

Investigation of the Effect of Gum Arabic-Rice Husk Hybrid Filler on the Mechanical Properties of Polystyrene Composite

Shuaibu Musa Abubakar*, Aliyu, Suleiman, Mohammed Abdullahi Baba, Shamsuddeen, Umar Abdullahi, Ali Sani Mohammed Aminu Adamu Bayero, and ⁷Jamilu Musa Babangida
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Abstract : *This study investigates the effect of Gum Arabic-Rice Husk (GA-RH) on the mechanical properties of polystyrene (PS) composites. Polystyrene, widely used in packaging, construction, and electronics, faces limitations in mechanical strength and flammability. The GA-RH offers a natural, cost-effective reinforcement solution. The research evaluated PS composites with varying hybrid GA-RH filler compositions (from 100/0 to 80/20 PS/GA-RH proportion) through physical and mechanical tests such as tensile strength, hardness, and impact strength. Key findings revealed that the addition of GA-RH influenced the composite's density, water absorption, and mechanical performance. The optimal composition, 97.5 % PS and 2.5 % GA-RH, showed the highest tensile strength (32.13 MPa) and modulus of elasticity (434.46 MPa). While the hardness showed improvement up to 85 % PS and 15 % GA-RH. This study concluded that for applications requiring higher tensile strength and modulus up to 2.5 GA-RH in PS is recommended, while for improved hardness, up to 15% GA-RH in PS can be used.*

Keywords: Polystyrene, Gum arabic, Ricehusk, Hibrid filler, Mechanical properties

Shuaibu Musa Abubakar

Department of Polymer Technology, Nigerian Institute of Leather and Science Technology, Zaria, Nigeria

Email: shuaibupolymer@gmail.com

Orcid id: <https://orcid.org/0009-0007-6807-5817>

Aliyu Suleiman

Department of Polymer Technology, Nigerian Institute of Leather and Science Technology, Zaria, Nigeria

Email: suadisaliyusuleiman@gmail.com

Orcid id: <https://orcid.org/0000-0002-1849-9554>

Mohammed Abdullahi Baba

Department of Polymer and Textile Engineering, Ahmadu Bello University, Zaria, Nigeria

Email: mohammedbaba700@gmail.com

Orcid id: <https://orcid.org/0000-0001-6114-3222>

Shamsuddeen Umar Abdullahi

Directorate of Research and Development, Nigerian Institute of Leather and Science Technology, Zaria, Nigeria

Email: ashamsuddeen9@gmail.com

Orcid id: <https://orcid.org/0009-0006-4909-6973>

Ali Sani Mohammed

Department of Polymer Technology, Nigerian Institute of Leather and Science Technology, Zaria, Nigeria

Email: alisanee2@gmail.com

Orcid id: <https://orcid.org/0009-0000-7309-3736>

Aminu Adamu Bayero

Department of Leather and Leather Technology, Directorate of Leather and Leather Products, Nigerian Institute of Leather and Science Technology, Zaria, Nigeria

Email: fagacinbasawa54@gmail.com

Orcid id: <https://orcid.org/0009-0006-5155-1103>

Jamilu Musa Babangida

Directorate of Research and Development,
Nigerian Institute of Leather and Science
Technology, Zaria, Nigeria

Email: abuzahra170524@nilest.edu.ng

Orcid id: <https://orcid.org/0007-0007-4349-0694>

1.0 Introduction

Polymer matrix composite (PMC) is a composite material composed of reinforcement(s) bound together by an organic polymer matrix. PMCs are designed to transfer loads of a matrix to the reinforcer. The different systems are combined judiciously to achieve a system with more useful structural or functional properties non-attainable by any of the individual constituents alone (Shuaibu *et al.*, 2020). Polymer composites are becoming an essential part of modern materials due to their high advantages, such as minimal flammability, low weight, corrosion resistance, high fatigue strength, and faster assembly. They are extensively used as materials in making aircraft structures, electronic packaging to medical equipment, and space vehicles to home building (Alina *et al.*, 2019). The basic difference between blends and composites is that the two main constituents in the composites remain recognizable, while these may not be recognizable in blends. The predominant useful materials used in our day-to-day life are wood, concrete, ceramics, and so on. Surprisingly, the most important polymeric composites are found in nature, and these are known as natural composites. The connective tissues in mammals belong to the most advanced polymer composites known to mankind, where the fibrous protein, collagen, is the reinforcement. It functions both as soft and hard connective tissue. Composites are combinations of materials differing in composition, where the individual constituents retain their separate identities. These separate

constituents act together to give the necessary mechanical strength or stiffness to the composite part (Shuaibu *et al.*, 2020). Composite material is a material composed of two or more distinct phases (matrix phase and dispersed phase) and having bulk properties significantly different from those of any of the constituents. Matrix phase is the primary phase having a continuous character. Matrix is usually more ductile and a less hard phase. It holds the dispersed phase and shares a load with it. The dispersed (reinforcing) phase is embedded in the matrix in a discontinuous form. This secondary phase is called the dispersed phase. The dispersed phase is usually stronger than the matrix; therefore, it is sometimes called the reinforcing phase (Zhang *et al.*, 2020b).

