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Effects of UV Exposure on the Physical, Chemical, and Mechanical Properties of Silica Microballoon Reinforced Epoxy Composites

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Abstract

Epoxy-based composites are widely used in various applications due to their excellent mechanical properties and durability, but their performance under prolonged UV exposure remains a critical concern. This study examines the impact of UV exposure on the physical, chemical, and mechanical properties of epoxy-silica microballoon composites over curing periods of 0, 200, and 400 hours. Results indicate that UV treatment increased the density from 1.0073 g/cm^3 to 1.0129 g/cm^3. SEM images showed a reduction in fragmentation of epoxy microballoons, indicating stronger bonding. EDX results revealed some changes in elemental composition, with a notable decrease in the percentage of sodium from 0.81 wt.% to 0.18 wt.% and silicon from 7.16 wt.% to 0.12 wt.%. FTIR analysis identified a new hydrogen bond formations at 3350 cm^{-1}. Mechanical testing showed that UV treatment significantly increased the flexural stress from 36.83 MPa to 49.98 MPa. Additionally, hardness (Shore D) increased from 78.4 to 80.2 Shore D. These findings highlighted the significant effects of UV exposure on the structural integrity and bonding mechanisms of the composites, offering valuable insights for their use in UV-prone environments.

Keywords: *UV Exposure, Epoxy Composites, Mechanical Properties, Silica Microballoons, Chemical Structure Analysis*

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INTRODUCTION

Composites are advanced materials that consist of two or more distinct phases, typically a matrix and a filler, which work together to offer superior properties not achievable by any single component. The matrix, often a polymer resin like epoxy, binds the filler materials and distributes applied loads, enhancing the overall strength and durability of the composite. Epoxy resins are particularly valued for their excellent mechanical properties, chemical resistance, and strong adhesion, and they can be combined with various fillers. For instance, carbon fibers significantly increase tensile strength and stiffness , while glass fibers enhance thermal and electrical properties [1]. Recent research has focused on the incorporation of microballoons, such as those made from glass or polymer, which reduce the composite's density while maintaining mechanical integrity. Particularly, silica microballoons have shown promising results in improving impact resistance and durability [2],[3].

Silica microballoons are increasingly utilized in composites due to their ability to enhance mechanical, thermal, and chemical properties. Mechanically, they improve strength and stiffness by creating a more homogeneous stress distribution within the composite [4]. For example, their inclusion can increase tensile strength from 30 MPa to 45 MPa [5]. Thermally, silica microballoons reduce thermal conductivity and improve insulation properties, lowering thermal conductivity by 15%. Chemically, their inert nature enhances the composite's resistance to chemical degradation and environmental damage, prolonging material lifespan and maintaining structural integrity under harsh conditions [6]. Although some studies have explored the mechanical and thermal benefits of silica microballoons in composites, comprehensive data on their performance under long-term UV exposure remain limited, necessitating further research in this area [7].

Several researchers have explored the effects of incorporating silica microballoons into epoxy composites and the impacts of UV exposure on these materials. For instance, [8] investigated the mechanical enhancement of epoxy-silica microballoon composites, while [9] focused on their thermal properties. However, the impact of UV exposure remains less studied. UV variation is crucial as it simulates long-term environmental aging, affecting the durability and performance of composites. Studies like those by [10] highlight the need to understand UV-induced changes to predict the longevity and reliability of these materials in real-world applications. Expanding on these works, researchers such as [11] have begun to investigate the combined effects of silica microballoons and UV exposure on epoxy composites. They found that UV exposure can significantly alter the chemical structure and mechanical properties, necessitating a comprehensive understanding of these changes.

The goal of this study is to investigate the specific effects of UV exposure on the mechanical, thermal, and chemical properties of epoxy-hardener-silica microballoon composites. By examining the influence of UV treatment duration on these properties, this research aims to fill the gap in current understanding and provide deeper insights into the long-term performance of these composites under UV radiation.

