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MECHANICAL AND MICROSTRUCTURAL ANALYSIS OF MICRO-SIZED EXPANDED PERLITE AND ALUMINUM HYDROXIDE REINFORCED EPOXY COMPOSITES

MİKRO BOYUTLU GENLEŞTİRİLMİŞ PERLİT VE ALÜMİNYUM HİDROKSİT TAKVİYELİ EPOKSİ KOMPOZİTLERİN MEKANİK VE MİKROYAPISAL ANALİZİ

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ABSTRACT

This study investigates the mechanical properties and microstructure of epoxy composites reinforced with micro-sized expanded perlite and aluminum hydroxide fillers. Tensile and compressive tests were conducted according to ASTM standards to evaluate the effects of filler content on performance. The pure epoxy sample exhibited a tensile strength of 5.04 MPa. Mineral-based fillers improved mechanical behavior. The tensile strength increased to 6.39 MPa in the hybrid composite containing 5 wt.% expanded perlite and 5 wt.% aluminum hydroxide, while the highest tensile strength of 6.93 MPa was achieved in the composite containing 10 wt.% expanded perlite and 10 wt.% aluminum hydroxide. Similar improvements were observed in compressive properties. The compressive strength of pure epoxy, measured as 63.82 MPa, increased to 84.21 MPa in the hybrid composite containing 5 wt.% expanded perlite and 5 wt.% aluminum hydroxide. The maximum compressive strength, 85.62 MPa, was obtained in the composite reinforced with 10 wt.% aluminum hydroxide. SEM analyses confirmed filler distribution within the epoxy matrix and confirmed interfacial bonding quality. However, particle agglomeration was observed at higher filler contents and may adversely affect mechanical performance. Overall, it was understood that filler ratio and homogeneous distribution are important parameters in improving composite performance.

Keywords: Expanded perlite, aluminum hydroxide, epoxy polymer composite, tensile test, scanning electron microscopy analysis

ÖZET

Bu çalışma, mikro boyutlu genleştirilmiş perlit ve alüminyum hidroksit dolgu maddeleriyle güçlendirilmiş epoksi kompozitlerin mekanik özelliklerini ve mikro yapısını araştırmaktadır. Dolgu maddesi içeriğinin performansa etkilerini değerlendirmek için ASTM standartlarına göre çekme ve basma testleri yapılmıştır. Saf epoksi numunesi 5,04 MPa çekme dayanımı sergilemiştir. Mineral bazlı dolgu maddeleri mekanik davranışı iyileştirmiştir. %5 ağırlık oranında genleştirilmiş perlit ve %5 ağırlık oranında alüminyum hidroksit içeren hibrit kompozitte çekme dayanımı 6,39 MPa'ya yükselirken, %10 ağırlık oranında genleştirilmiş perlit ve %10 ağırlık oranında alüminyum hidroksit içeren kompozitte en yüksek çekme dayanımı olan 6,93 MPa elde edilmiştir. Basma dayanımı özelliklerinde de benzer iyileşmeler gözlemlenmiştir. Saf epoksinin 63,82 MPa olarak ölçülen basma dayanımı, %5 ağırlık oranında genleştirilmiş perlit ve %5 ağırlık oranında alüminyum hidroksit içeren hibrit kompozitte 84,21 MPa'ya yükselmiştir. Maksimum basma dayanımı, %10 ağırlık oranında alüminyum hidroksit ile güçlendirilmiş kompozitte 85,62 MPa olarak elde edilmiştir. SEM analizleri, dolgu maddesinin epoksi matris içindeki dağılımını ve arayüzey bağlama kalitesini doğrulamıştır. Bununla birlikte, daha yüksek dolgu maddesi içeriklerinde partikül kümelenmesi



gözlemlenmiş ve bu durumun mekanik performansı olumsuz etkilediği görülmüştür. Genel olarak, dolgu maddesi oranı ve homojen dağılımın kompozit performansını iyileştirmede önemli parametreler olduğu anlaşılmıştır.

Anahtar Kelimeler: Genleştirilmiş perlit, alüminyum hidroksit, epoksi polimer kompozit, çekme testi, taramalı elektron mikroskobu analizi

INTRODUCTION

The swift progress of technology has escalated competition within industries, creating considerable demand in materials science. Because of their natural constraints, including poor thermo-mechanical characteristics, polymers have been the subject of thorough research efforts to address these issues (Wu et al., 2023; Islam et al., 2024). Epoxy resins (EPs), a class of thermosetting polymers, are among the most widely used materials in high-performance polymer composites. EPs are recognized for their excellent properties, such as ease of processing, low cost, outstanding electrical insulation, strong adhesion, low shrinkage, and superior chemical resistance. These features benefit EPs in a variety of industries such as automotive, packaging, textiles, and biomedical devices (Hao et al., 2025; Parvizi et al., 2025; Ramon et al., 2018; Wang et al., 2014).

Incorporating different reinforcing materials into the epoxy matrix can improve the mechanical properties of epoxy-based composites. Studies show that incorporating metallic, ceramic, biomaterial, and volcanic particle fillers can significantly improve the mechanical properties of epoxy composites by promoting stronger interface bonding between the filler and the matrix (Matykiewicz et al., 2021; Macquart et al., 2018; Daramola & Akintayo, 2017). The composites showed a notable improvement in their mechanical properties when the particle size of the reinforcing components decreased (Akaluzia et al., 2021).

