With technological progress and increased production, we believe that the prices will gradually decrease. Therefore, we classify these SEP toughening technologies as "practical epoxy resin toughening technologies", or more accurately, as "future practical epoxy resin toughening technologies".

2. Experimental Section

2.1. Experimental Materials

The main materials used in this paper were shown in table 1.

Table 1. *Major materials.*

Name	model	Composition and specification	Manufacture
Epoxy resin	128R	epoxy equivalent: 190g/eq, Viscosity: 12000~15000 mPa.s	Taiwan South Asia company
Benzyl glycidyl ether	XY-692	epoxy equivalent: 220g/eq, Viscosity: 2~8 mPa.s	Anhui hengyuan new material co., Ltd.

Name	model	Composition and specification	Manufacture
LCP	A950	density: 1.40g/cm^3	Bori Corporation of Japan
PEEK	330UPF	density: 1.30 g/cm^3, particle size: 900 mesh	Jilin Zhongyan Polymer Co., Ltd
PSF	P-1700	density: 1.24 g/cm^3	Solvay Chemical Company, USA
PI	PI-1	density: 1.31 g/cm^3	Zigong Zhongtiansheng New Materials Technology Co., Ltd
TPI	VAT001	density: 1.33 g/cm^3, Tg: 245 ℃	Wanrun Co., Ltd
PPS	P-32	density: 1.30 g/cm^3, melt flow rate: 330g/10min	Shandong Binhua Binyang Ranhua Co., Ltd
PAR	U-100	density: 1.19 g/cm^3	NUC Corporation of Japan (Unika)
Pyromellitic anhydride	-	purity: 98%	Shanghai McLean Biochemical Technology Co., Ltd
Fumed silica	TS-720	purity: 99%	CABOT Corp, USA

2.2. Experiment Instrument

INSTON 5567 electronic universal material testing machine, INSTRON company, USA (shear strength and compression strength test); INSTON 5967 electronic universal material testing machine, INSTRON company, USA (tensile strength and breaking elongation test); INSTRON CAST 9050 impact testing machine, INSTRON company, USA (Impact performance test); SDTA2+ thermomechanical analyzer, mettler toledo Company, USA; SM7120 high impedance meter, HIOKI Corporation, Japan; DT2-100-50-SP high voltage breakdown instrument, sepelec, France; WY-2858 dielectric loss meter, Shanghai wuyi electronic equipment Co., Ltd; NDJ-1Fmax touch screen viscometer, Shanghai xiniu leibo instrument Co., Ltd; ApreoS scanning electron microscope thermo fisher, USA.

2.3. Preparation of Materials

2.3.1. Preparation of Toughened Epoxy Resin

SEP is added to the epoxy resin for modification. The toughening method adopted in this paper is to treat the corresponding engineering plastics into powder and directly add them to the epoxy resin components, and then investigate their effects on the curing properties of the epoxy components. These engineering plastics have good heat resistance, high glass transition temperature and melting temperature (as shown in Table 2), and epoxy resins generally occur thermal oxidation decomposition at 180-200 ℃ under aerobic conditions when heated, and decomposition occurs even under oxygen-free conditions to 300 ℃. Therefore, SEP cannot be dissolved into the liquid epoxy resin by melting. For this purpose, we use plastic powder with the smallest possible particle size, which is blended and uniformly dispersed into epoxy resin as a toughening component. Then, this component is cured with a curing agent system under appropriate curing conditions and its performance was compared.

Table 2. *Tg and melting temperature of SEP.*

Name	model	Tg/ ℃	melting temperature / ℃
PEEK	330UPF	≥200	343-387
PI	PI-1	≥200	300-400
TPI	VAT001	245	260-450
PPS	P-32	≥200	280-380
PSF	P-1700	174	329-385
LCP	A950	≥180	300-390
PAR	U-100	193	300-350

From the existing obtained several SEP, they can be classified into powder, flocculent, and granular forms. In order to fully mix it with epoxy resin, large-sized particles need to be processed into powder form through methods such as crushing. PEEK, PI, TPI, and PPS in powder state can be directly blended into epoxy resin, while LCP, PAR, and PSF in non-powder state need to be pulverized to aid dispersion. For this purpose, LCP, PAR, and PSF particles were frozen at -70 ℃ for 6 hours, and then crushed and stirred at high speed grinder. Among them, PSF formed small flocculent particles, while LCP became pulp like fiber aggregates after grinding, and PAR was still granular.

Through experimental testing, it has been found that several materials such as PEEK, PI, TPI, PPS, PSF, etc. can be uniformly dispersed into epoxy resin components and can be used for epoxy modification research; After LCP grinding, it appeared as a pulp, and when added to epoxy resin, its viscosity increased significantly, resulting in a high oil absorption value and the addition amount should not be too high; PAR cannot be dispersed into the resin at all. Therefore, the toughening modification of epoxy resin by PSF, PEEK, PI, TPI, PPS and LCP engineering plastics was studied. Looking forward to obtaining powdered PAR materials in the future, or using specific methods to powder them, it is necessary to add their performance comparison as a follow-up addition to the content of this article for comparison.