The silica microballoon reinforced epoxy composites were fabricated by varying the duration of UV treatment. The physical properties were assessed using density measurement, then correlating with the morphology using scanning electron microscope (SEM). The Fourier-transform infrared spectroscopy (FTIR) and energy dispersive X-ray spectroscopy (EDX) were used to analyze the chemical changes during the UV treatment. Specifically, the mechanical properties were analyzed using flexural and hardness testing.

METHODS AND ANALYSIS

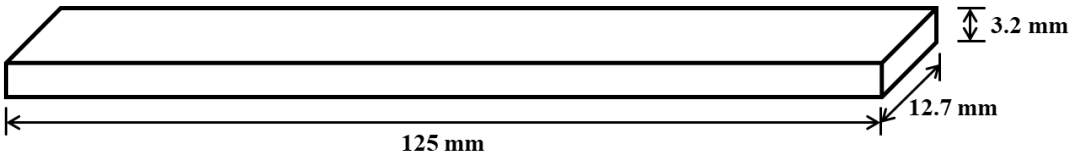
The fabrication process of the syntactic foam composites begins with precise measurement and preparation of the materials. The primary materials used are bisphenol

A epichlorohydrin epoxy resin and EPH 555-cycloaliphatic amine hardener, both purchased from PT. Justus Kimiaraya, and 3M™ Glass Bubbles iM16K silica microballoons, sourced from PT. 3M Indonesia. To achieve the desired composition of 80% matrix and 20% microballoons by volume, these volume fractions are converted to their respective weights based on their densities as follows: Epoxy (185.23 grams), Hardener (80.53 grams), and Microballoons (27.78 grams). The epoxy resin and hardener are mixed in a fixed ratio of 2:1 by weight. This mixture is initially stirred at 100 rpm for 10 minutes to ensure homogeneity before the addition of microballoons. After the microballoons are thoroughly incorporated, the hardener is added, and the mixture is stirred for an additional 5 minutes at the same speed.

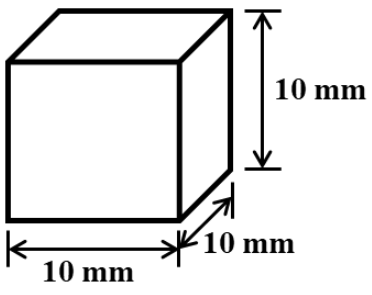
Following the mixing process, the composite mixture is poured into molds to create specimens for various tests, including flexural (ASTM D790), hardness (ASTM D2240), and density (ASTM D792) testing. Scanning Electron Microscopy (SEM) was utilized to examine the surface morphology of the fracture areas from the flexural test results, providing detailed images of the composite's microstructure. SEM coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDX) was performed on these fracture areas to analyze the elemental composition and distribution within the material, which helps in identifying any chemical changes due to the fabrication process or testing conditions.

The dimensions of the specimens are illustrated in Figure 1. The specimens were left to cure at room temperature (approximately 27°C) for 24 hours. To ensure complete curing, a post-curing step was carried out in an oven at 50°C for 4 hours. This step is critical to enhancing the mechanical properties and ensuring the stability of the composite material. Additionally, the specimens were subjected to UV exposure for varying durations (0 hours, 200 hours, and 400 hours) to study the effects of UV radiation on the material properties. After UV treatment, the specimens were conditioned in a chamber for 48 hours to reach a stable state before testing.