Perlite, a naturally occurring filler, forms as amorphous volcanic glass. It is formed by the rapid cooling of lava or magma, resulting in a material with a relatively high-water content compared to other volcanic glasses (Angelopoulos, 2024; Angelopoulos et al., 2016). When heated to temperatures between 850 and 900°C, perlite expands, increasing its volume by up to 20 times and forming expanded perlite (EP) (Sarı et al., 2009; Topçu & Işıkdag, 2007). This unique method produces a lightweight and porous material, making EP an attractive filler option. EP is primarily composed of silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and various metal oxides, which enhance its chemical stability, low thermal conductivity, and high strength (Zujovic et al., 2018). The qualities of these materials have made EP a reliable option in construction, agriculture, and environmental fields, as well as in the production of flame-retardant, acoustic, and filtration products, guaranteeing its wide range of applications and reliability (Qu et al., 2025; Güler et al., 2021).

Despite its advantageous properties, the use of perlite as a reinforcement in polymer composites has not yet been extensively studied. In most research, perlite has been used in powder form rather than in its hollow spherical shape. For example, Atagür et al. (2018) and Sahraeian et al. (2013, 2012) investigated the addition of ground perlite to low-density polyethylene (LDPE) and high-density polyethylene (HDPE) composites, respectively. They observed increases in modulus, tensile strength, and flexural strength in LDPE/Perlite and HDPE/Perlite composites, but also a decrease in impact strength. These results indicate that perlite reinforcement can increase the stiffness and strength of the matrix, but may negatively affect the impact resistance of the material. Similarly, Sahraeian et al. (2019) discovered that adding perlite filler to polypropylene (PP) matrices increased tensile strength and elastic modulus. However, this also led to a decrease in resistance to impacts (Sahraeian et al., 2020).

In addition, Alsaadi and Erklığ (2018) investigated the addition of micro-perlite to epoxy/glass fiber composites and reported improvements in fracture toughness, tensile and flexural strength, and modulus of flexure. Their study showed that increasing the micro-perlite content improved these mechanical properties up to a certain percentage of the filler, after which the weak interface bond between the filler and the matrix led to a decrease in strength. This approach indicates the need to optimize the filler content to achieve a balance of mechanical performance.

Polystyrene (PS) is a thermoplastic polymer that is used in a wide range of important applications throughout industry, such as electronics, food packaging, household goods, medical products, and insulation materials. Although there is no specific research on the incorporation of EP as a filler in PS composites, de Oliveira et al. (2019) showed that adding 10% and 20% EP to the PS matrix increased the thermal stability and hardness of the composite but led to a significant decrease in impact resistance. These results indicate that PS/Perlite composites can be effective lightweight packaging materials that improve thermal insulation properties.

Besides EP, aluminum hydroxide ($\text{Al}(\text{OH})_3$) is also widely used as a flame-retardant filler in polymer composites. $\text{Al}(\text{OH})_3$ has a flame-retardant effect by releasing water vapor from its structure at temperatures above approximately 220°C . Due to its non-toxicity, low cost, and environmental friendliness, it is preferred and used in many different areas such as rubber, foam, and cable insulation. In the study by Zielonka et al. (2022), it was stated that the addition of 30% $\text{Al}(\text{OH})_3$ to epoxy composites significantly increased flame resistance, but caused a slight decrease in tensile strength. This shows that $\text{Al}(\text{OH})_3$ reinforced composites may have some limitations in applications carrying high mechanical loads, but may provide advantages in applications where fire resistance is important (Lei et al., 2024; Liu et al., 2022; Petersen et al., 2015).

However, the effect of $\text{Al}(\text{OH})_3$ on mechanical properties in epoxy composites may vary depending on various parameters such as filler ratio, particle distribution, and interaction between the filler and polymer matrix. While some studies report that high filling rates reduce mechanical strength, it is stated that low and medium $\text{Al}(\text{OH})_3$ contributions can contribute positively to mechanical behavior if the particles are more homogeneously distributed within the epoxy structure.

As mentioned, Santhosh et al. (2020) reported that the addition of $\text{Al}(\text{OH})_3$ to E-glass/phenolic resin composites significantly increased fire resistance, while 15% $\text{Al}(\text{OH})_3$ content provided better flame-retardant properties, although it caused a slight decrease in tensile strength. Azhary et al. (2022) stated that the thermal stability of epoxy composites increased significantly with the addition of 25% $\text{Al}(\text{OH})_3$. However, mechanical properties such as tensile and flexural strength decreased at higher filler loadings. These studies highlight that $\text{Al}(\text{OH})_3$ can be used as an effective flame retardant in epoxy composites and emphasize the importance of optimizing filler content to strike a balance between mechanical strength and fire resistance (Shaker et al., 2023; Iqbal et al., 2018).

This study aims to investigate the mechanical and microstructural properties of micro-sized EP and $\text{Al}(\text{OH})_3$ reinforced epoxy composites. By examining the effects of these fillers at different concentrations on the epoxy matrix, the study aims to evaluate their contribution to the tensile and compressive strengths of the composites and to investigate the synergistic effects of the reinforcement materials. Furthermore, the effect of filler distribution and the interfacial bond between the matrix and fillers on mechanical performance is also analyzed.