For the sake of discussion, in this paper, SEP was added according to 10% of the total weight of epoxy resin except LCP. Due to the large increase in viscosity caused by the addition of LCP, it was difficult to prepare samples, and the dosage was changed to 3%. These SEP powders were mixed with epoxy resin, homogenized by a homogenizer, and then mixed with the curing agent homogeneous phthalic anhydride powder, and then cured under the curing condition of 150 ℃/3h. The ratio and dosage were shown in Table 3.

Table 3. *Ratio and dosage.*

Component	No	1#	2#	3#	4#	5#	6#	7#
	SEP Type	**Blank**	**PEEK**	**PI**	**TPI**	**PPS**	**PSF**	**LCP**
A	128R/g	95	95	95	95	95	95	95
	XY-692/g	5	5	5	5	5	5	5
	QS-720/g	2	2	2	2	2	2	2
	PEEK/g	0	10	0	0	0	0	0
	PI/g	0	0	10	0	0	0	0
	TPI/g	0	0	0	10	0	0	0
	PPS /g	0	0	0	0	10	0	0
	PSF/g	0	0	0	0	0	10	0
	LCP/g	0	0	0	0	0	0	3
B	PMDA/g	43	43	43	43	43	43	43

2.3.2. Adhesive Curing and Sample Preparation

The adhesive A and B components were mixed and stirred according to the specified ratio, and then homogenized and mixed with a homogenizer to make the specified sample, which was cured according to 150 ℃/3h.

2.4. Measurement and Characterization

(1) The tensile spline was cut after brittle fracture, and the fracture section was treated with gold spray. The microscopic morphology was observed by scanning electron microscopy (SEM).
(2) Viscosity test was carried out at room temperature according to Chinese National Standard GB/T2794-2022.
(3) Mechanical properties tests such as tensile properties, bending properties, impact properties, compression properties were measured according to Chinese National Standard GB/T 2567-2021 *resin casting performance test method*. The impact properties sample was 80mm×10mm×4mm without notch. The specimens for tensile strength and elongation at break tests were dumbbell shaped, with an external dimension of 250mm×20mm×4mm and a tensile width of 10mm. Cylindrical specimens of compression strength were Φ10mm x 25mm. The size of the cast specimen used for bending performance testing was 100mm*15mm*4mm.
(4) Glass transition temperature (Tg) and coefficient of thermal expansion (CTE) were measured using thermal mechanical analysis (TMA).
(5) The determination of the electrical properties of materials, such as volume resistivity, electrical strength, and dielectric loss factor, shall refer to Chinese national standards GB/T 1410-2006, GB/T1408.1-2016 and GB/T 1409-2006, respectively.

3. Results and Discussion

3.1. Appearance and Viscosity

Several SEP powders were added to the epoxy resin. Due to the color of the plastic powder itself, the color of the original translucent resin changed, and the viscosity increased which was shown in Table 4. The content of LCP in the table is 3% of the total amount of resin components, and the content of other SEP is 10% of the total amount of resin components.

Table 4. *Effect of SEP on the appearance and viscosity of epoxy resin.*

SEP Type	BLANK	PEEK	PI	TPI	PPS	PSF	LCP
Appearance	**Pale milky paste**	**Pale yellow paste**	**Orange-yellow paste**	**Yellow paste**	**Grey paste**	**grayish white paste**	**Grayish pulp paste**
Thixotropic index	2.1	2.4	3.5	2.1	3.3	2.5	3.4

The viscosity of the adhesive at different speeds is shown in Figure 1.