There are different forms of composites classification, one of which composite materials are essentially classified into three categories, such as metal composites, ceramic composites, and polymer composites. Out of these three types, polymer composites, due to their low weight-to-strength ratio, find mammoth applications in automobiles, aircraft, spacecraft, boats, ships, civil construction, packaging, sporting goods, etc. (He *et al.*, 2019). The use of polymeric composite materials rises exponentially due to their good mechanical behaviour, chemical resistance and corrosion resistance, but their fire resistance behaviour raises a serious safety issue regarding the uses of polymeric composite materials. Chemically, all polymeric materials comprise of hydro-carbon chains and when they are exposed to fire, burn rapidly with the release of high amounts of heat, flame and smoke (Liu *et al.*, 2019).

Reinforcement of polymer composites is principally valuable in those areas where composite produces improvement of some properties with simultaneous determination of other properties such as mechanical strength, modulus, stiffness, etc, thus in order to retain



the advantage of composites production, it becomes necessary to compensate for the loss of properties by reinforcement with suitable fillers (Gupta, 2002). Properties of a given polymer can be improved in various ways, by incorporation of reinforcing fillers (Shuaibu *et al.*, 2020). Polystyrene (PS) is a plastic product with a wide range of applications due to its abundant sources, simple synthesis process, ease of processing, rigidity, dimensional stability and transparency (Chen *et al.*, 2023). However, PS has the disadvantages of having low mechanical properties, especially low tensile strength, and flammable, releasing large amounts of smoke from combustion which limits the application of PS.

At the advent of the industrial revolution, there were very few materials that we as humans were using, but as science and technology developed, our need for newer and better materials increased; the quest for that has not stopped today. The scientific community developed artificial materials called composites. To make them cost-effective, the scientific community started to look for materials hitherto considered as waste. Rice husk, an abundant agricultural waste, fulfils all the above-mentioned criteria and, as such, has been thoroughly used to develop biocomposites.

Rice is the staple crop of India and is produced in copious amounts, and the husk produced is mostly used for burning, which adds to the already beleaguered state of environmental pollution. It is estimated that the production of rice husk worldwide is approximately 759.6 million tons in 2017, of which 22 % of this is husk (167.10 million tonnes), which give an enormous amount of virtually free of cost raw material if it can be brought to a good scientific use (Edem *et al.*, 2024).

2.0 Materials and Methods

2.1 Materials

The Materials used are Polystyrene (PS), Gum Arabic (GA) and Rice husk (RH). The

Polystyrene (PS) with an estimated molecular weight of 100, 000 (Trade name/model 5250) was procured from BDH Chemical limited, England. The melt flow rate is 7 g/10 min (200 °C/5 kg)..

The constituents were mixed and compounded using two mill machine. The cooled compounded samples were then placed into a lubricated 100 x 4 mm mold and transferred into a compression molding machine. The samples were compressed in this machine at a temperature of 177 °C, at 4 Pa pressure for 1 hr. The molded sample composites were kept in labelled polyethylene bags for further laboratory examination tests.

2.2 Methods

2.2.1 Density measurement

The density of the composite was determined using a gas pycnometer (AccuPyc II 1340, Micrometrics, Norcross, USA) was used to measure the density of both the unmodified PS and the PS composite. This device used the gas displacement method for an accurate volume measurement. Once the sample was placed in a chamber with a known volume, the helium gas was released and allowed to expand into the other precision internal volume. The sealed chamber with the sample in it was then pressurized to achieve the desired pressure with gas displacement. Density of approximately 2 g of 100 g PS and PS/GA-RH composite at various hybrid filler loading was weighted, M, was transferred to a 10 mL graduated cylinder, and the cylinder was mechanically tapped up and down 100 times. Then, the volume of each of the sample composites with and without filler occupied (V) was recorded. The density (ρ) was calculated using Equation 1:

$$\text{Density } (\rho) = \frac{M}{V} \quad (1)$$

2.2.2 Water Absorption

Water absorption of the molded samples of composites was determined according to the ASTM standard method (D1037-99).



Composite samples $20 \times 20 \times 4 \text{ mm}^3$ were properly cut off from the composites developed for water absorption testing and dried in an oven at 50°C for 24 hours. The water absorption testing was carried out according to the following procedures. Firstly, the pre-dried composite samples were immersed fully in a water bath kept at room temperature. In regular intervals of process, the samples were removed from the water bath and wiped with tissue paper to remove surface water, and immediately, water uptake was measured gravimetrically by using an electronic balance. Following, the equipped samples composites were wholly immersed in the water bath again to continue the sorption process until the equilibrium condition was reached. The results of absorbed moisture were presented as the mass of absorbed water by dry composite mass. The moisture content was computed using Equation (2). Percentage mass lost or gained (% S) was calculated by applying equation 2

$$\text{water Absorption: } \frac{S_2 - S_1}{S_1} \times 100 \% \quad (2)$$

where S_1 and S_2 are the initial mass and the new mass of the specimen sample before and after the water absorption, respectively.

2.2.3 Tensile test of the composites produced with and without filler

The tensile test was determined according to ASTM 683-2018 standards using an Instron Universal Tensometer testing machine (model W 9875). The data generated were used to determine the tensile strength, tensile strain, Young's modulus, and percentage elongation (Shuaibu *et al.*, 2020; Asyraf *et al.*, 2021).

