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EFFECT OF MODIFICATION WITH POLYETHER POLYOL AND LIQUID SILICON RUBBER ON THE MECHANICAL PROPERTIES OF EPOXY SYSTEM

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ABSTRACT

Epoxy resins are widely used for their strength, chemical resistance, and adhesion, but they are naturally brittle. The objective of this study was to investigate the effects of the addition of a polyurethane (PU) base (polyol) and liquid silicone rubber (LSR (as toughening agents to the epoxy resin. This research focuses on developing a modified flexible epoxy resin by added the toughening agents to epoxy resin was evaluated in various weight ratios (3%, 6%, 9%, and 12%) with (1-methylethyl-1,1'-biphenyl, izoforon diamine) as a hardener. To evaluate the impact of strengthening materials, epoxy samples were tested before and after the addition the toughening agents above. Surprisingly, the mechanical properties exhibited significant improvement according to the results. In case of LSR/Epoxy, (tensile modulus, tensile strength, fracture toughness, and impact strength) were modified at 6wt% LSR. In case of PU/Epoxy, a mechanical property was modified depending on the addition percentage of PU. In conclusion, the 6wt% LSR is the best ratio to modified epoxy. In comparing to PU, each percentage modify a specific property, this difference take place because of the soft elastic flexible nature of PU.

KEYWORDS

Epoxy, fracture toughness, impact strength , liquid silicon rubber, polyether polyol.