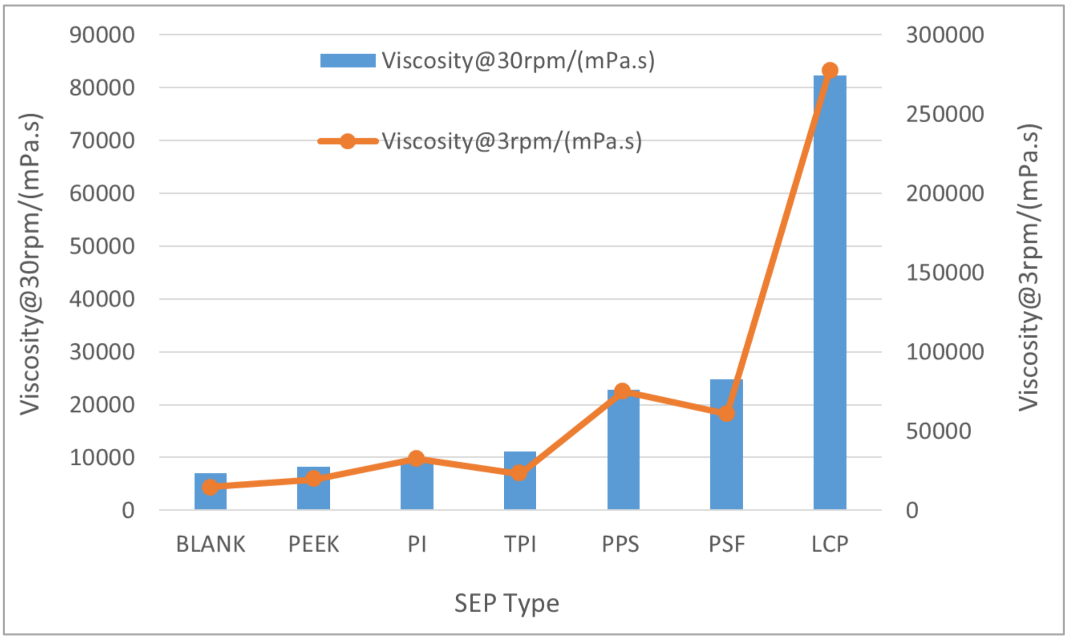

Figure 1. *Viscosity of Modified Resin at Different Rotational Speeds.*

Plastic particles have different particle sizes and surface conditions, and their interactions with epoxy resin is different, which was manifested by varying oil absorption values of epoxy resin and varying viscosity when dispersed in the resin. PEEK, PI, and TPI have a particle size of about 500-900 mesh, high particle regularity, and are easily dispersed in epoxy resin, with little increase in viscosity; The particle size of PPS is relatively coarse, about 300 mesh, and there are also micro rod-shaped substances present, which have a high oil absorption value and lead to a significant increase in viscosity; After PSF crushing, it appears flocculent and has poor dispersion, with an increase in viscosity of over 200%. After LCP crushing, it forms fibrous aggregates in the form of pulp, which are dispersed in epoxy resin and easily form pulp aggregates, leading to a sharp increase in viscosity. Even with only 3% added, its viscosity is still the highest in this article.

3.2. Micromorphology

Figure 2 showed the SEM images with section magnification of 3000 times of epoxy cured material without SEP (Blank) added and with SEP added.

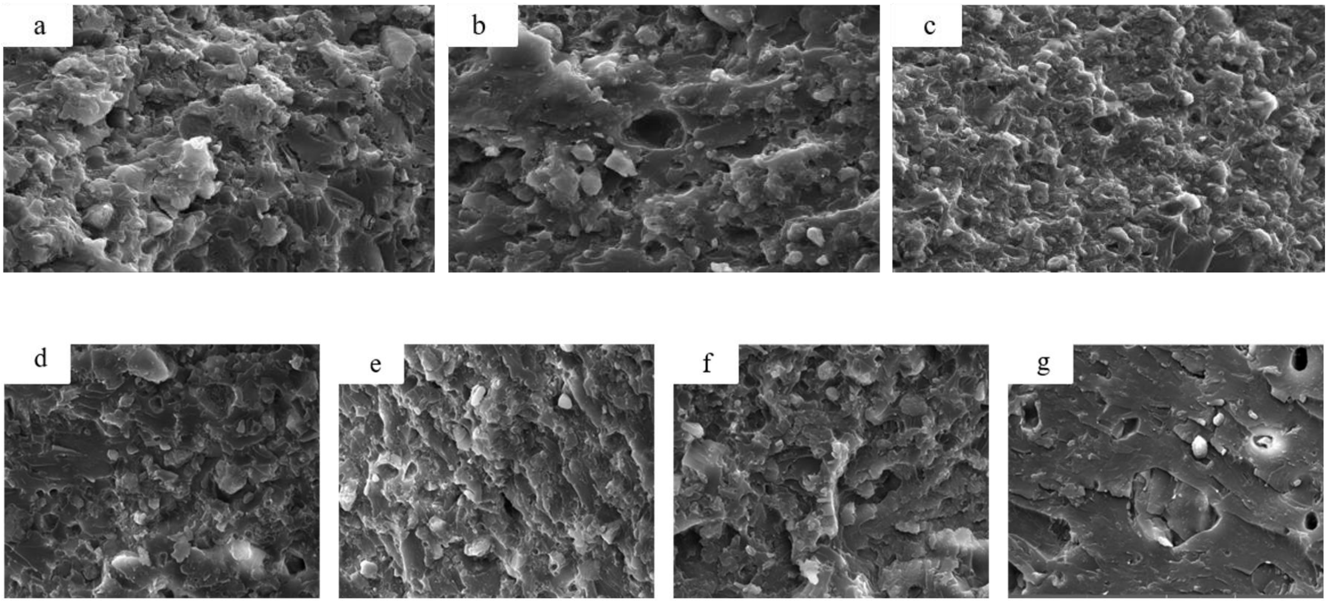

Figure 2. *The cross-sectional morphology of SEP modified epoxy resin (The SEP in picture a to g are Blank, Peek, PI, TPI, PPS, PSF, and LCP respectively).*

It can be seen from these SEM images that compared with BLANK samples, the modified SEP systems of PEEK, PI, TPI, PPS and PSF have more uniform cross sections, and the plastic particles are well integrated with the epoxy resin body without obvious interface. LCP has the worst dispersion, the plastic particles are not tightly wrapped by epoxy resin, and there are obvious defects such as cavities and air holes, which are closely related to the modification effect.

3.3. Mechanical Properties

3.3.1. The Impact on Tensile Performance

The curing agent used in this article, phthalic anhydride (PMDA), has a high crosslinking density after curing with epoxy resin. The cured material has good heat resistance and high brittleness. The comparison of tensile strength and modulus between the materials without added plastic particles with added 10% plastic powder (LCP added 3%) was shown in Figure 3.