2.2.4 Hardness test of the composites produced with and without filler

The hardness test was performed by placing the molded ($20 \times 20 \times 4 \text{ mm}^3$) specimen on the hard flat surface of the machine. The hardness machine needle was indented into the specimen (6.4 mm) and the hardness readings was manually recorded as the pointer of the hardness tester stop at a given calibration of the

machine under specified force and time (ASTM D2240-08-2018) (Trinh, *et al.*, 2023).

2.2.5 Determination of the Impact strength of the composites produced with and without filler

The impact test of this research was carried out in accordance with the American Society for Testing Materials (ASTM D-2018) with a Resil Release impact machine. A test piece of dimension $100 \text{ mm} \times 4 \text{ mm}$ was cut and placed on the Impactor specimen holder, and the impact hammer was released and the impact values were recorded as averages (He & Wang, 2019).

2.2.6 Flexural test of the composites produced with and without filler

The flexural test was conducted according to ASTM D7264 - 2018 (Jacob *et al.*, 2018). The prepared molded samples ($100 \times 20 \times 4 \text{ mm}^3$) composite of different compositions were placed on the machine-supported beam and then the force was applied at the center of the sample specimen, and the values of the flexural parameters were then recorded as the piece specimen reached its highest bend.

3.0 Results and Discussion

3.1 Density and Water Absorption

It can be observed from the results of the density measurement (Fig. 1) that the values ranged from 1.03 g/cm^3 to 0.84 g/cm^3 . In the case of the first four samples (100/0, 97.5/2.5, 95/5, and 90/10), there was no significant variation in density. However, the 95/5 and 90/10 samples showed a slight increase, both recording 1.03 g/cm^3 . Finally, the 80/20 sample showed a significant decrease of about 8.5 % compared to virgin PS. This suggests that at higher filler loadings, the density of the polystyrene composite decreases, which is a typical effect when organic fillers are incorporated into polymers. A similar trend has been reported by Davis *et al.* (2006).

From the water absorption test (Fig. 2), it can be seen that as the GA-RH hybrid filler loading



increased, the water absorption rate also increased significantly. This effect can be attributed to the hydrophilic nature of the rice husk component in the hybrid filler. Since the hybrid filler is hydrophilic, its presence promotes higher water uptake. The PS reinforced with 20% GA-RH hybrid filler showed the highest water absorption (7.88%). This was followed by composites with 15 %, 10 %, and 5 % filler loadings, which recorded weight gains of 2.91 %, 0.54 %, and 0.54 %,

respectively. By contrast, virgin PS, being hydrophobic (Shuaibu et al., 2020), sustained 0.0 % water absorption throughout the test.

3.2 Mechanical properties

Figs. 3 - 9 illustrate the graphical presentation of the effect of composite composition on the tensile strength, Elongation at break, modulus of elasticity, Hardness, Impact strength, flexural strength, flexural strain, and flexural modulus of elasticity, respectively.