1. INTRODUCTION

Epoxy resins are a type of thermosetting polymer that has widespread application as a structural material, coating, and adhesive in diverse fields. These fields include the aerospace, automotive, and electronics industries. The popularity of epoxy resins stems from their high mechanical properties, excellent heat resistance, and solvent resistance. Their unique qualities arise from the chemical bonds that form their crosslinked structure. However, this crosslinked structure's restriction of molecular mobility also contributes to the material's lower fracture toughness compared to other engineering thermoset polymers. (Yao, Dongdong, Li, Yuchen, Zhang, Xin and Fan, Wendi, Zheng, 2024),(Januszewski, Dutkiewicz and Nowicki, Marek, Szołyga, Mariusz, Kownacki, 2021). Extensive research has been conducted over the past few decades to improve the toughness of epoxy resin through the inclusion of functionalized rubbers, engineering thermoplastics, and block copolymers.(Neves, Roberta Motta, Ornaghi, Heitor Luiz, Zattera and Amico, 2022; Li, Gang, Wu, Yu, Xuecheng, Zhang, Ruoyu, Sun and Cao, Liqiang, Zhu, 2023). Toughened epoxy is commonly used in scientific studies because it enhances the finished material's strength. (Aiza Jaafar, Zainol and Ishak, N. S., Ilyas, R. A. , Sapuan, 2021). Researchers have employed a variety of methods, including chemical modifications involving chain extenders or plasticizers, to toughen brittle epoxy-based systems. The next most frequent approach involves adding a second phase, typically in the form of liquid rubber. Among the various ways to improve the mechanical properties of epoxy resins (EPs), one of the most popular is the addition of reactive liquid rubbers (Jaiganesh, Vinothkumar and P, 2022) EPs have been modified with rubbers containing terminal functional groups, such as hydroxy-terminated polybutadiene (HTPB)(Januszewski, Rafał, Dutkiewicz, Michał, Nowicki, Szołyga and Kownacki, 2021), carboxyl-terminated polybutadiene (CTPB), (Liu, Yuanjin, Yao and Bu, Yue, Sun, 2021) epoxy-terminated polybutadiene (ETPB), amino-terminated polybutadiene (ATPBs) with aliphatic or aromatic linker between the amine group and the polybutadiene (PB) chain(Abdollahi, Hossein, Samadi, Ali , Amiri, Farzaneh, Mousapour-Khaneshan, Zarrintaj and Kavanlouei, 2022), as well as a copolymer made of carboxyl-terminated acrylonitrile-butadiene (CTBN)(Januszewski, Dutkiewicz and Nowicki, Marek, Szołyga, Mariusz, Kownacki, 2021). Polysiloxanes are ideal toughening agents due to their highly flexible backbone of Si-O-Si, low glass transition temperature, excellent thermal and oxidative stability, low surface tension, and good weatherability. However, due to the low compatibility between the soft segments of PDMS (poly(dimethylsiloxane)) and the polar hard segments in epoxy, primarily resulting from the absence of hydrogen bonding, pure PDMS has extremely limited utility as a toughening agent (Chea, 2022).Combining an epoxy resin with silicone rubber shows great promise for uses that call for high impact strength. It was thus of interest to assess the mix's mechanical properties between epoxy resin and silicone rubber(Farhan and Jaffer, 2020; Kumar, Kumar and Han, Sung Soo., Park, 2021). Fahriadi Pakaya et.al.(Pakaya, Ardhyananta and Wicaksono, 2017a) investigated the mechanical properties and thermal stability of thermoset epoxy as a function of RTV silicone rubber composition (0%, 5%, 10%, 15%, and 20% by weight). The addition of 15% RTV silicone rubber resulted in a maximum increase in energy and impact strength, reaching 0.294 J/m² and 6175 J/m², respectively. However, there was a loss in tensile strength, elongation at break, and hardness. Specifically, when 15% silicone rubber is added to the system, the maximum degradation temperature occurs at 328°C for 5% degradation and 349°C for 10% degradation. Ahmed Farhan and Harith Jaffer prepared blends of epoxy and room temperature silicone rubber (SR) as well as unsaturated polyester (UPE). According to the results of the experiments, the impact strength of EP/SR and UPE/SR blend specimens reached the greatest values of 8.13 KJ/m² and 11.91 KJ/m², respectively, when SR was added at 10% and 5%. However, the hardness value for both EP/SR and UPE/SR dropped somewhat over the range of 3% to 20% SR content. Additionally, both EP/SR and UPE/SR exhibited a significant drop in flexural strength within the 3% to 20% SR concentration range (Farhan and Jaffer, 2020). On the other hand, polyurethane (PU) (specifically, PU polyol) is used to create interpenetrating polymer networks (IPNs) with epoxy resin (EP). This combination aims to enhance the toughness and elasticity of EP due to PU’s remarkable properties, including great elasticity, high impact strength (IS), and excellent chemical and thermal resistance (Kostrzewa, Bakar and Białkowska, A., Szymańska, J., Kucharczyk, 2019). Some of the most adaptable thermoplastics are polyols (PU), which may be used in a wide variety of applications(Ahmed, Naveed, Niaz and Ahmed, Saad, Javid, Muhammad Tariq, Ali, Muhammad, Tariq, 2023). Polyol's soft segments, which are made up of linear long-chain molecules, make it a useful material in many applications (with an abundance of hydroxyl groups ready for chemical reaction) (Velayati, Mahin, Sabouri, Zahra, Masoudi, Abdolhossein, Mostafapour, Asma, Khatami, Mehrdad, Darroudi, 2022). Jajam et al. investigated how adding a reactive polyol (PU) diluent and amino-functionalized multi-walled carbon nanotubes to epoxy composites affected their fracture behavior. Four types of samples were prepared: pure epoxy, epoxy with carbon nanotubes (0.3 wt. %), epoxy with polyurethane (polyol) (10 phr), and a hybrid epoxy with CNTs (0.3 wt. %) and PU polyol (10 phr). Each of the modified systems exhibited a considerable improvement over pure epoxy in terms of quasi-static crack initiation toughness (KIC). Notably, the hybrid epoxy/CNT/PU (polyol) system demonstrated the greatest KIC with an impressive ~70%

improvement compared to the other formulations (Jajam, Rahman and Hosur, M. V., Tippur, 2014). Hui Jin et al. studied various types of interpenetrating polymer networks (IPNs) using epoxy (EP) resin and polyol (PU) generated from soybean oil-based polyol in varying mass ratios (ranging from 10% to 35%). The tensile results reveal that PU(polyol)/EP IPNs had lower tensile strength and modulus than those of the neat epoxy, but the elongation at break of IPNs was greater than that of the neat epoxy resin. Interestingly, when the PU (polyol) content of the IPNs was raised, the elongation at break also increased (Jin, Zhang and Wang, Chengshuang, Sun, Yifan, Yuan, Zuanru, Pan, Youqiang, Xie, Hongfeng, Cheng, 2014). In this study, we considered the incorporation of toughening agents such as polyurethane (PU) base (polyol) and liquid silicone rubber (LSR) directly with epoxy resin. The properties of epoxy compositions with different toughening agent concentrations were measured and compared. The current research prepared compositions with toughening agent additives at 3%, 6%, 9%, and 12% weight ratios, and the characterization properties were measured. Additionally, the research presents good results in terms of fracture toughness, impact strength, and tensile strength of the samples.