When materials are subjected to tensile stress, many micro-cracks will occur. SEP powder particles dispersed in the resin can prevent rapid crack propagation, thus exhibiting a certain improvement in tensile strength and modulus. Among several SEP, PEEK, PI, TPI, and PPS are well dispersed in the epoxy resin. It can also be clearly seen from the SEM image in Figure 2 that these materials can effectively disperse tensile stress, prevent micro-cracks from occurring, and exhibit an increase in tensile strength and modulus. Among them, the improvement in PPS was the most significant. On the other hand, PSF is a small flocculent material with poor compatibility in epoxy resin and is more prone to aggregation. When subjected to tension, these flocculent materials are prone to weak interfaces such as local voids and defects at the interface with epoxy resin. When dispersed in epoxy resin, some clusters may entangle and the infiltration with epoxy resin is insufficient. When subjected to tension, they first fracture in these areas, resulting in a decrease in tensile strength. LCP cannot be fully and uniformly dispersed in epoxy resin, forming a pulp like aggregate. There is a weak interfacial layer between internal fiber bundles, and when cured with epoxy resin, there is also an insufficiently wetted weak interfacial layer at the fiber/epoxy interface; In addition, there are obvious defects such as pores and air pockets. Therefore, these weak interface layers and defects are first broken under tensile action, showing a decrease in tensile strength and modulus after cured.

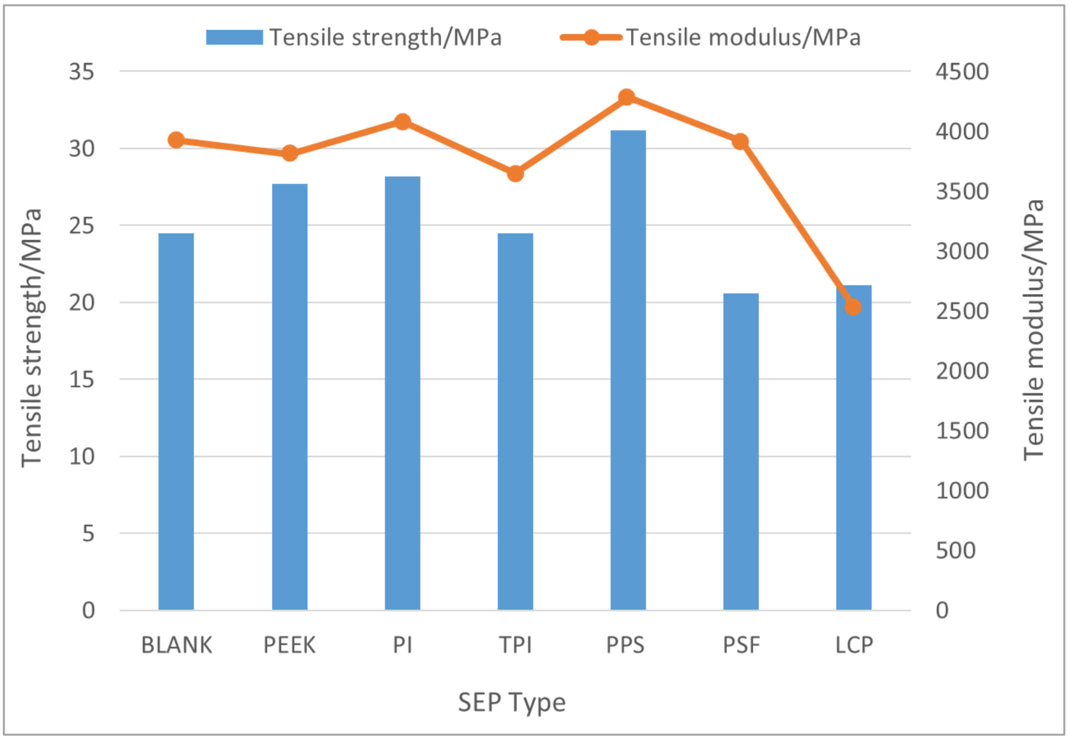

Figure 3*. Effect of SEP on tensile properties.*

Among these SEP, the LCP, PEEK, PI, and TPI are all relatively rigid varieties, and their impact on tensile performance mainly lies in preventing the propagation of micro-cracks, with no significant improvement in fracture elongation. PPS and PSF body materials have better toughness. When subjected to tensile stress, in addition to the aforementioned crack propagation prevention effect, the toughness of their plastic particles causes a slight increase in fracture elongation. The elongation at break of the material is shown in Figure 4.