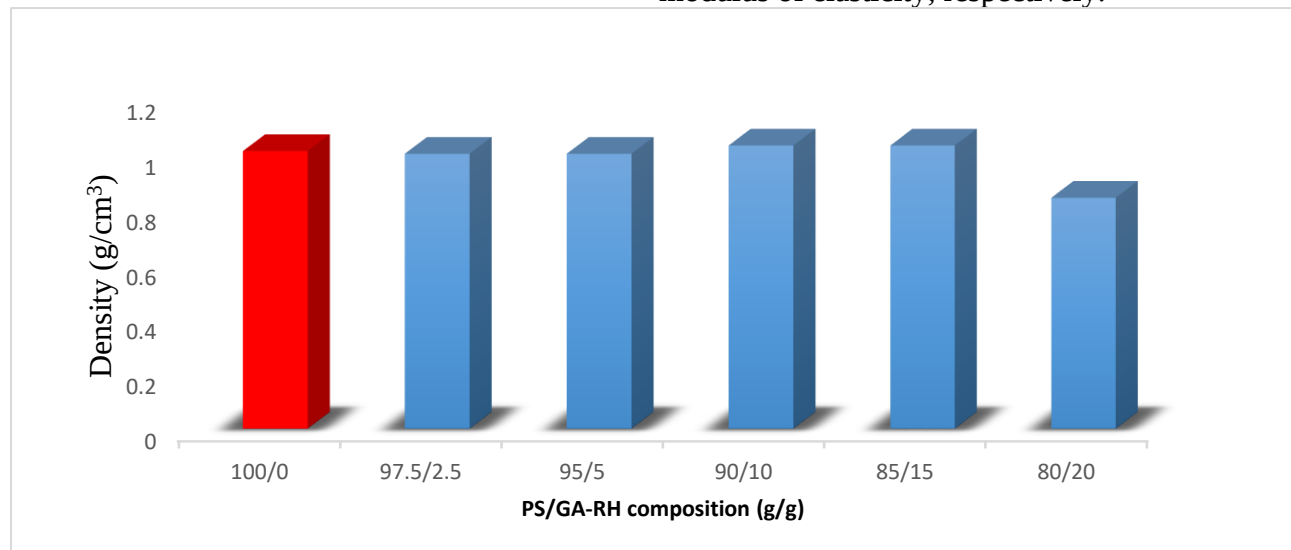


Fig. 1: Density of the prepared PS/GA-RH composite with and without filler

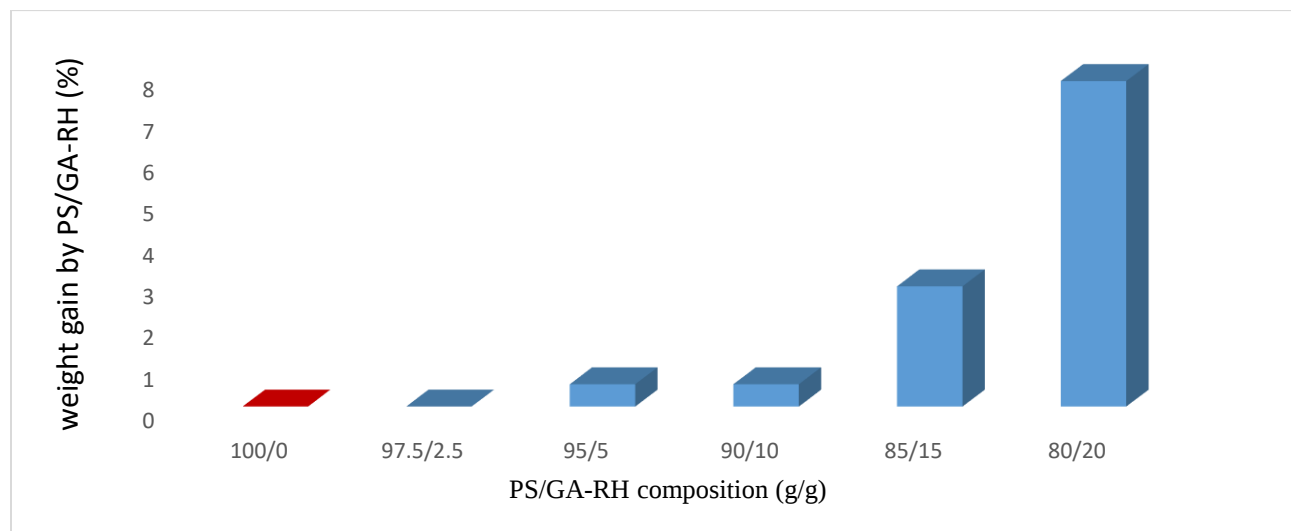


Fig. 2: Effect of water absorption on of the prepared PS/GA-RH composite with and without filler