The analysis of the fabricated composites involves multiple testing methodologies. Flexural tests are conducted using the Shimadzu Autograph AGS-X Series Trapezium X to determine the strength and flexibility of the composites, which provide insights into the load-bearing capacity of the material. Hardness using Shore-D hardness tester (SHD-D-Gold, ASTM D2240) tests measure the resistance of the composite to deformation, which is a critical property for many structural applications. Density measurements are carried



(a)



(b)

Figure 1. The specimen dimension for (a) flexural, (b) hardness and density testing

out to ensure that the composite has been fabricated to the desired specifications and to understand the distribution of microballoons within the matrix. Scanning Electron Microscopy (SEM) is employed to analyze the morphology and distribution of the microballoons within the epoxy matrix. Energy Dispersive X-ray Spectroscopy (EDX) is used alongside SEM to provide elemental analysis and mapping of the composite materials. The Fourier-transform infrared spectroscopy (FTIR) was utilized using ATR method to analyze the chemical bonding.

The comprehensive methodology employed in this study ensures the precise fabrication and thorough analysis of the syntactic foam composites. The controlled curing and post-curing processes, along with the varied UV exposure treatments, provide valuable data on the material's stability and durability under different conditions. The combination of flexural, hardness, density, SEM, and SEM EDX tests offers a detailed understanding of the mechanical and structural properties of the composites. This multi-faceted approach not only confirms the successful integration of microballoons into the epoxy matrix but also highlights the potential of these composites for various practical applications where lightweight and robust materials are required.

RESULTS AND DISCUSSIONS

Density Characterization

The density of the silica microballoon reinforced epoxy composites exhibited a slight increase with prolonged UV exposure. Initially, at 0 hours, the density was recorded at 1.0073 g/cm^3. After 200 hours of UV treatment, the density increased to 1.0113 g/cm^3, and further increased to 1.0129 g/cm^3 at 400 hours. This gradual rise in density, as seen in Figure 2, suggests a possible densification effect or cross-linking enhancement within the composite matrix due to UV-induced reactions.

Moreover, this constant increase of the density as longer UV exposure has similar results to the previous study. The longer UV exposure gave the atoms of the resin more energy to move and run into a better arrangement during the treatment process [12]. The formation of additional chemical bonds, as supported by FTIR analysis, and the reduction in epoxy microballoon fragments, as well as compact arrangement observed in SEM images, likely contribute to the observed density increase. The slight increase in density could also be correlated with the minor changes in elemental composition detected by

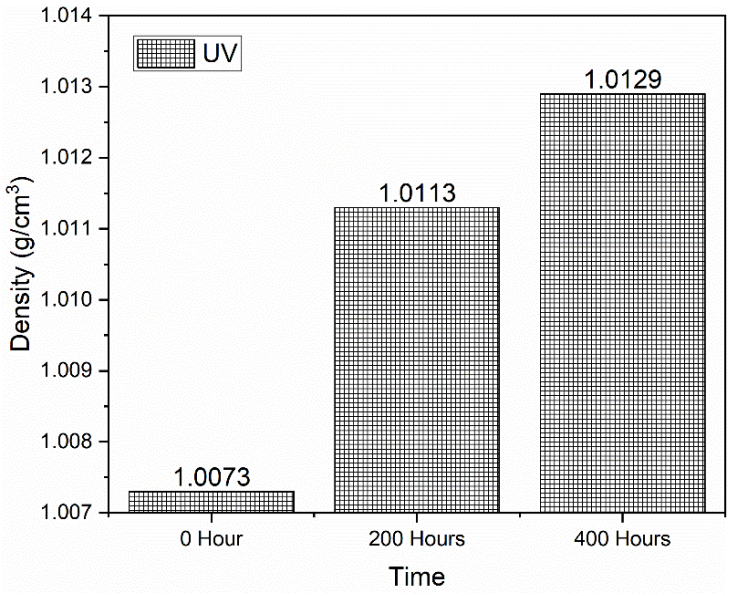


Figure 2. Density results of the silica microballoon reinforced epoxy composites with increased UV exposure time