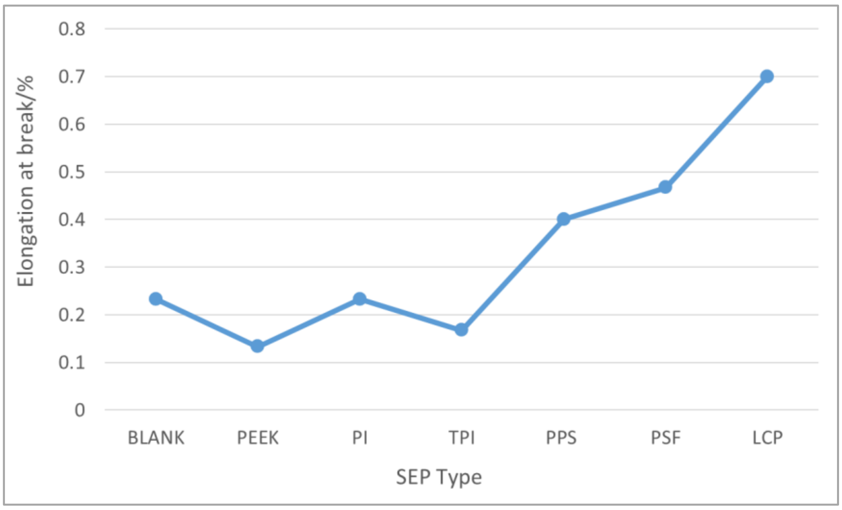

Figure 4*. Effect of SEP on elongation at break.*

The addition of PPS increased the tensile strength by 27.4%, the tensile modulus by 16% and the elongation at break by 71%, which has the most obvious effect on the overall tensile property.

More interesting is the LCP. Although the tensile strength and tensile modulus decreased due to the poor dispersion in epoxy resin, the slurry fiber formed a similar fiber-reinforced composite after curing with epoxy resin, which greatly improved the elongation at break of the material.

3.3.2. The Impact on Compression Performance

Due to the high rigidity, cohesive strength, and compressive strength of the epoxy system cured by PMDA, the body material is not easily compressed. The introduced SEP itself contains a large number of rigid elements, and its compressive strength is higher than that of pure epoxy. Therefore, the compressive performance of the introduced SEP is slightly increased, as shown in Figure 5.

The compression strength and compression modulus exhibit similar patterns, except for PSF with better toughness where the compression strength and compression modulus slightly decrease, the other types all show a slight increase. LCP, due to its poor dispersion, is prone to defects such as voids and air pockets at the interface between pulp aggregates and epoxy resin. When compressed, these areas first break, resulting in a decrease in compressive strength and modulus.

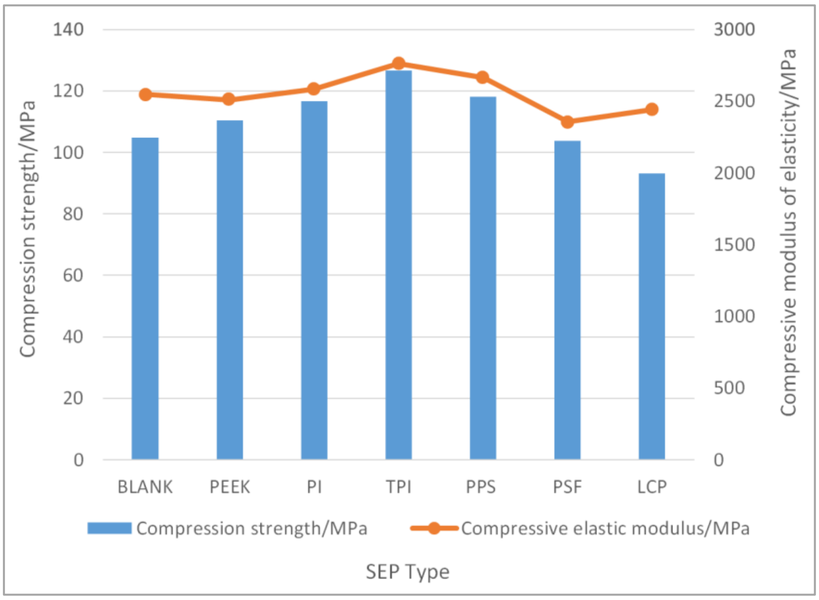

Figure 5. *Effect of SEP on compressive properties.*

3.3.3. The Impact on Bending Performance

The addition of plastic particles leads to some stress gradients between the epoxy resin plastic particles. Under bending stress, this bonding force is lower than that of pure epoxy resin, indicating that the bending strength of epoxy resin with SEP addition is lower than that of pure epoxy, as shown in Figure 6. The bending modulus remains at the same level as the original state of the epoxy resin, with slight fluctuations.

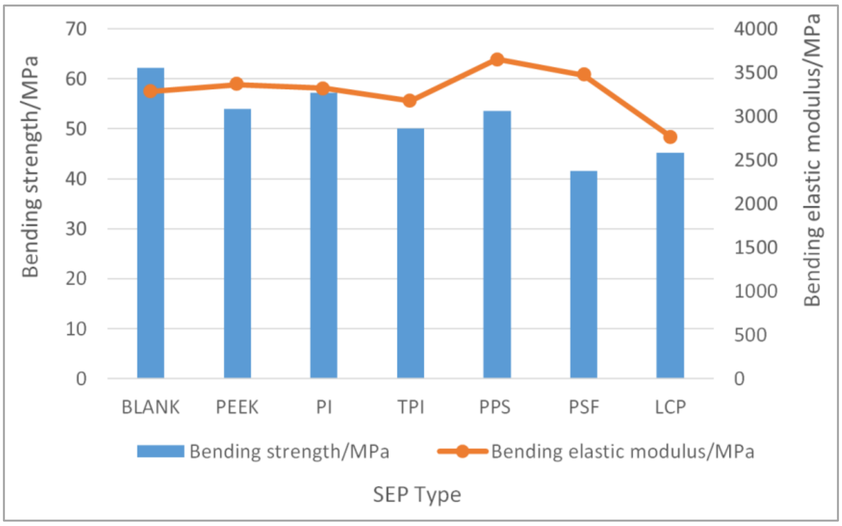

Figure 6. *Effect of SEP on bending properties.*

3.3.4. The Impact on Impact Performance

One important role of using SEP to modify epoxy resin is to improve its impact resistance. Figure 7 showed the influence of plastic particles on the impact performance of materials.