EXPERIMENTAL WORK

Materials

In this study, an EPs system commercially known as Resinin Norm Medium and its curing agent (Component B), supplied by Marker Chemical Industry Ltd. Co. in Türkiye, were used. The epoxy system is based on Bisphenol A (BPA) and does not contain solvent. According to the manufacturer's technical specifications, the density of the mixed A+B system is approximately 1.120 kg/m^3 . The hardener used in the study is amine-based, and all composite specimens were prepared using a 2:1 (A:B) resin-to-hardener ratio. The viscosity of the resin ranges from 600 to 900 mPa·s, while the viscosity of the curing agent is about 50 to 100 mPa·s at 25°C . The gelation time for the epoxy-hardener system is approximately 20 minutes at 23°C for a 100 g mixture, and the entire curing time is 7 days. The EP and $\text{Al}(\text{OH})_3$ particles were procured from Egenanotek. Prior to their incorporation, the particles were ground and sieved using a $106\text{-}\mu\text{m}$ mesh to ensure uniform particle size distribution. According to manufacturer specifications, the chemical purity of $\text{Al}(\text{OH})_3$ powder is higher than 99%. EP mainly consists of amorphous aluminosilicate, and its typical oxide composition is approximately SiO_2 (72-75%), Al_2O_3 (12-15%), K_2O (3-5%), Na_2O (2-3%), and $\text{CaO}+\text{MgO}$ (<2%). These fillers are incorporated into the epoxy system to improve the mechanical properties of composites.

Specimen Preparation

As shown in Figure 1, the specimens to be used in tensile and compression tests were produced according to a specific systematic approach to ensure consistent and reliable mechanical evaluations. All experiments were performed in triplicate, and the results obtained are given as the average values of the measurements. The samples for the tensile test were prepared in accordance with the ASTM D638 standard (Type 4), with a total length of 115 mm, a width of 6 mm in narrow section, and a thickness of 3.6 mm. The measurement length was selected as 33 mm, and a radius of 14 mm was considered at the transition from the gripping area to the narrow section. For compression tests, cylindrical specimens with a height of 25.4 mm and a diameter of 12.7 mm were prepared according to the ASTM D695 standard. A total of seven different composite formulations were prepared for this study, and each specimen was assigned a unique code to prevent confusion and ensure traceability. The pure epoxy specimen was named T1.

The composite containing 5% $\text{Al}(\text{OH})_3$ by weight was coded T2, and the composite containing 5% perlite by weight was coded T3. For compression testing, cylindrical specimens with a height of 25.4 mm and a diameter of 12.7 mm were prepared according to ASTM D695. Seven different composite formulations were developed in this study. To prevent confusion and ensure traceability, each specimen was assigned a unique code. The pure epoxy specimen was named T1. The composite containing 5% $\text{Al}(\text{OH})_3$ by weight was coded T2, and the composite containing 5% perlite by weight was coded T3. The double-filled (hybrid) composite containing 5% EP and 5% $\text{Al}(\text{OH})_3$ by weight was defined as T4. Additionally, composites containing 10 wt% $\text{Al}(\text{OH})_3$ and 10% EP were coded as T5 and T6, respectively. Finally, the hybrid composite containing 10 wt% EP and 10 wt% $\text{Al}(\text{OH})_3$ was designated as T7. These codes were used consistently in all mechanical and microstructural analyzes performed in this study.

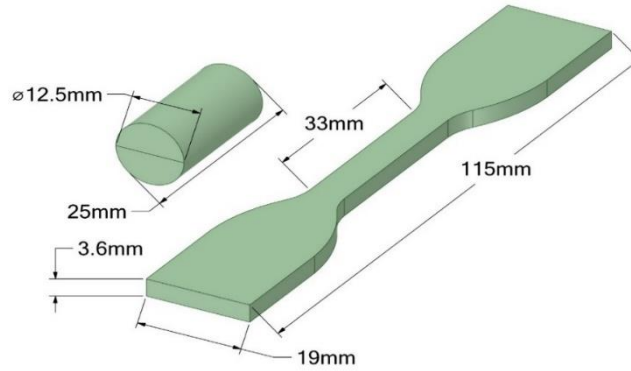


Figure 1. Dimensions of Tensile and Compression Test Specimens.

As shown in Figure 2, the epoxy sample preparation process consists of multiple stages. First, EP was manually mixed for 5 min using a mixer. Then, mixing was applied for another 5 minutes using a magnetic stirrer to ensure complete homogeneity. Following this step, reinforcement particles were added to the epoxy and the mixture was mixed again with a magnetic stirrer for 15 minutes to ensure homogeneous distribution of the particles within the structure. In the next step, the mixture was treated with a 30 W ultrasonic homogenizer for 30 min to improve particle dispersion and remove air bubbles. To ensure temperature control during this process, the mixture was kept in an ice bath for 30 minutes. Then, the samples were kept in a vacuum oven for 15 minutes under 1 bar vacuum to remove air bubbles in the mixture. Finally, the mixture was placed in the vacuum oven again for 30 min under 1 bar vacuum to completely remove any remaining air voids. In the final stage, the prepared epoxy mixture was carefully poured by hand into silicone molds to obtain the samples. In the final stage, the epoxy samples poured into the molds were cured in an oven at 70 °C for 2 hours. The curing process ensures complete hardening of the epoxy and makes the samples ready for mechanical testing. This step is important for achieving homogeneous curing of the material and obtaining the desired mechanical properties like strength and durability. Figure 3 shows the casting of tensile and compression specimens in Room Temperature Vulcanized (RTV) silicone molds and the final removal of the tensile specimens from the molds. This step is very important because it guarantees the homogeneous curing of the material and the achievement of the desired mechanical properties, such as strength and durability.