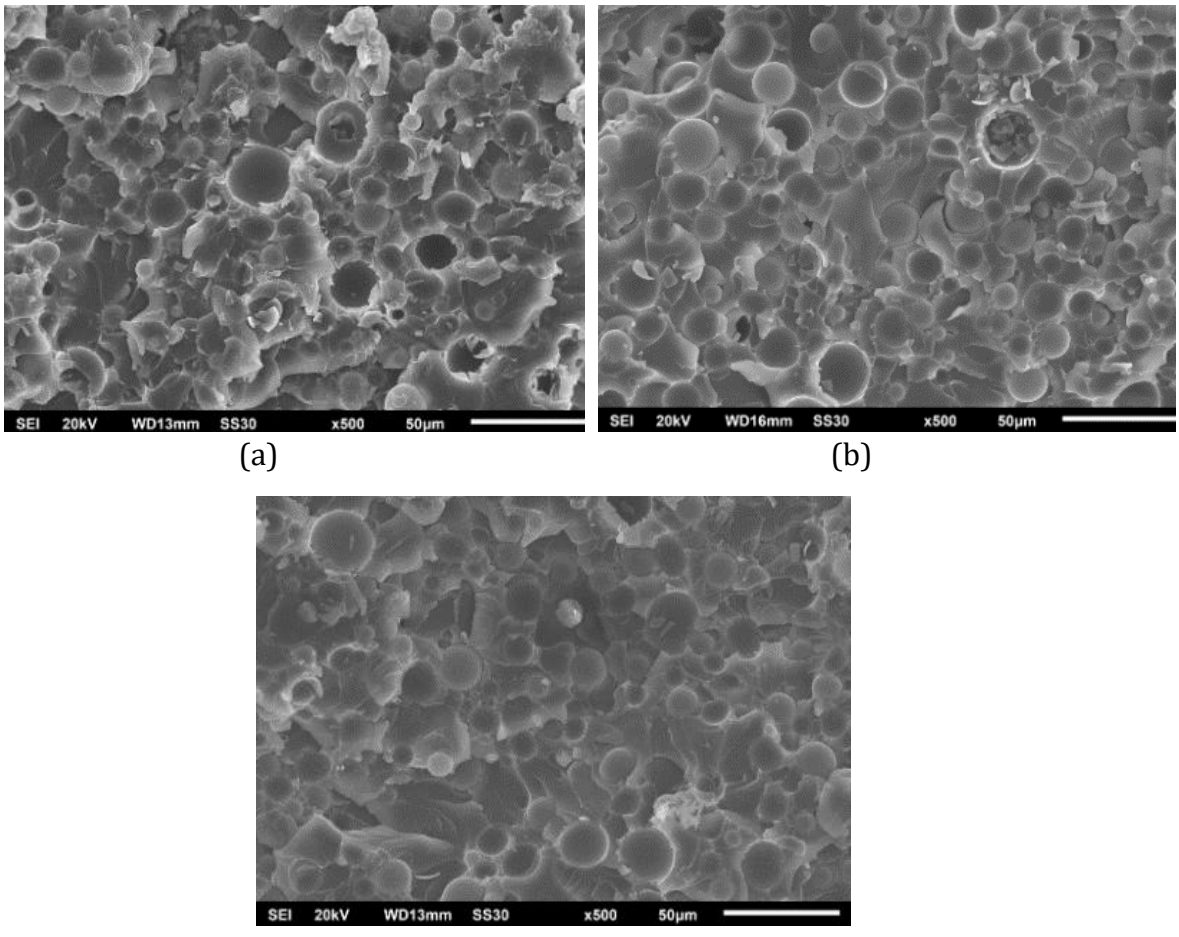
EDX analysis, reflecting a more compact and interconnected composite structure over time.

SEM-EDX Characterization

The SEM analysis (Figure 3) revealed significant changes in the microstructure of the silica microballoon reinforced epoxy composites with increased UV exposure. At 0 hours, the composite displayed numerous fragmented epoxy microballoons, indicating weaker bonding and a less cohesive matrix. After 200 hours of UV treatment, the presence of these fragments noticeably decreased, suggesting an improvement in the interfacial adhesion between the epoxy and the microballoons. By 400 hours, only a few epoxy microballoon fragments were visible, reflecting the strongest bonding and the most cohesive matrix observed among the three time points.