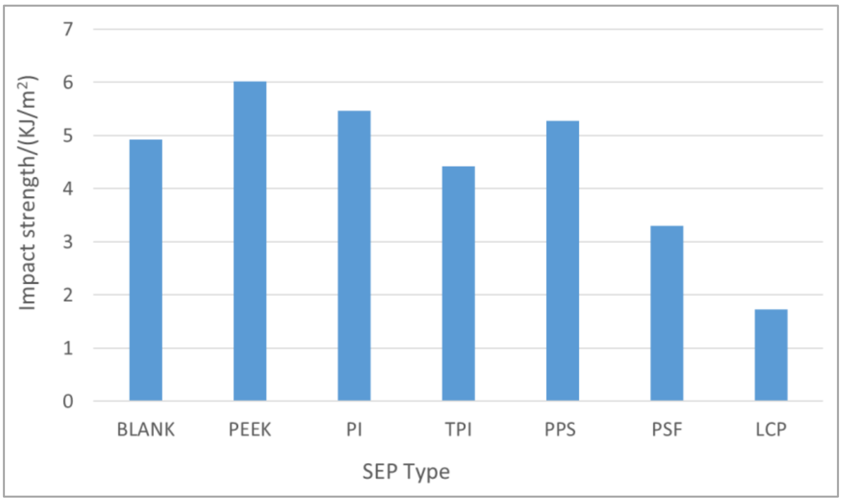

Figure 7. *Effect of SEP on impact strength.*

From the perspective of these engineering plastics in this article, PEEK, PI, and PPS materials are uniformly dispersed in epoxy resin. During the resin cured process, micro-phase separation occurs between plastic molecules and epoxy resin, forming structures such as island structures, particle crack bridging, and crack path deviation, which can improve the toughness of epoxy resin; In addition, some active groups in SEP enter the epoxy resin cross-linked network and become network nodes. When subjected to impact energy, they can disperse stress and withstand the impact energy, showing a certain improvement in impact performance. PSF, due to its short fiber state, is prone to agglomeration during epoxy curing, resulting in local fiber concentration. There is a weak interface layer with poor wetting between the short fibers and epoxy resin, which can easily generate internal stress, leading to a slight decrease in impact performance.

The expected impact strength of LCP modified epoxy resin will be improved, but the test results did not meet expectations. Although fiber-reinforced epoxy resin can improve impact strength, the dispersion of LCP in epoxy resin in this article is too poor, and the defects such as voids and voids greatly damage its impact performance.

3.4. Heat Resistance

The influence of several SEP on the glass transition temperature of epoxy resin was tested using TMA method, and the thermal expansion coefficients of materials in the range of 25-65 ℃ were compared and analyzed.

Figure 8 summarized the effects of several SEP on the glass transition temperature of epoxy resin. The use of several SEP has resulted in an increase in Tg, among which PI, PPS, and PSF have increased by more than 20 ℃, demonstrating excellent heat resistance.

The impact of modified epoxy on heat resistance includes: firstly, several SEP themselves contain a large number of rigid elements, and their heat resistance is better than that of pure epoxy, resulting in improved heat resistance; Secondly, rigid plastic powder is added to the epoxy resin, occupying a portion of its volume, making it more difficult for the molecular chain segments of the curing system to move and contributing to the improvement of heat resistance. Zhang [23] sdudied the crosslinking model between epoxy resin and PI powder and obtained the change in the free volume fraction of the system. It was found that as the epoxy system cured, the crosslinking points between PI molecular chains and epoxy increased, and the rigid PI molecular chains played a greater role in the crosslinking system. The free volume fraction gradually decreased, the mobility weakened, and the glass transition temperature increased. The other SEP powders have a curing reaction mechanism similar to that of PI powder in epoxy resin, which also leads to an increase in the glass transition temperature of the modified epoxy resin.

There are two factors that affect the thermal expansion coefficient of engineering plastic powder. On the one hand, plastic powder added to epoxy resin occupies a portion of the volume, and PSF material itself has a certain toughness, making it easier to expand during heating, which will lead to an increase in the coefficient of thermal expansion; On the other hand, the active groups in plastic powder form cross-linking structures or intermolecular forces with the epoxy resin matrix, which reduces the mobility of molecular chains and leads to a decrease in the coefficient of thermal expansion. The final coefficient of thermal expansion is the result of the combined action of the above two factors.