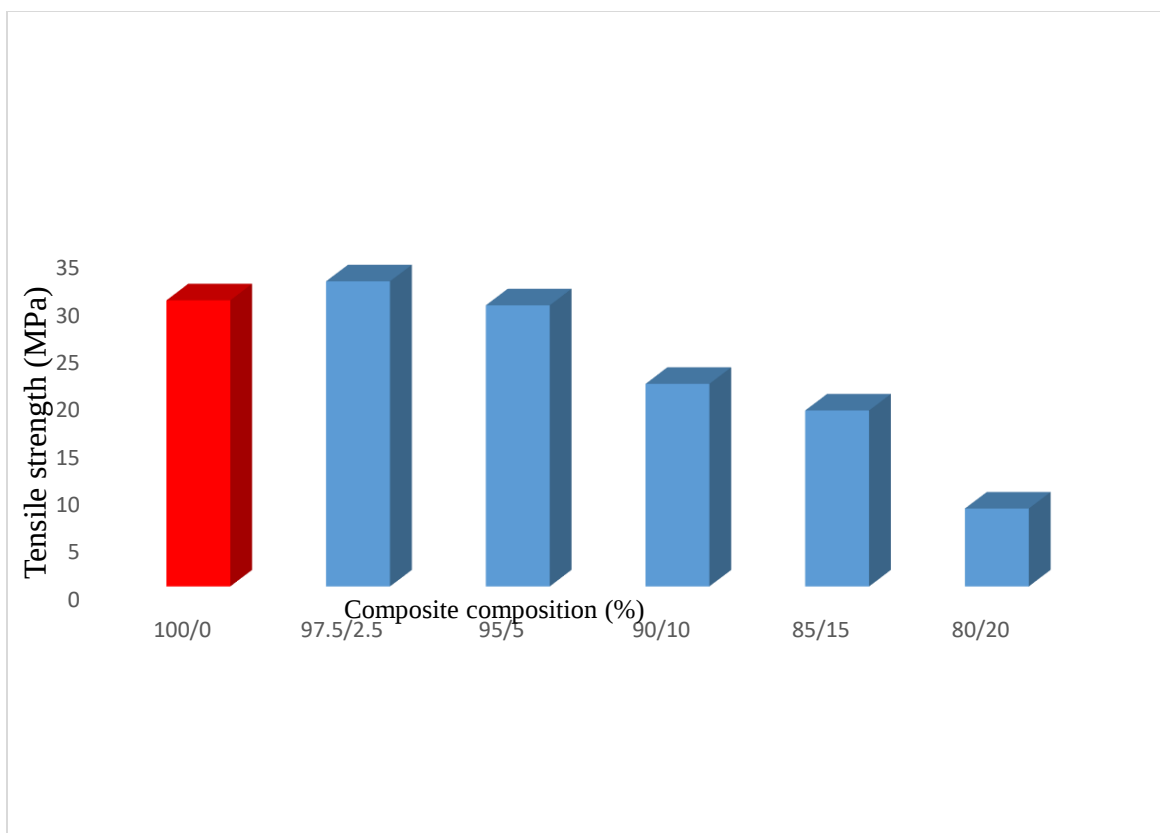


Fig. 3: Effect of composite composition on tensile strength

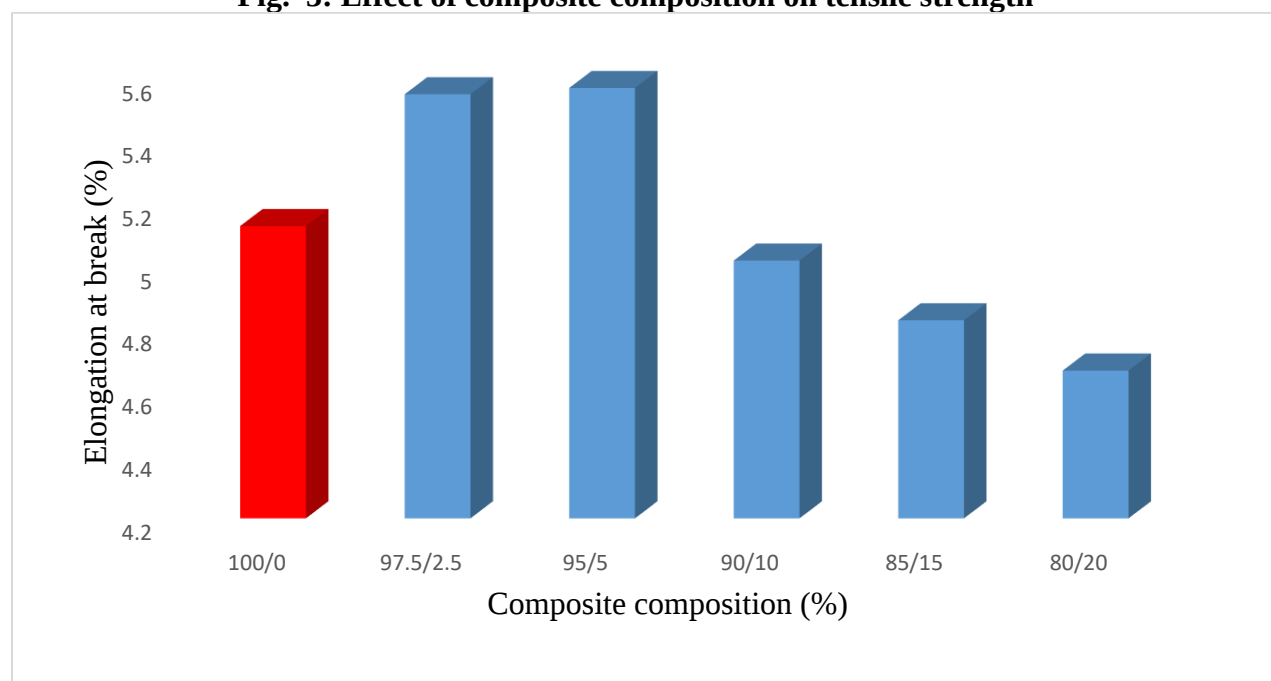


Fig. 4: Effect of composite composition on elongation at break



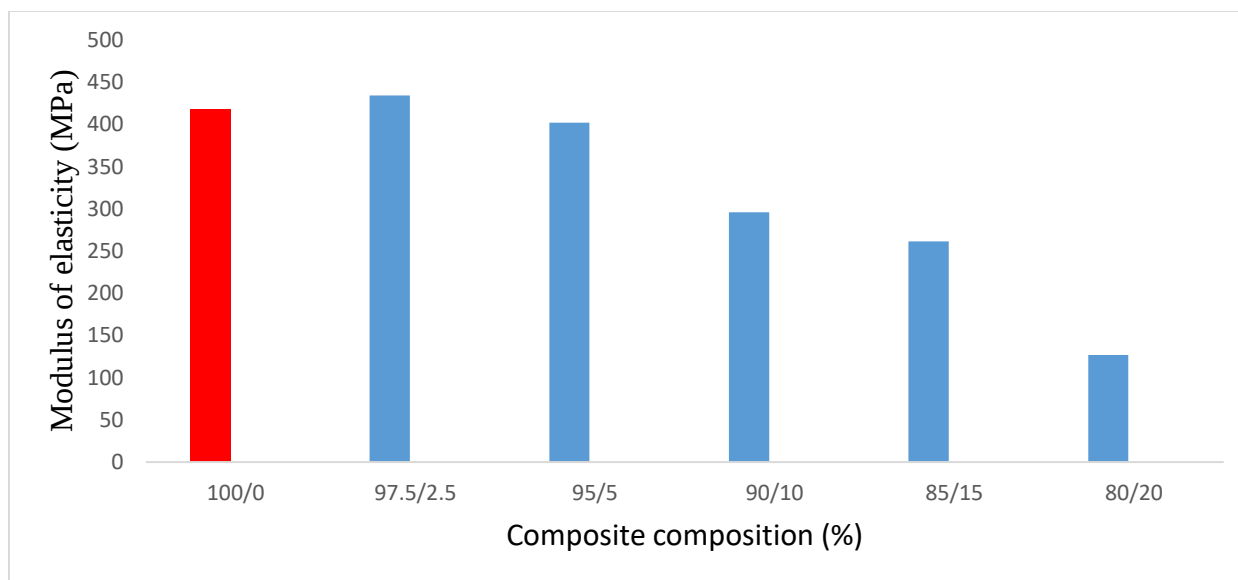


Fig. 5: Effect of composite composition on modulus of elasticity

3.2.1 Tensile properties

The results of tensile strength, elongation at break, and modulus of elasticity are presented in Figs. 3, 4, and 5. The addition of GA-RH hybrid filler to PS slightly improved the tensile strength by 6.63% (32.13 MPa) at 2.5% filler loading compared with virgin PS. This improvement is attributed to better dispersion and strong interfacial interaction between PS and the GA-RH filler, consistent with findings by Zhang *et al.* (2020a).