The composite with UV exposure time shows a tighter and smoother bonding than the composite with no UV exposure due to the rearrangement and shortened distance of molecular chains [13]. This progressive reduction in microballoon fragmentation is consistent with the enhanced mechanical properties which are further discussed in the next section. Moreover, the formation of additional chemical bonds, as indicated by the FTIR analysis, which collectively contributes to a more robust and durable composite structure under prolonged UV exposure.

The EDX analysis provided insights into the elemental composition changes in the silica microballoon reinforced epoxy composites with UV exposure, as displayed in Table 1. Initially, at 0 hours, the composite showed a composition of 61.84% carbon, 28.31%



(a) (b)

(c)

Figure 3. SEM images of the silica microballoon reinforced epoxy composites with (a) 0; (b) 200; and (c) 400 hours UV exposure time

Table 1. EDX results of the silica microballoon reinforced epoxy composites with increased UV exposure time

Element	0 Hour (wt.%)	200 Hours (wt.%)	400 Hours (wt.%)
C	61.84	62.81	62.55
O	28.31	28.13	28.51
Na	0.81	0.72	0.18
Si	7.16	6.63	0.12
Ca	1.87	1.7	0.19

oxygen, 0.81% sodium, 7.16% silicon, and 1.87% calcium. After 200 hours of UV treatment, the carbon content slightly increased to 62.81%, while oxygen and silicon content slightly decreased to 28.13% and 6.63%, respectively. Sodium and calcium contents also showed a reduction. By 400 hours, the carbon content was slightly lower at 62.55%, with a minor increase in oxygen to 28.51%, and a substantial decrease in silicon and calcium to 0.12% and 0.19%, respectively. These variations suggest that UV exposure influences the composite's elemental distribution, likely due to the degradation of certain components and the formation of new chemical bonds. The reduction in silicon and calcium content, alongside the changes in carbon and oxygen, indicates possible decomposition or diffusion processes, contributing to the densification and improved mechanical properties observed in the composites over time [14].

FTIR Characterization

The FTIR characterization resulted in the chemical bonding and structural changes of the silica microballoon reinforced epoxy composites subjected to UV exposure. Key peaks were observed at 3350, 2925, 2866, 1650, 1600, 1503, 1297, 1236, 1183, 1040, 960, and 829 cm^{-1}. The peak at 1650 cm^{-1} corresponds to C=O stretching, indicative of epoxy interaction with microballoons, and was more pronounced after UV treatment, suggesting enhanced cross-linking. The peak at 3350 cm^{-1}, associated with hydrogen bonding, showed increased intensity after 200 and 400 hours, signifying the formation of hydrogen bonds between the hardener, epoxy, and microballoons. These results are provided in Figure 4. Initially, at 0 hours, only hydrogen bonds between the microballoons and hardener were evident. However, after 200 and 400 hours, additional hydrogen bonds formed among the epoxy, microballoons, and hardener, reflecting a more interconnected and stable chemical structure. These changes corroborate the improvements in mechanical properties and the reduced microballoon fragmentation observed in SEM analysis, indicating that prolonged UV exposure facilitates stronger chemical interactions within the composite [15].

Flexural Characterization

The flexural properties of the silica microballoon reinforced epoxy composites exhibited notable improvements with increasing UV exposure time. Initially, at 0 hours, the flexural stress was 36.83 MPa, the flexural strain was 1.27%, and the flexural modulus was 3085.88 MPa. After 200 hours of UV treatment, the flexural stress increased significantly to 47.78 MPa, with a corresponding flexural strain of 1.62%, while the flexural modulus slightly decreased to 3055.77 MPa. At 400 hours, the flexural stress further improved to 49.98 MPa, and the flexural strain reached 1.71%, though the flexural modulus continued to decline to 2976.73 MPa.