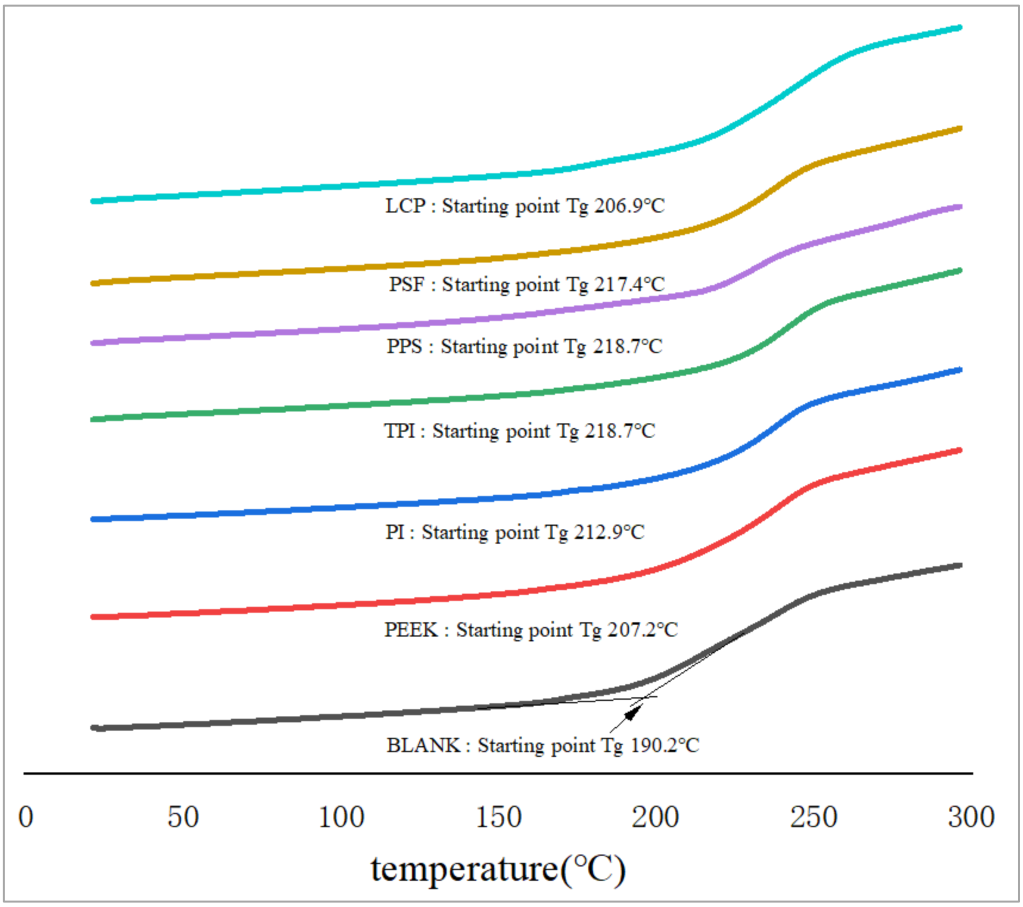

Figure 8. TMA diagram of special engineering plastic modified epoxy.

In this article, PEEK, PI, and TPI materials are the second main factor that leads to a decrease in thermal expansion coefficient; PPS, PSF, and LCP are the first factors that play a major role, manifested by an increase in the coefficient of thermal expansion. The specific changes are shown in Figure 9.

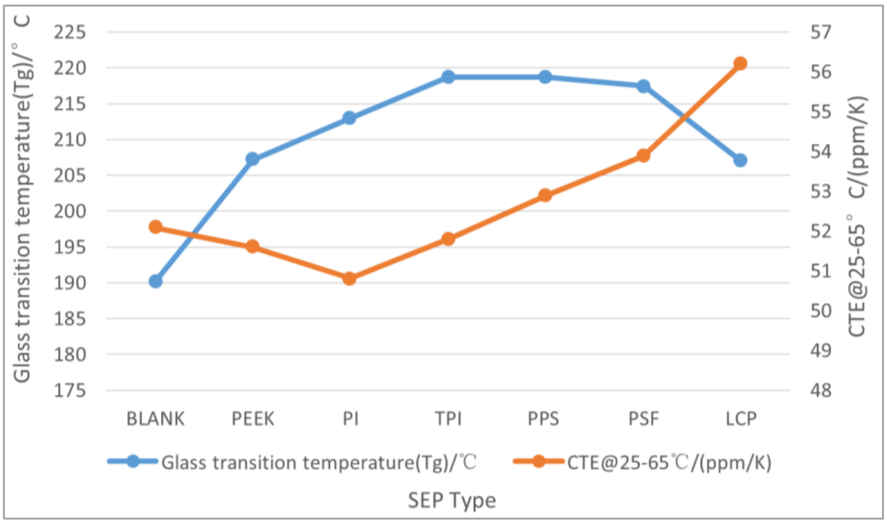

Figure 9. Effect of SEP on Tg and CTE.

3.5. Electrical Performance

SEP has a significant impact on electrical performance, with changes in volume resistivity shown in Table 5. Except for PI causing a certain degree of reduction in volume resistance, the introduction of other materials has improved the insulation resistance of the material. Among them, PEEK has increased by more than 225%, and LCP has also significantly increased.