2. EXPERIMENTATION

2.1. Materials and Apparatus

- Epoxy Sikadur 52 (produced by Sikadur, Turkey) is based on bisphenol F-(epichlorohydrin) and hardener (isophorone diamine). It is a versatile two-part epoxy adhesive designed for various applications, including crack grouting, injection resin, sealing interior and exterior slabs, and wearability improvement. Epoxy Sikadur 52 is an excellent choice for crack repair and grouting due to its moisture tolerance, low viscosity, and high-strength properties. Whether you’re dealing with concrete cracks or need to improve the durability of slabs, this epoxy adhesive can be a reliable solution.

- The toughening agent (PU polyol) used in the preparation of samples is the Quickmast 120 type. This type is a PU base resin with polyether polyol, and it has a yellowish-green color. Its relative density at 25°C ranges from 1.1 to 1.2 g/cm^3. The toughening agent was supplied by the company agent, DCP, Hilla, Iraq, and it was manufactured by DCP Saudi Co.

Room temperature vulcanization silicone rubber (RTV), also known as liquid silicone rubber (LSR), is a type of liquid silicone elastomer. LSR vulcanizes at room temperature and possesses good self-leveling ability. It was purchased from HONG YE JIE in China (Shenzhen Hong Ye Jie Technology Co., no date).

2.2. Mechanical Test.

Regarding the mechanical characteristics of unmodified epoxy(neat epoxy), PU/epoxy and LSR/epoxy blends, respectively. The tensile test was carried out following the ASTM D-638-03(Annual Book of ASTM Standard, 2003) standard test method and using a microcomputer-controlled electronic universal testing machine model (WDW-5E) made in China with a 5 N load cell.

The impact test was carried out according to ISO 179 (Annual Book of ISO Standard, 1997). The Gant (HAMBURG) company developed the Charpy test, and the Model WP 400 was used in this test. Charpy impact strength of unnotched test samples, a_{cu}, in kilojoules per square meter could be calculated as Eq. 1 shows:

$$a_{\mathrm{cU}} = \frac{W_{\mathrm{B}}}{bh} \times 10^3 \qquad (1)$$

Where

h is the thickness, in millimeters, of the test specimen

b is the width, in millimeters, of the specimen

W_B is the energy at the break, in joules.

After completing the preparation process of fracture toughness (SENB type) samples, An incision was made in the center of the original slit of the sample called a "sharp crack introduced by the razor. Where, it was placed the sample using a certain weight and a force called a force of the hand, as shown in picture 1. This method is used in many studies to create an incision that is a stress center with a length of 2 mm.

Fracture toughness for each sample was measured using a single edge-notched three-point bending test. The WDW/5E universal testing machine, operating at 5 KN, was utilized. The tests were conducted in accordance with ASTM D5045 (Annual Book of ASTM Standard, 2014), with a crosshead speed of 10 mm/minute. The samples were rectangular bars, measuring 53 mm by 9 mm by 8 mm in size, with V-shaped notches approximately 4 mm from the center. The crack tip was initiated using a brand new razor blade.

Picture 1. Method of creating incision for SENB fracture toughness samples

The accuracy of the results was ensured by taking at least three measurements with a support span of 40 mm. To calculate the K_{IC}, we used equation (2):

$$K_{IC} = \frac{P_{max}}{BW^{1/2}} \cdot f\left(\frac{a}{W}\right) \tag{2}$$

$$f\left(\frac{a}{w}\right) = \frac{\left(2+\frac{a}{w}\right)\left\{0.886+4.64\left(\frac{a}{w}\right)-13.32\left(\frac{a}{w}\right)^2+14.72\left(\frac{a}{w}\right)^3-5.6\left(\frac{a}{w}\right)^4\right\}}{\left(1-\frac{a}{w}\right)^{3/2}} \tag{3}$$

The maximum load at failure, P_{max}, is expressed in kilo newtons, B is the thickness of the specimen in millimeters, W is the width of the specimen in millimeters,(a) is the crack length in millimeters, and f(a/W) is the expression for the ratio of the crack length to the width of the specimen (given in ASTM D5045) (Annual Book of ASTM Standard, 2014) This takes into account the sample's shape.