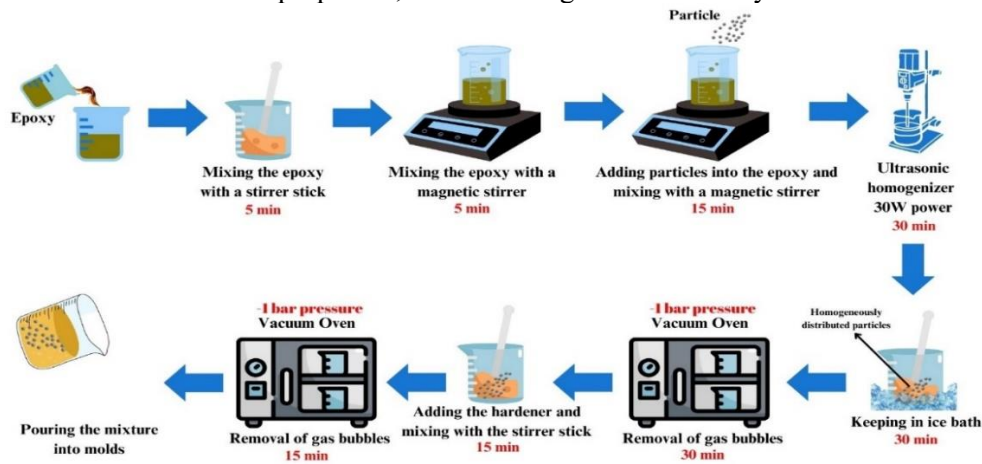


Figure 2. Schematic Representation of The Epoxy Specimen Preparation Process.

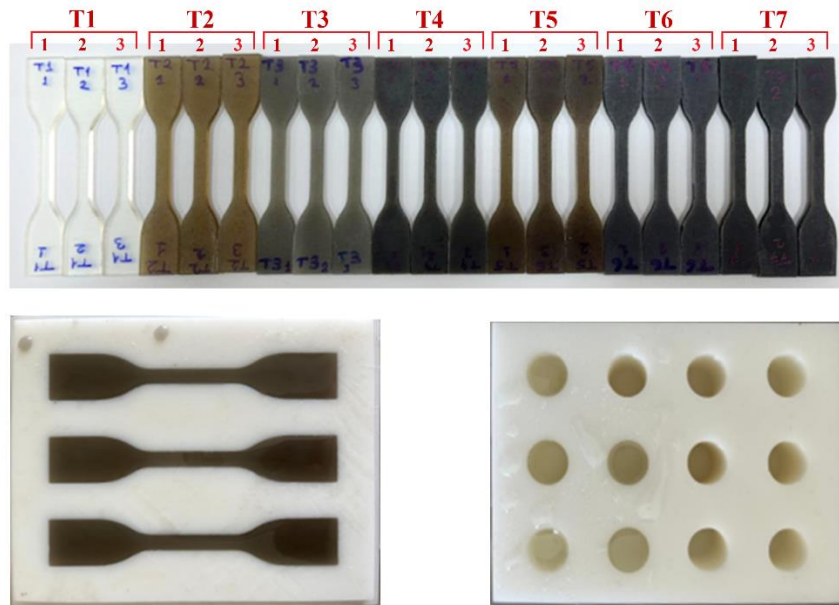


Figure 3. Casting of Tensile and Compression Specimens in RTV Silicone Molds, and The Demolded Form of The Tensile Specimens.

The ultrasonic mixing and vacuum degassing processes resulted in a better homogeneous dispersion of the reinforcement particles within the epoxy matrix. This minimized the formation of air bubbles during the sample preparation. To obtain reliable data, the tensile and compression properties of epoxy composites were measured by different number of samples and preparation methods.

Test Procedure

ZwickRoell universal testing machine was used to conduct tensile tests in accordance with ASTM D638 criteria. Before the tensile testing, 0.1 MPa of preload was given. The test speed and elastic modulus measurement rate were set at 5 mm/min, and the initial grip distance was set at 60 mm. Under ASTM D695 standard, compression testing was conducted using the same testing machine with a crosshead speed of 5 mm/min. Parameters, including deformation, maximum force (Fmax), and fracture force (FBreak) were constantly measured during the testing. The collected information was utilized to assess the mechanical characteristics of the samples.

Following tensile and compressive tests, Scanning Electron Microscopy (SEM) studies were carried out. These analyses were conducted using a JEOL JSM-6060 model SEM apparatus. For thorough examination, fracture surfaces were covered with a thin layer of gold; images were taken at a 15 kV acceleration voltage. The tested samples were analyzed for fracture mechanisms and microstructural properties using SEM images.

RESULTS AND DISCUSSION

Tensile Test

Table 1. Tensile Strengths of Epoxy Composites by Specimen Code

Specimen Composition	Code	Tensile Strength (MPa)
Neat Epoxy	T1	5.04
5% Aluminum Hydroxide	T2	4.95
5% Perlite	T3	5.01
5% Perlite + 5% Aluminum Hydroxide	T4	6.39
10% Aluminum Hydroxide	T5	6.22
10% Perlite	T6	6.43
10% Perlite + 10% Aluminum Hydroxide	T7	6.93