After this initial improvement, further filler additions led to a steady decline in tensile properties. Elongation at break increased for composites with 2.5% and 5% filler loadings, suggesting a transition from rigid and brittle PS to a tougher material. This improvement is likely due to stress transfer: gum Arabic contributes toughness while rice husk imparts hardness (Alina *et al.*, 2019). Similar observations were reported by Zhou *et al.* (2022).

However, with filler loadings beyond 5%, both tensile strength and elongation at break decreased, indicating that excessive GA-RH filler reduced dispersion within the PS matrix, leading to brittleness. For instance, the composite with 2.5% GA-RH showed the

highest tensile modulus (434.46 MPa), while the lowest values were recorded at 80/20 (8.2 MPa tensile strength and 126.76 MPa modulus), which reflects poor interfacial interaction. Comparable results were reported by Et alg *et al.* (2023).

The overall trend indicates that there exists an optimal filler concentration (around 2.5–5 wt%) at which both strength and ductility can be enhanced simultaneously. Beyond this threshold, filler agglomeration and weak interfacial bonding reduce the stress transfer efficiency, thus compromising the mechanical integrity of the composite.

This behavior is typical of natural fiber-reinforced composites where the balance between matrix continuity and filler dispersion determines the mechanical outcome. At lower filler contents, the hybrid GA-RH particles are well dispersed and act as reinforcement sites, while at higher filler loadings, the probability of particle–particle contact increases, forming stress concentration zones that initiate micro-cracks during loading.

It is also worth noting that the increase in modulus of elasticity at low filler content suggests that the GA-RH hybrid filler not only improved stiffness but also restricted polymer



chain mobility. However, at high filler loadings, the loss of modulus is an indication of poor stress distribution and weak filler–matrix adhesion.

Therefore, these findings highlight the importance of optimizing filler loading to

balance tensile strength, elongation at break, and stiffness for desired applications of PS-based composites.

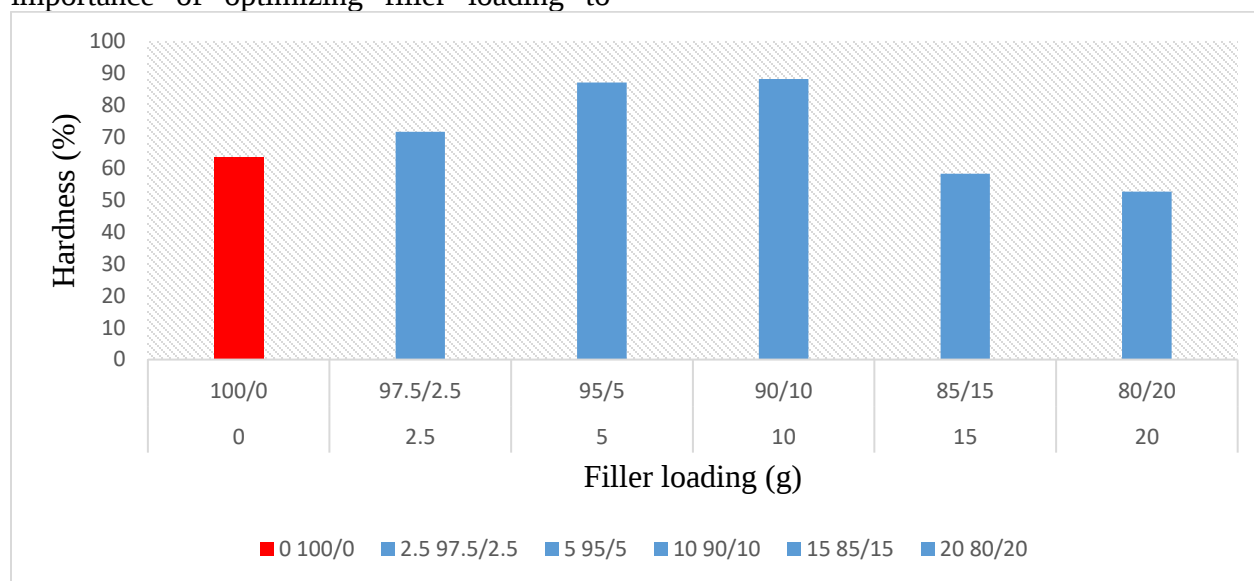


Fig. 6: Effect of composite composition and filler loading on show A Hardness

3.2.2 Hardness

The results obtained from the hardness analysis of PS and PS/GA-RH composites established that virgin PS exhibited a lower hardness value compared with the reinforced systems. For instance, the PS/GA-RH composites recorded hardness values of 71.53 % for 95/5 (PS/GA-RH), 87% for 90/10 (PS/GA-RH), and 88.07 % for 85/15 (PS/GA-RH), respectively, demonstrating a consistent improvement in hardness with increasing filler content up to 15 wt %.