The results (see Figure 5) indicate that UV exposure enhances the composite's ability to withstand higher stress and strain before failure, likely due to increased cross-linking and chemical bonding, as confirmed by FTIR analysis. However, the decrease in

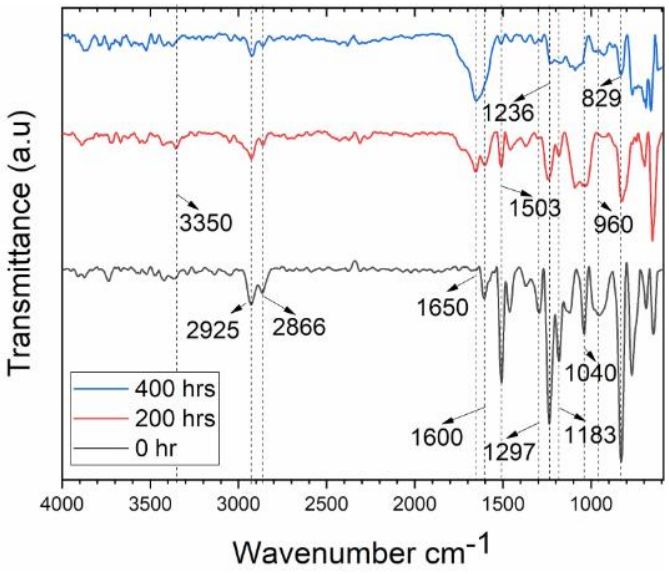
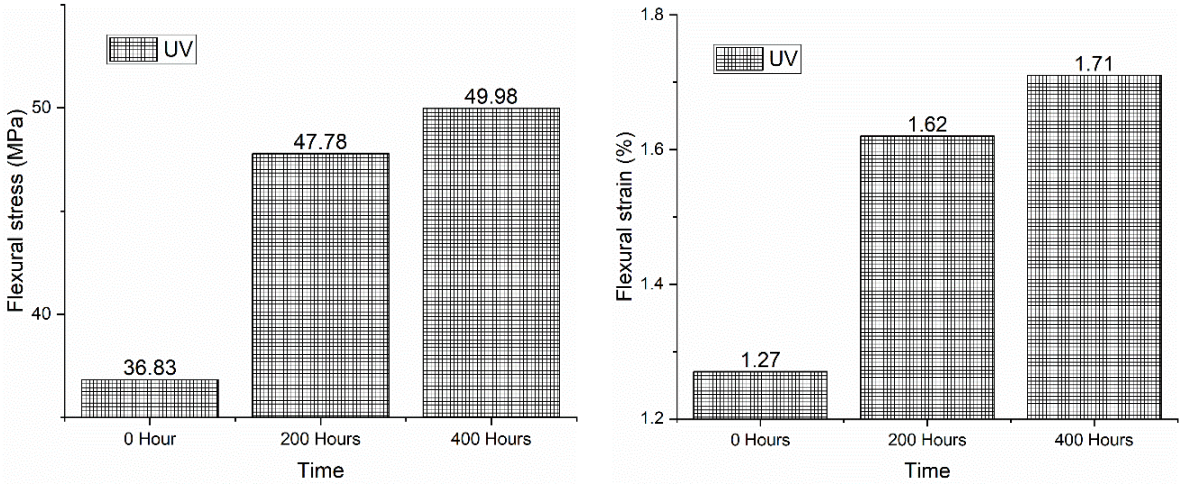


Figure 4. FTIR results of the silica microballoon reinforced epoxy composites with increased UV exposure time