To assess how mineral filler additions affect the mechanical properties of the epoxy matrix, composite samples were made in compliance with tensile testing requirements. Table 1 provides a summary of the tensile strength values, filler ratios, and filler content of the epoxy composite samples (T1-T7) that were made. Accepted as the reference sample for comparison was Sample T1, a pure epoxy sample exhibiting a tensile strength of 5.04 MPa. Determined as 4.95 MPa, the tensile strength of sample T2 showed a somewhat decrease; sample T3 behaved somewhat similarly to the reference sample, with a value of 5.01 MPa (Figs. 4 and 5). These little variations found at low filler ratios match earlier research indicating that low doses of hard mineral fillers have no appreciable impact on the tensile behavior of the epoxy matrix. A notable improvement was seen in specimen T4, nevertheless, and its tensile strength reached 6.39 MPa (Figure 6). This outcome, which is notably higher than the T1 reference sample, confirms that the combination of several fillers might produce a synergistic amplification effect. Similar synergistic improvements have also been reported in hybrid inorganic-epoxy systems (Othman et al., 2022). Sample T5 achieved a tensile strength of 6.22 MPa, exhibiting higher performance than T1 (Figure 4). Sample T6 showed the highest tensile strength among single-fill composites, reaching 6.43 MPa (Figure 5). This trend is consistent with studies reporting that the use of certain mineral fillers in high proportions can improve interfacial load transfer and enhance the mechanical performance of epoxy composites (Norzali et al., 2011). The highest tensile strength was obtained in sample T7, reaching 6.93 MPa, surpassing all other samples (Figures 6 and 7). This result shows that the synergistic effect created by the combination of EP and $\text{Al}(\text{OH})_3$ fillers becomes more pronounced. Similar strengthening mechanisms have also been reported in epoxy composites containing multiple fillers (Kar et al., 2024).

Overall, the results obtained appear to be consistent with the general trends reported in the literature for mineral-filled epoxy systems. $\text{Al}(\text{OH})_3$, due to its hard particle structure, can cause a decrease in tensile strength at low filler ratios; however, at higher ratios or in hybrid filler combinations, it can contribute to an increase in strength as the load transfer mechanism becomes more effective. It is known that EP can lead to limited decreases in tensile strength at low ratios, but can provide significant improvements at high filler levels when the particle morphology and interfacial bonding are suitable. In particular, the behaviors observed in samples T3, T6, and T7 appear to coincide well with these general trends described in the literature.

The primary mechanical property investigated in this study was tensile strength; however, tensile modulus and elongation at fracture values were not measured. Nevertheless, it is known that hard fillers such as $\text{Al}(\text{OH})_3$ and EP can affect the stiffness and ductility behavior of epoxy systems depending on the filler distribution, interfacial bonding, and reinforcement ratio. Limited improvements in elongation at fracture behavior can also be observed in some composite formulations. Considering the significant increases in tensile strength obtained in hybrid T4 and T7 samples, it is assessed that an increase in stiffness may also occur. However, it is thought that the elongation behavior may vary depending on the distribution of filler particles, interfacial adhesion, and the hybrid reinforcement structure.

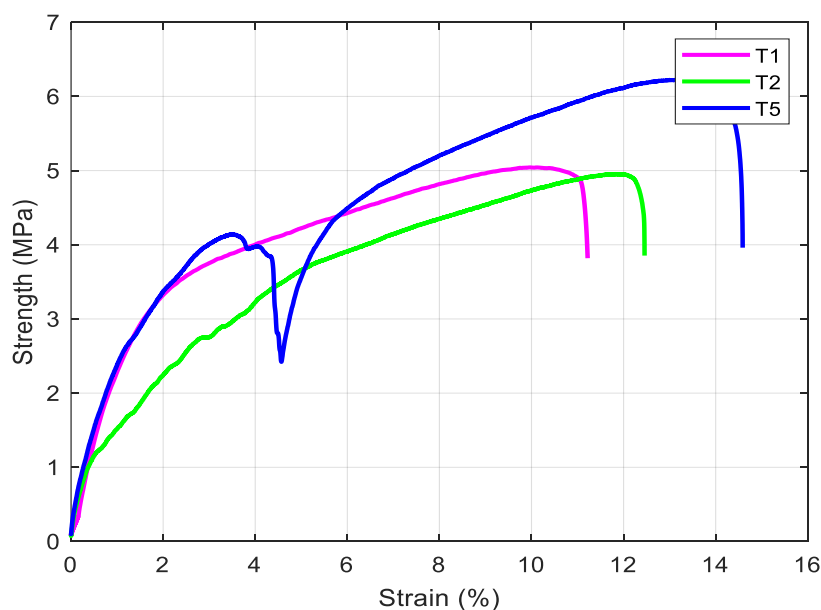


Figure 4. The Effect of Changes in $\text{Al}(\text{OH})_3$ Concentrations on the Tensile Strength of EPs.

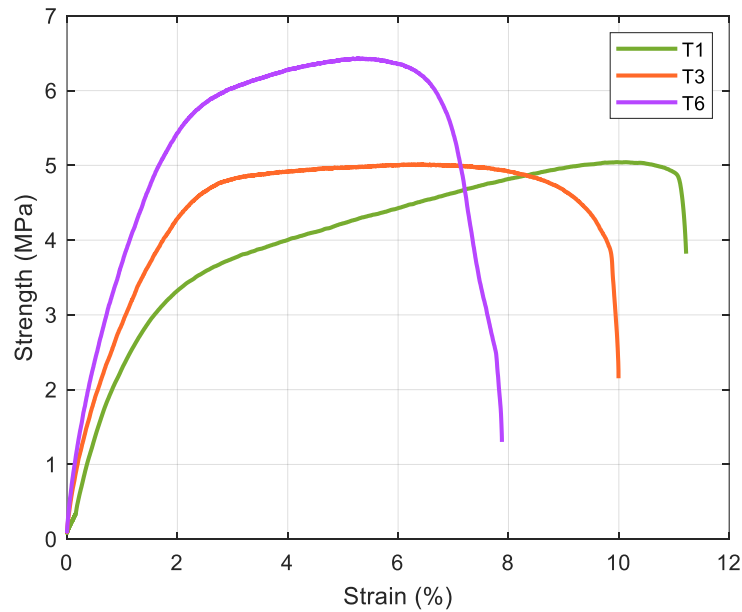


Figure 5. Effect of Different EP Concentrations on the Tensile Strength of EPs.