Interestingly, beyond this loading level, particularly at 20 wt% GA-RH filler, the hardness values drastically reduced. This decline can be attributed to filler agglomeration and poor dispersion at higher concentrations, which disrupts the uniform stress distribution within the matrix. A similar observation was reported by Rizal *et al.* (2018).

The improved hardness at moderate filler contents suggests that the hybrid filler effectively enhances the load-bearing capacity of the matrix by restricting polymer chain movement and improving resistance to surface indentation. This enhancement is related to the combined molecular composition of gum Arabic, which provides toughness, and rice husk, which contributes rigidity through its silica-rich structure (Callister *et al.*, 2018). Moreover, the synergistic reinforcement effect of GA and RH is comparable to other lignocellulosic fillers, such as cashew nut shell powder, which have been shown to improve hardness by stiffening the polymer matrix.

From the plotted chart, the highest hardness value was achieved at 85/15 (PS/GA-RH), recording 88.07%. This indicates that 15 wt% hybrid filler represents an optimal loading where filler–matrix adhesion and particle dispersion are maximized before the negative



effects of agglomeration set in. Therefore, the results confirmed that the hybrid filler not only enhances hardness but also transforms PS from a brittle polymer into a harder material,

widening its potential application in structural and packaging materials where higher surface resistance is required.

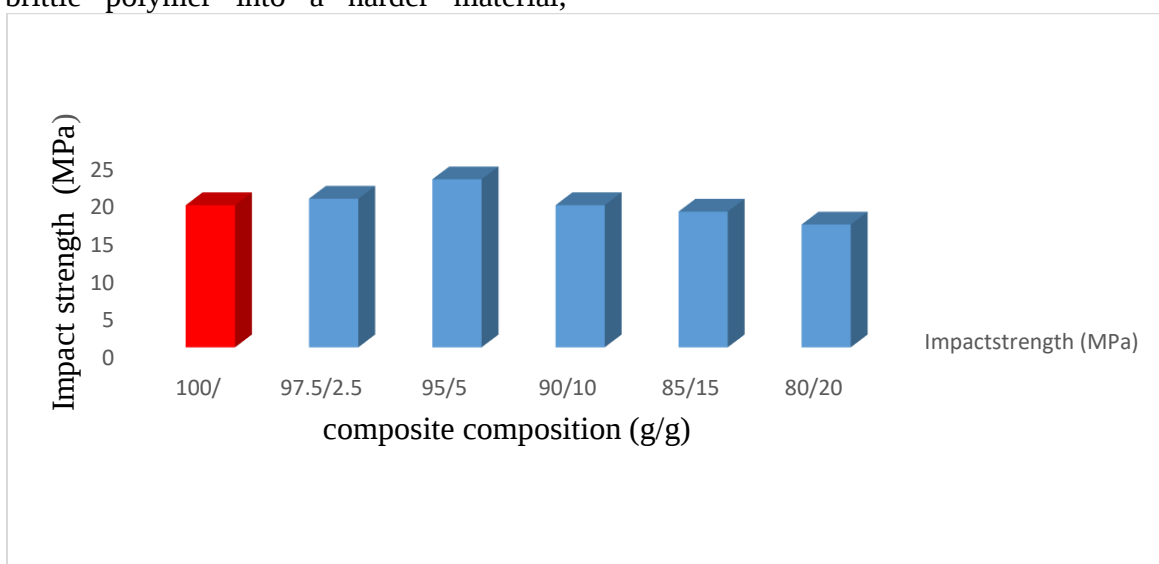


Fig. 7 Effect of composite composition and filler loading on Impact strength

3.2.3 Impact strength

Fig. 7 shows the effect of hybrid filler (GA-RH) loading on the impact strength of virgin PS and PS/GA-RH composites. It was evident that the incorporation of GA-RH significantly improved the impact strength of the composites compared to virgin PS, confirming the reinforcing ability of the hybrid filler. The composition of 95 g PS/5 g GA-RH exhibited the highest impact strength among the prepared composites, surpassing that of the unfilled PS. This result is consistent with the findings of Uşurelu and Panaitescu (2023).

The enhancement in impact strength up to 90/10 (PS/GA-RH) can be attributed to the improved interfacial bonding between the polymer matrix and the hybrid filler. Gum Arabic, due to its adhesive and flexible characteristics, enhances ductility, while rice husk contributes rigidity, leading to a synergistic balance of toughness and hardness. This synergy results in better energy absorption under impact, as reflected in the experimental data.

However, when the filler loading exceeded 10 g (above 90/10 PS/GA-RH), a decrease in impact strength was observed. This reduction is likely due to filler agglomeration and poor dispersion at higher loadings, which reduce interfacial adhesion and create stress concentration sites within the polymer matrix. Consequently, the material becomes less capable of dissipating impact energy, shifting its mechanical behavior from hard, ductile, and tough to soft and brittle. A similar observation has been reported by other research groups (Madueke *et al.*, 2023).

From the overall trend, it can be inferred that an optimal filler concentration exists, specifically at 5 wt% GA-RH—where interfacial compatibility and energy dissipation mechanisms are maximized. Beyond this level, the negative effects of filler agglomeration outweigh the reinforcing benefits, resulting in diminished impact performance. This underscores the importance of controlled filler loading and uniform dispersion in achieving



desired mechanical properties in hybrid polymer composites.