Typical volume resistivity of epoxy resin approximately at the level of 10^{15} Ω. cm, while the volume resistivity of SEP such as PEEK and PPS is at the level of 10^{16} Ω. cm. Therefore, the dispersion of engineering plastic powder with better insulation properties into epoxy resin leads to an increase in volume resistivity, which is also related to the degree of dispersion uniformity and the interaction between plastic powder groups and epoxy resin molecules during the curing process.

Table 5. *Impact of SEP on Electrical Properties.*

Model	BLANK	PEEK	PI	TPI	PPS	PSF	LCP
ρ_v /(Ω.cm *10^{15})	6.53	21.25	3.39	10.25	9.9	7.37	15.7
increment /(Ω.cm *10^{15})	-	14.72	-3.14	3.72	3.37	0.84	9.17
Increase proportion/%	-	225.4	-48.1	57	51.6	12.9	140.4

The impact on dielectric loss and electrical strength is shown in Table 6.

Table 6. *Effect of SEP on the Dielectric Loss and Electrical Strength of Epoxy Resin.*

SEP Type	BLANK	PEEK	PI	TPI	PPS	PSF	LCP
tg δ (1MHZ) *10^{-3}	8.7	7.7	2.35	7.7	7.5	8.05	19.3
Eb (KV/mm)	20.6	23.5	20.8	21.8	21.3	19	14.8

Except for LCP, other SEP has effectively reduced the dielectric loss of the system and improved its electrical strength. These types of SEP all have good electrical insulation properties, and their excellent electrical performance is fully utilized in epoxy resin modification systems. The effect of epoxy modification is obvious, making them a very good choice for scenarios that require high electrical performance.

The electrical performance of LCP body material is excellent, and adding it to epoxy resin has a significant improvement effect on volume resistivity. However, due to poor dispersion in epoxy resin, defects such as bubbles and pores are easily formed in the cured casting body. Under the action of voltage, these areas are first broken or broken down, leading to a decrease in electrical strength and an increase in dielectric loss.

3.6. Comprehensive Evaluation of SEP on Epoxy Resin Modification

Comprehensive evaluation of the modification effect of several SEP on epoxy resin is shown in Table 7. Using blank samples as the benchmark, A-E scores show that A is the best and E is the worst. Among them, the blank sample has the best dispersion, the lowest viscosity, and the lowest price, so it is set as A. Other performance values are set to the median value C. Compare and evaluate the results of SEP modification with it.

Table 7. *Comprehensive evaluation of the impact of SEP on epoxy resin modification.*

SEP	BLANK	PEEK	PI	TPI	PPS	PSF	LCP	PAR
Dispersibility	A	A	A	A	B	C	D	E

SEP	BLANK	PEEK	PI	TPI	PPS	PSF	LCP	PAR
Viscosity	A	A	B	B	D	D	E	no data
Tensile properties	C	A	A	B	A	E	C	no data
Compression properties	C	B	B	A	A	D	D	no data
Bending properties	C	D	D	D	D	D	E	no data
Impact performance	C	A	A	C	A	D	E	no data
Electrical performance	C	A	E	A	A	C	A/D*1	no data
Heat resistance	C	A	A	D	B	A	A	no data
Price	A	E	E	E	B	B	B	C

*1: The effect of LCP on electrical performance: volume resistivity A, electrical strength D.

It should be noted that the conclusions in the table only match the brand and model corresponding to the SEP received in this article. We believe that with the development of technology and the expansion of production scale, some materials with higher prices in the table may gradually decrease; PAR that are difficult to add now may also become easily dispersed into epoxy resins in future development. We hope to rewrite the table and gather all effective data together, so that these SEP can play their special effects in modifying epoxy resins in more fields.

4. Conclusions

The main conclusions drawn from this research were as follows:

(1) SEP powders, including PEEK, PI, TPI, PPS, PSF, and LCP, can modify the properties of epoxy resins through blending, and their particle size has a significant impact on the modification effect; PAR is difficult to uniformly disperse and cannot modify the properties of epoxy resin through blending.

(2) Different types of SEP structures have different effects on the modification of epoxy resin, and the SEP morphology and dispersion state in epoxy resin have important effects on the modification of epoxy resin.

(3) Uniformly dispersed PEEK, PI, TPI, and PPS have a certain improvement effect on the mechanical properties of epoxy resin, including tensile, compressive, and impact properties; The mechanical properties of PSF modified epoxy with flocculent structure, including tensile strength, compressive strength, and impact strength, actually decrease; The dispersion of pulp like LCP in epoxy resin is poor, and there is no significant improvement in the mechanical properties of epoxy resin.

(4) Significant improvement in electrical insulation and heat resistance of several SEP modified epoxy resins.

Abbreviations

SEP: Special Engineering Plastics
PEEK: Polyether Ether Ketone
PI: Polyimide
TPI: Thermoplastic Polyimide
PPS: Polyphenylene Sulfide
PSF: Polysulfone
LCP: Liquid Crystal Polymer
PAR: Polyaromatic
CTE: Coefficient of Thermal Expansion
SEM: Scanning Electron Microscopy
TMA: Thermal Mechanical Analysis

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Wang Hong: Resources

Conflicts of Interest

The authors declare no conflicts of interest.

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