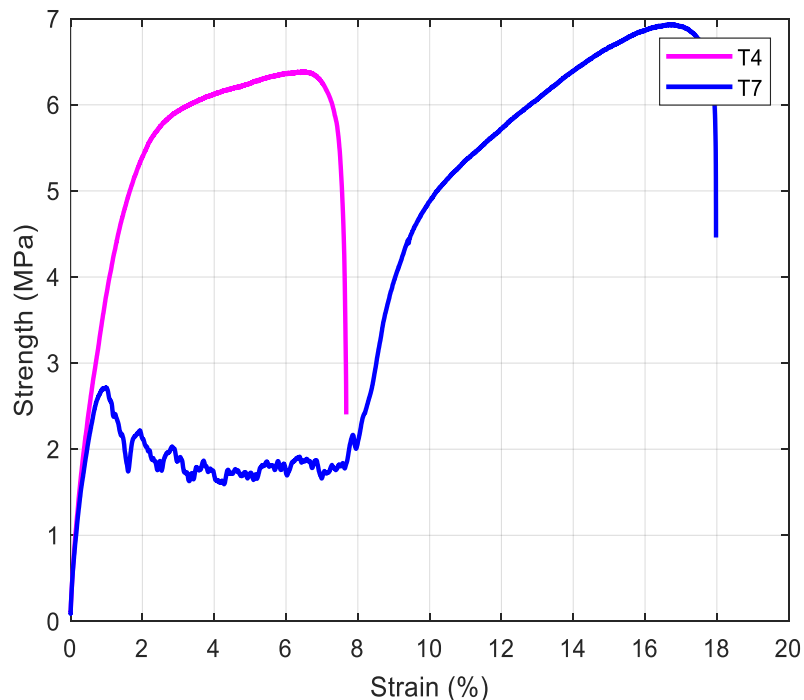


Figure 6. Effect of Combined Fillers EP and $\text{Al}(\text{OH})_3$ on the Tensile Strength of EPs.

Compression Test

Figure 8 shows the variation in compressive strength for all samples (T1-T7); the red horizontal line represents the reference value of pure epoxy (T1) with a compressive strength of 63.82 MPa. The observed trend for compressive strength differs from the tensile strength (Figure 5), which is typical for brittle thermoset matrices such as epoxy.

Sample T2 showed a compressive strength of 58.20 MPa, representing approximately an 8.8% decrease compared to sample T1. This suggests that the matrix structure may lead to the formation of micro-defects and local stress concentrations when a tiny amount of $\text{Al}(\text{OH})_3$ is added. This will partially weaken the network that carries the load. Nevertheless, sample T5 reached a compressive strength of 85.62 MPa, showing an increase of approximately 34.2% compared to sample T1. At much higher filler ratios, it is thought that $\text{Al}(\text{OH})_3$ particles contribute more effectively to load transfer, limiting matrix deformation and thus increasing compressive strength. Similar studies have also reported that high ceramic filler ratios increase compressive rigidity and resistance to crack propagation in mineral-filled epoxy systems (Sun and Wu, 2025). In the perlite-reinforced composites in this study, sample T3 reached a compressive strength of 83.04 MPa, showing an improvement of approximately 30.1% compared to T1. This result

shows that silicate-based hard EP particles positively affect the compressive performance of the epoxy matrix by limiting crack propagation. With the EP ratio further increased to its highest level in sample T6, the compressive strength was measured at 66.69 MPa, which represents only an increase of approximately 4.5% compared to sample T1. The agglomeration behavior of EP particles at high filler ratios is likely linked to this little improvement; it disturbs matrix homogeneity and somewhat lowers the reinforcing effect. Hybrid composites nevertheless showed a noteworthy synergistic effect. With a compressive strength of 84.21 MPa, Sample T4 was among the best-performing composites and showed around 31.9% increase from T1. This outcome suggests that combining $\text{Al}(\text{OH})_3$ with EP helps to balance the stress distribution within the matrix. Moreover, sample T7 had a greater value than pure epoxy; it had a compressive strength of 78.34 MPa, which is around 22.8% greater. This value, however, was less than that of samples T4 and T5. This implies that by raising particle clustering and microstructural discontinuities, too much filler content might partially lessen the synergistic effect.

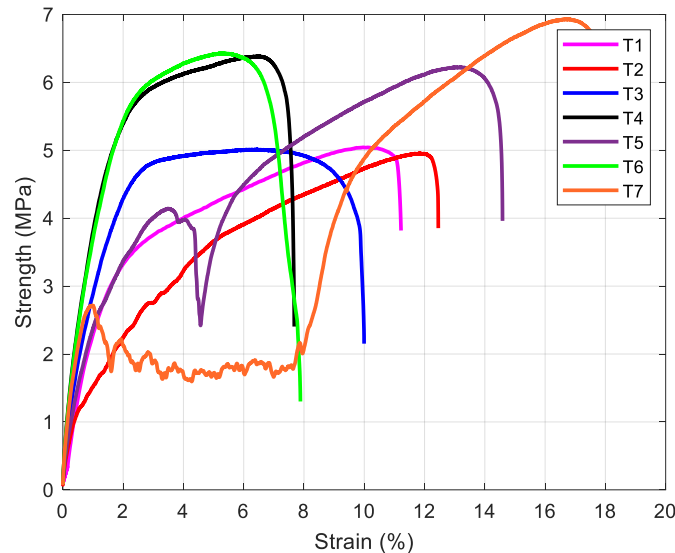


Figure 7. Comparative Representation of the Tensile Strength of All Samples, Including Combined Filler Composites (T4 and T7).