2.3. Samples preparations

Table 1 illustrates the preparation procedure of an unmodified epoxy blend (consisting of epoxy resin and hardener). The hardener was mixed with epoxy at a ratio of 2:1 for 10 minutes using a mechanical stirrer with a speed of 500 rpm. Mechanical stirring is a common method for mixing various materials, but whether it’s the best method depends on the specific application and the properties of the materials being mixed. Mechanical stirring ensures thorough mixing by creating turbulence and distributing components evenly. Additionally, when using the correct stirrer and settings, mechanical stirring provides consistent results. After that, the mixture was put in the degassing system under vacuum at room temperature for 10-15 minutes to eliminate bubbles. Finally, the mixture was poured into a mold made of silicon, which had been previously prepared, and left to cure for 24 hours at room temperature. This process resulted in obtaining unmodified epoxy samples for different tests, as shown in Fig. 1.

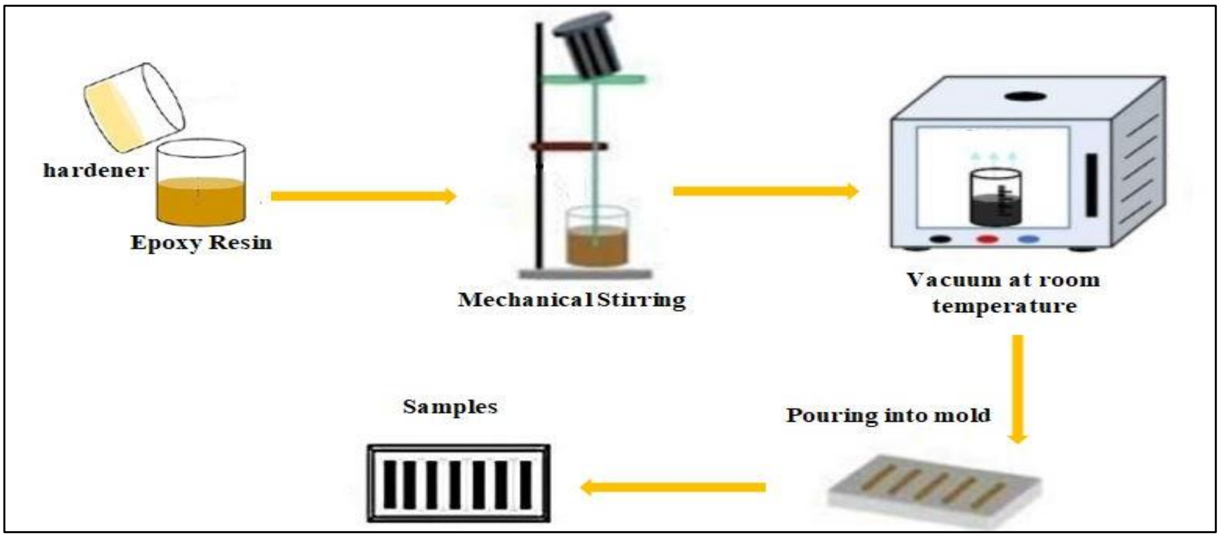

Fig. 1 The preparation procedure of unmodified epoxy samples

In order to prepare modified epoxy systems using two types of toughening agents (PU base and LSR), a certain amount of each toughening agent was added to epoxy resin at different weight ratios (3%, 6%, 9%, and 12%). The toughening agents were incorporated into the epoxy using a mechanical stirrer for 10–30 minutes. Subsequently, the hardener (at a 2:1 ratio) was added and mixed for an additional 10 minutes using the same mechanical stirrer at a speed of 500 rpm. The resulting mixture was then placed in a degassing system under vacuum at room temperature for 10–15 minutes to remove any bubbles. After degassing, the mixture was poured into silicon molds and left to cure for 24 hours at room temperature. This process yielded different samples of modified epoxy polymer blends. These steps were repeated for each case involving the two types of toughening agents. Fig. 2 illustrates the procedure used to prepare the modifier epoxy polymer blend samples.

Table 1. Sample composition of toughening agent /epoxy blends prepared in this study

Sample number	Matrix Polymer blends	Toughening agent	Samples Composition
1	Unmodified epoxy (neat epoxy)	No toughening agent	EP
2	Modified epoxy	(Quick mast 120) PU base	3% PU/EP
3	=	=	6% PU/EP
4	=	=	9% PU/EP
5	=	=	12% PU/EP
6	=	Liquid silicon rubber	3% LSR/EP
7	=	=	6% LSR/EP
8	=	=	9% LSR/EP
9	=	=	12% LSR/EP