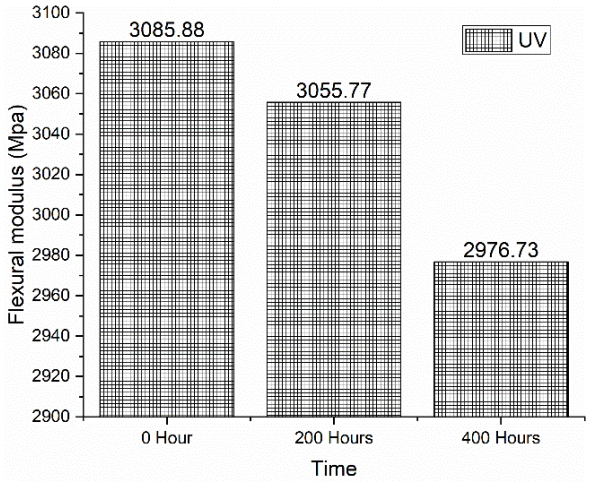


Figure 5. Flexural test results of the silica microballoon reinforced epoxy composites with the value of (a) stress, (b) strain, and (c) modulus

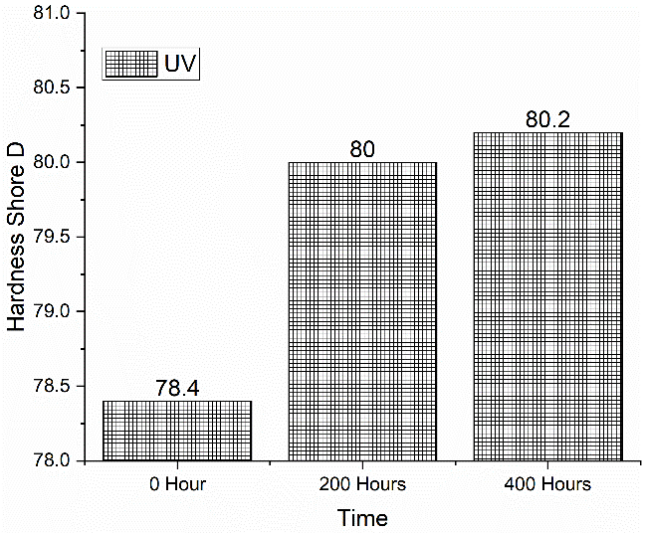


Figure 6. Hardness of the silica microballoon reinforced epoxy composites with increased UV exposure time

flexural modulus suggests a trade-off with stiffness, potentially due to the formation of a more ductile network within the composite matrix [16], enhancing its overall toughness and durability under flexural loads.

Hardness Characterization

Hardness tests were conducted on syntactic foam composites using the Shore D Hardness Durometer, following the ASTM D2240 standard. The hardness measurements were taken at three different time intervals of UV exposure. Figure 6 represents the hardness measurements at various stages. Initially, the hardness was recorded at 78.4 Shore D. After 200 hours of exposure to UV radiation, it increased to 80 Shore D. Following an extended UV exposure of 400 hours, there was a slight additional increase, reaching 80.2 Shore D.

The observed increase in hardness with prolonged UV exposure suggests a significant improvement in the mechanical properties of the syntactic foam composites. This enhancement can be attributed to the effects of post-curing under UV radiation, which is known to enhance the cross-linking of polymers. This higher hardness value with the increased UV exposure time aligns with the higher flexural strength value.

CONCLUSIONS

The study concludes that UV exposure significantly enhances the physical, chemical, and mechanical properties of silica microballoon reinforced epoxy composites. With extended UV treatment, the composites showed increased density, improved interfacial adhesion, and reduced fragmentation of epoxy microballoons. EDX analysis indicated changes in elemental composition, supporting densification and improved cross-linking. FTIR results confirmed the formation of additional hydrogen bonds, enhancing structural integrity. Flexural properties improved with higher stress and strain capacities, although with a slight reduction in modulus, suggesting increased ductility. Hardness measurements showed a consistent increase, reflecting greater resistance to surface deformation. Overall, UV exposure is an effective method to strengthen these composites, making them more robust and durable for various applications.

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DECLARATION OF CONFLICTING INTERESTS

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