The compression test results indicate that compression test data reveal that when the right filler ratio and combination are used, mineral fillers can dramatically boost the compressive strength of epoxy composites. However, it seems that too much filler can make reinforcement less effective because it makes the structure less uniform and increases the amount of stress it can hold in certain places.

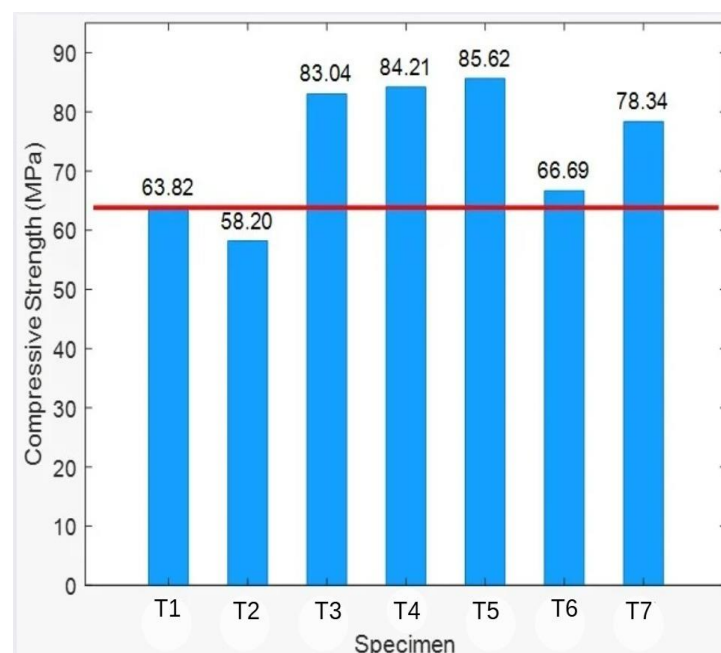


Figure 8. Variation of Compressive Strength of Epoxy Composites As A Function of Filler Content.

SEM Analysis

SEM studies done following tensile and compression tests provided crucial new insights on epoxy composites reinforced with $\text{Al}(\text{OH})_3$ and EP fillers in terms of filler-matrix interactions and fracture processes. The microstructures of the composites varied greatly based on the type and amount of filler used employed, as seen in Figure 9. Notably, it was found that the fracture surfaces developed a more uneven and rough texture as the filler content increased, especially in hybrid composite samples. These findings show that filler changes the path of crack propagation and boosts crack deflection and energy absorption ability during fracture.

SEM micrographs of the T2 sample (5% $\text{Al}(\text{OH})_3$) reveal that $\text{Al}(\text{OH})_3$ particles are uniformly distributed inside the epoxy matrix (Figure 9(a)). Some particles stayed bonded to the matrix structure even after fracture in this image. This suggests a strong interaction between the matrix and the filler material, as well as more effective load transfer during loading. Despite this, some particles showed fractures. Local bond ruptures are believed to be brought on by these cracks, which then lead to stress concentrations and crack initiation sites. The separation and fracture in some areas show that the filler-matrix connection is not completely homogeneous, which could influence the mechanical properties, even if the fracture surface usually displays a more consistent structure.

The T3 sample (5% EP) shows a clear porous structure of the EP particles on the fracture surface in Figure 9(b). Although many particles are still embedded in the epoxy matrix, some regions exhibit notable fracture and separation marks, indicating weaker bonding between the EP particles and the matrix in those areas. The porous nature of the EP leads to a rougher fracture surface, which enhances crack deflection and increases the energy absorption capacity. However, tensile zones seen in the separation areas do not fully contribute to load transfer, likely limiting the composite's overall mechanical strength.

SEM images of T5 sample (10% $\text{Al}(\text{OH})_3$) in Figure 9(d) show a denser distribution of $\text{Al}(\text{OH})_3$ particles in the matrix. Although most of the particles are strongly bound to the matrix structure, particle fractures and detachments are also observable in some regions. This indicates that the local fracture zones become more obvious with the increase in the infill ratio. The rougher fracture surface is believed to cause the matrix to absorb more energy during the crack propagation. However, it is also assumed that the generated fracture and detachment regions could become weak spots where damage can originate, possibly negatively affecting the overall mechanical performance.

In the T6 sample (10% EP), it was observed that EP particles were more prominent at the fracture surface, and some particles separated from the matrix (Figure 9(e)). It is thought that the high EP ratio increases the stress concentrations within the structure, which may promote premature fracture under tensile loading. However, the rougher structure of the fracture surface revealed that porous EP particles contribute to energy absorption capacity and crack propagation. Nevertheless, it is thought that the observed separation and fracture zones may negatively affect the overall tensile strength of the composite.

In sample T4, a hybrid composite containing 5% EP and 5% $\text{Al}(\text{OH})_3$, both filler types were observed to be more evenly distributed within the structure (Figure 9(c)). SEM analyses revealed that EP particles remained largely bound to the matrix structure, while some $\text{Al}(\text{OH})_3$ particles showed limited fractures. The combined use of two different fillers improved toughness by increasing energy absorption during crack propagation, and this was further supported by a rough fracture surface. This hybrid filler combination is thought to provide better mechanical performance compared to single-filler composites by ensuring a more balanced filler-matrix interaction.