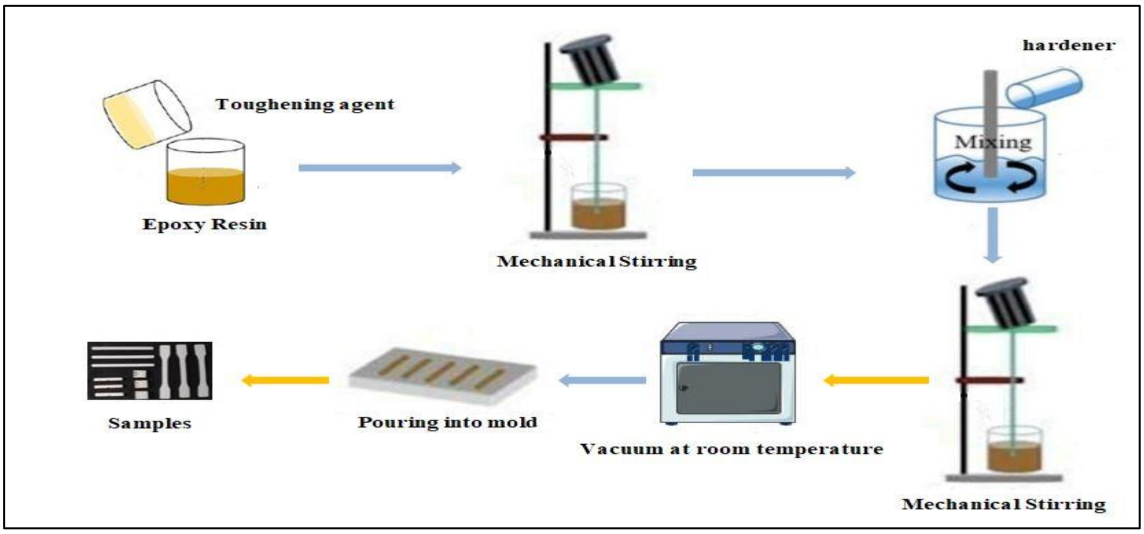

Fig. 2. The procedure used for preparing modified epoxy blends

3. RESULTS AND DESCUSSION

3.1. Results of the Tensile Test Results

Fig. 3 illustrates the tensile properties of unmodified epoxy and two toughening agents/epoxy blends. The goal was to study the effect of adding PU polyol on the mechanical properties of the epoxy. Specifically, the tensile strength, elastic modulus, and elongation were investigated. In Fig. 3(a, b, and c), we observe the tensile properties of epoxy blended with different PU polyol contents. As PU polyol is added, both tensile strength and elastic modulus decrease significantly. This reduction in tensile strength suggests that the crosslink densities of the epoxy/PU polyol blend samples may be low, leading to a decrease in elastic modulus. For instance, when the addition amount reaches 12 wt %, the tensile strength and modulus decrease by approximately 29.4% and 39.2%, respectively (as shown in Table 2). The elastic modulus reflects the material's ability to resist deformation. In comparison to rigid chain epoxy resins, flexible polyether chains are more easily deformed under external forces. Consequently, PU polyol reduces the elastic modulus of the material, aligning with findings from previous studies (Zhang, Kun, Huang, Jinrui, Wang and Li, Wenbin, Nie, 2023),(Wu, Tao, Guo and Hu, Jin-Ming, Li, Yuan-Qing, Fu, Yu-Tong, Fu, 2022). In contrast, the elongation of the blended system increases significantly with an increase in PU polyol content. This phenomenon is attributed to PU polyol, which acts as a plasticizer. By adding PU polyol as a toughening agent between the epoxy chains, some of the interactions between the polymer segments are disrupted. As a result, the segments become more flexible, allowing the polymer matrix to withstand large deformations before breaking. Consequently, the elongation of the tested samples improves.

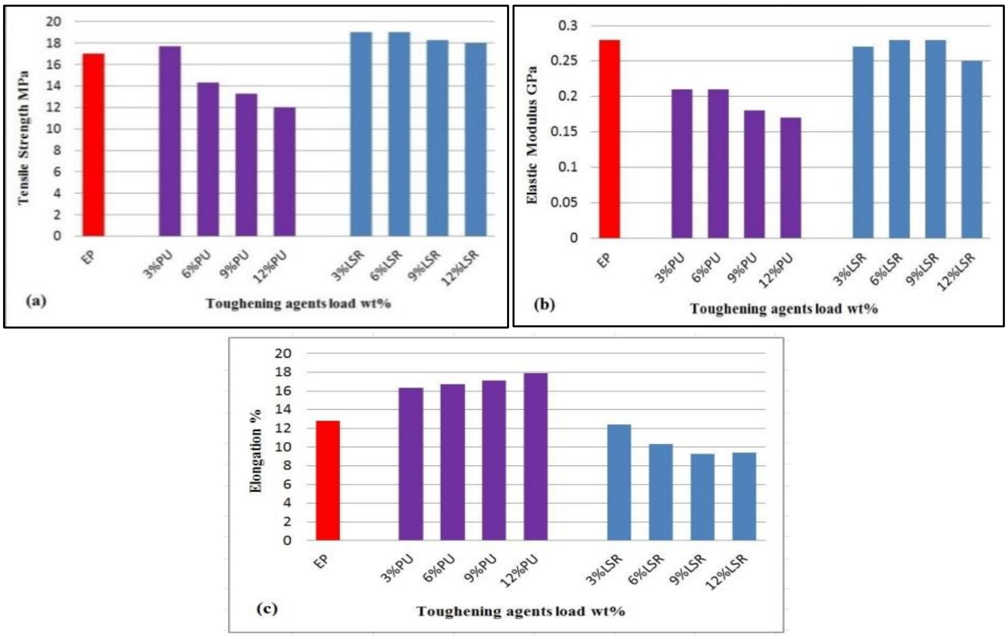

Fig. 3. Tensile properties (a) tensile strength (b) elastic modulus (c) elongation of PU/epoxy and LSR/epoxy blends, respectively.

Fig. 3(a) shows that the tensile strength of LSR/EP blends is either slightly enhanced or kept constant within the experimental concentration range. This behavior is attributed to the plasticizer, which is less rigid than epoxy cross-linked chains. As a result, it allows them to stretch under stress, demonstrating plastic behavior prior to failure. This action not only increases the ductility of the material but can also enhance the strength for optimal loading, similar to findings by (Okoro, Chinedu, Mohammed, Zaheeruddin, Jeelani and Rangari, 2021). The epoxy matrix has a cross-link structure, which makes it inherently brittle. The molecular chains between the crosslink sites in the matrix are too short to conform, preventing the sample from withstanding a sufficient amount of tensile force. Conformity is necessary to reduce stress concentration and facilitate stress transfer. When liquid rubber is incorporated into the epoxy (EP) matrix, an incomplete structure network forms, thereby reducing the crosslinking density of cured EP networks. As a result, the material exhibits lower rigidity or modulus. This aligns with findings from (Zhou, Wenying, Li, Xu, Cao, Dan, Li, Zhang and Li, Zhen , Chen, 2020) to improved ductility in the system (Sepetcioglu, 2021). By changing its conformation in response to tensile stress, the molecular chain in the cured blends was able to reduce the susceptibility of the matrix to defects(Wu, Tao, Guo and Hu, Jin-Ming, Li, Yuan-Qing, Fu, Yu-Tong, Fu, 2022), resulting in the blends having a comparatively high tensile strength Increases in LSR content in the epoxy matrix at high rubber content creates a plasticized matrix and reduce in tensile strength resulting value_ greater than that of neat EP. Both the tensile strength and the toughness of an epoxy resin are increased by mixing with liquid rubber. For given stress, a larger value of Young's modulus corresponds to a fewer elastic strain (Farhan and Jaffer, 2020) See Fig. 3 (b). The tensile modulus of the LSR/EP blend decreases with increasing silicone rubber content. This is because blends have more flexible polymer chains than pure (EP), which contributes to this reduction. This is because blends have more flexible polymer chains than pure (EP), which contributes to this reduction.

This implies a rise in strain rate and a decrease in stiffness (rigidity). As a result, these blends become capable of achieving formerly unrealized potential uses, similar to the findings by (Farhan and Jaffer, 2020). The tensile modulus of a polymer is strongly correlated with its molecular chain structure and crosslink density. These factors are determined by chemical crosslink points (covalent bonds) and physical crosslink points (hydrogen bonds and molecular chain entanglement points) within the polymer’s elastic deformation range. When the silicone rubber content in a blend increases, the tensile modulus decreases due to a reduction in the blend’s content of rigid segment structure and crosslink density. In other systems, similar results have been observed (Zhao, Song and Liang, Chang Sheng., Wang, Juan., Xu., 2015). As for the elongation for the LSR-modified blends, the same pattern as in Fig. 3 (c) is also found. When the loading content of the LSR goes from loading (3 wt%) to loading (12% wt), the size of the spherical regions is large and becomes a point defect, resulting in a reduction in the elongation of LSR/EP blends. This is agreed with the previous study of Carolan and et al (Carolan, Ivankovic and Kinloch, A. J., Sprenger, S., Taylor, 2016).