In sample T7 (10% EP + 10% $\text{Al}(\text{OH})_3$), SEM images revealed significant filler agglomerations, particularly around the EP particles (Figure 9(f)). These agglomerations were found to cause the formation of microvoids and stress concentration zones in the structure. It was particularly noteworthy that this was more pronounced in samples with lower filler ratios. Furthermore, fractures occurred in some regions of the filler particles, indicating a local weakening of the filler-matrix bond. Although the $\text{Al}(\text{OH})_3$ particles appeared to be generally homogeneously distributed, some porous structures were also formed due to particle fractures during the mixing process. These porous regions are thought to create weak points in the composite structure. Thus, it is believed that they reduce the overall compressive strength and facilitate crack propagation during testing.

Overall, the results of SEM analyses showed that the mechanical performance of hybrid epoxy composites was dependent on the type and ratio of filler material. Specifically, it was observed that lower filler ratios in hybrid

systems improved the interaction between the filler and the matrix, leading to more stable mechanical behavior. Conversely, it was determined that high filler ratios could negatively affect the overall mechanical performance of the composites by causing agglomeration and local separations within the structure. These findings highlight that appropriate filler distribution and strong filler-matrix interaction play a significant role in improving the mechanical properties of epoxy composites.

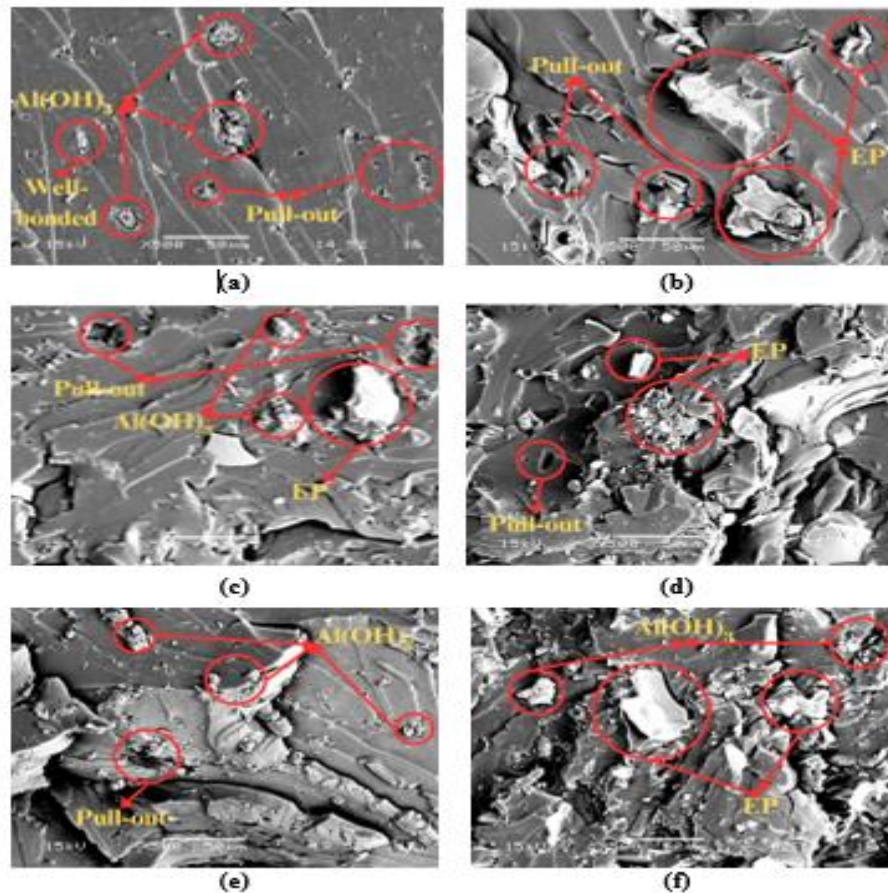


Figure 9. SEM micrographs of fracture surfaces (a) EPs + %5 $\text{Al}(\text{OH})_3$ (b) EPs + 5% EP (c) EPs + %10 $\text{Al}(\text{OH})_3$ (d) EPs + 10% EP (e) EPs + 5% EP + 5% $\text{Al}(\text{OH})_3$ (f) EPs + 10% EP + 10% $\text{Al}(\text{OH})_3$

CONCLUSIONS

This study demonstrated that the mechanical and microstructural properties of epoxy composites reinforced with micro-sized EP and $\text{Al}(\text{OH})_3$ vary depending on the filler content. Better interfacial bonding between the fillers and the matrix contributed to improved mechanical performance, particularly in hybrid composite structures. In tensile tests, the highest tensile strength was obtained in the hybrid composite containing 10% EP and 10% $\text{Al}(\text{OH})_3$. This improvement may be associated with the combined reinforcing effect of both fillers and their contribution to stress transfer within the epoxy matrix. However, SEM observations also indicated that higher filler concentrations promoted localized agglomeration in some regions of the composite structure. In compression tests, improved mechanical performance was generally observed with filler addition, although the effect varied depending on filler type and concentration. Moderate filler loadings provided more stable mechanical behavior, whereas excessive particle accumulation in certain formulations contributed to localized interfacial weaknesses.

SEM observations indicated that the filler distribution within the examined regions was relatively uniform, which may have contributed to the improved mechanical performance of the composites. The combined use of EP and $\text{Al}(\text{OH})_3$ fillers also appeared to enhance stress transfer within the epoxy matrix when used at appropriate proportions. Overall, the results show that the filler ratio and filler addition distribution directly affect the mechanical behavior of epoxy-based hybrid composites.

Artificial Intelligence Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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