Table 2. Mechanical properties of blends prepared from toughening agents/epoxy.

Blends	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Fracture toughness (MPa.m$^{0.5}$)	Impact strength (kJm^{-2})
Unmodified epoxy	17	0.28	12.8	1.2	5.3
PU/EP					
+ 3wt% PU	17.7	0.21	16.3	3	9.1
+ 6wt% PU	14.3	0.21	16.7	2.2	9
+ 9wt% PU	13.3	0.18	17.1	2.3	9.5
+ 12wt% PU	12	0.17	17.9	2.2	5.4
LSR/EP					
+ 3wt% LSR	19	0.27	12.4	2.9	10.9
+ 6wt% LSR	19	0.28	10.3	3.7	12.9
+ 9wt% LSR	18.3	0.28	9.3	3.5	9.1
+ 12wt% LSR	18	0.25	9.4	2.7	7.9

3.2. Fracture Toughness and Impact strength Tests results

The fracture toughness values of PU polyol/epoxy and LSR/epoxy blends are shown in Fig.4. The results indicate that the KIC (critical stress intensity factor) values of epoxy resins blended with PU polyol and LSR are significantly improved compared to neat epoxy. Interestingly, for epoxy resins blended with LSR, the improvement is even higher than with PU polyol. Specifically, a maximum increase in the KIC (around 208%) is observed for epoxy samples with an LSR content of 6% wt. compared to neat epoxy. The incorporation of flexible modifier chains from PU polyol likely contributes to an increase in free volume, which, in turn, enhances the KIC value for epoxy resin. Essentially, the liquid modifier acts as a plasticizer for the polymer matrix, requiring more energy for breaking, as previously suggested by (Kostrzewa, Bakar and Białkowska, A., Szymańska, J., Kucharczyk, 2019) Furthermore, plasticizers prevent polymer molecules from interacting with one another. Epoxy's self-crosslinking density was therefore lowered by the addition of a plasticizer (Islam, Rahman and Hosur, Mahesh, Jeelani, 2015). Spherical zones made of rubber that, when subjected to an external force, have the action of stress concentrators. Because of this, rubber cavitation will begin to develop, and the matrix that surrounds the rubber zones will begin to undergo plastic deformation. Cavitation of the LSR spherical zone may absorb energy, which leads to an increase in the fracture energy that is required to fracture, which, in turn, leads to an increase in fracture toughness by reducing the local yield stress and inducing significant shear yield (Yi, Wei and Lin, Heng, Zhou, 2018). The cavitation of rubber-rich zones has been attributed to being the main driving force behind shear yielding to be activated in the matrix by (Gunwant, Sah and Zaidi, 2018).

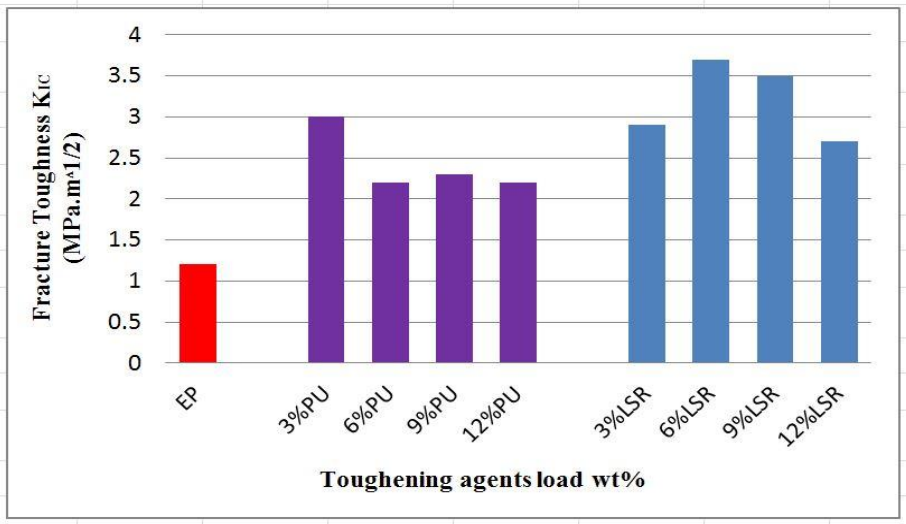

Fig. 4. Fracture toughness strength of PU/epoxy and LSR/epoxy blends, respectively.

Fig. 5 displays the impact strength of PU polyol/epoxy and LSR/epoxy blends for the entire load content range. Incorporating polyether polyol into a neat epoxy resin batch increases the epoxy's resistance to impact. Because PU (polyol) molecules are included between polymer chains, polymer segment-polymer segment interactions are broken, resulting in higher polymer segment flexibilities and allowing the epoxy matrix to withstand significant deformations before cracking. Some of the increased impact strength of epoxy with PU polyol (plasticizer) may be due to the modified samples' high shear yielding and high ductility (Białkowska, Anita, Bakar and Kucharczyk, Wojciech, Zarzyka, 2023). Fig. 5 shows that the impact strength of 6 wt% LSR-modified epoxy resin is 143% higher than that of neat epoxy (unmodified epoxy), demonstrating that silicone rubber serves as a good buffer and dispersion against the instantaneous impact and that LSR enhances the fracture toughness and impact performance of epoxy similar to (Yang, Jiayao, He, Xingwei, Wang, Hengxu, Liu, Lin, Peng, Yang and Fu, 2020). Additions of RTV silicone rubber improve the impact strength and energy, leading to the production of a second phase that hinders cracking and slows the growth of existing fractures. As agreed with (Pakaya, Ardhyananta and Wicaksono, 2017b), rubber, in general, is a material with high impact strength due to its flexibility.

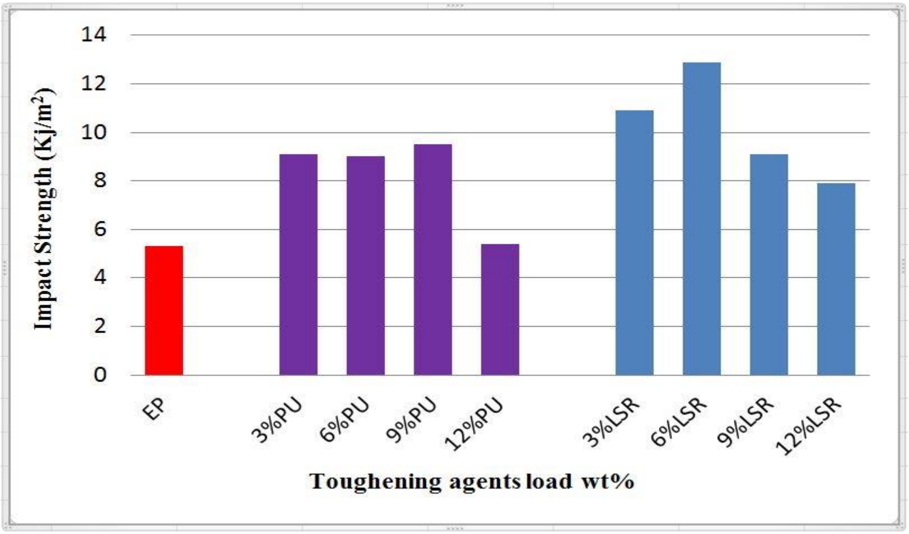

Fig. 5. Impact strength of PU/epoxy and LSR/epoxy blends, respectively

4. CONCLUSIONS

A modified, tougher version of epoxy resin has been successfully developed, with the liquid silicone rubber (LSR)-modified epoxy showing the most significant improvement in terms of impact resistance, overall strength (tensile strength), and resistance to cracking (fracture toughness). The most substantial increase in toughness for the LSR-modified epoxy occurred when 6% by weight of LSR was added, resulting in a KIC value of 3.7 MPa·m$^{0.5}$. This improvement is likely due to the rubber's ability to absorb energy and distribute stress within the epoxy when it is under load. However, beyond this optimal rubber percentage, mechanical characteristics steadily decrease due to the agglomeration of rubber segment chains, which act as interface defects and cause mechanical failures

The Polyether polyol (PU)-modified epoxy shows that at a 3% weight ratio, it can significantly increase the fracture toughness by up to 150%. However, there's a trade-off. Higher concentrations (specifically, 12% by weight) of polyether polyol can actually decrease the overall strength and stiffness (modulus) of the epoxy by around 29% and 39%, respectively. Compared to rigid chain epoxy resin, flexible polyether chains are more easily deformed under the influence of external forces. Therefore, PU polyol reduces the elastic modulus of the material. In simpler terms, a small amount of polyether polyol can make the epoxy tougher but less rigid.

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