3.2.4 Flexural strength

Fig. 8 shows the flexural properties at varying composite composition and different PS/GA-RH filler loading. The effect of the addition of the hybrid filler into the PS on the flexural strength is shown for different blend compositions in Figure 8. It can be observed that the flexural strength has generally reduced with the increase in the amount of hybrid filler

in the PS. The PS that is rigid and brittle becomes flexible since its bending property increased; however, its hardness property increases due to the presence of the RH in the composite. This means that there is a correlation between these results and those of the hardness test carried out on these same composites in this research. A similar result was reported by (Trinh *et al.*, 2023).

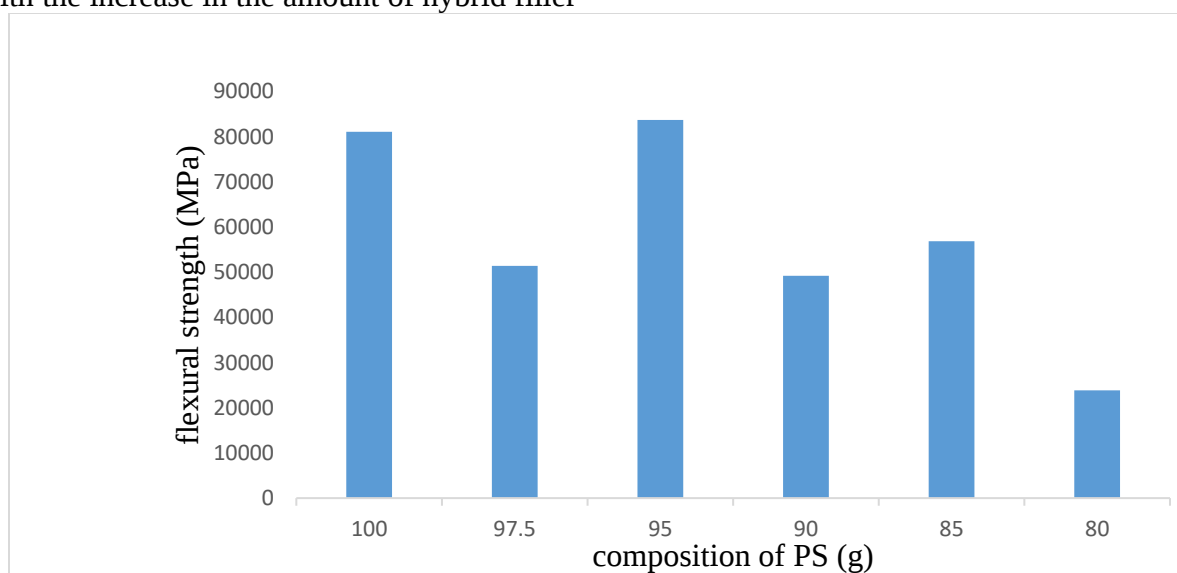


Fig. 8: Effect of PS/GA-RH on the flexural strength of the prepared composite

4. 0 Conclusion

The present study has evaluated the effect of Gum Arabic–Rice husk (GA-RH) hybrid filler on the mechanical and physical properties of polystyrene (PS). The findings revealed that the incorporation of GA-RH significantly influenced the tensile, flexural, impact, and hardness properties of the composites. The 97.5% PS/2.5% GA-RH composite exhibited the highest tensile strength of 32.13 MPa and modulus of elasticity of 434.46 MPa compared to unmodified PS, indicating strong interfacial interaction and effective stress transfer between the filler and the matrix. The mechanical properties such as tensile strength, percentage elongation at break, modulus of

elasticity, impact strength, and flexural strength, showed improvements at lower filler loadings, particularly at 2.5% and 5% GA-RH addition, but declined at higher filler concentrations due to filler agglomeration and poor dispersion. The density of the produced composites showed only slight deviation from virgin polystyrene, indicating that the hybrid filler did not drastically alter the bulk weight of the material. The hardness values improved with the addition of GA-RH up to 15%, with the highest value recorded at 88.07% for the 85/15 PS/GA-RH composite. Similarly, the impact strength was enhanced at 5% filler loading, beyond which a decline was observed,



suggesting an optimum loading level for improved toughness.

In conclusion, the study established that Gum Arabic–Rice husk hybrid filler can be effectively used to reinforce polystyrene, producing composites with enhanced tensile, hardness, and impact properties at optimized filler concentrations. The hybridization of fillers leverages the toughness imparted by Gum Arabic and the rigidity contributed by rice husk, creating a balanced reinforcement effect that improves the performance of polystyrene. However, excessive loading of the filler negatively impacts mechanical properties due to agglomeration and poor filler dispersion within the matrix.

It is recommended that future studies should explore surface modification of the GA-RH hybrid filler to improve compatibility and dispersion within the polystyrene matrix, thereby extending the range of effective filler loadings. Additionally, the processing parameters such as mixing speed, temperature, and time should be optimized to minimize agglomeration at higher filler contents. Further research should also assess the thermal stability, biodegradability, and long-term durability of the composites for broader industrial applications, particularly in packaging, automotive, and construction sectors where lightweight and improved mechanical performance are required.

5.0 References

- Alina, E. C., Augusta, R. G., Valentin R., Cristian, A., Nicolae, G. H., Mona, M., Sergiu, S., and Tanta, V. I. (2019). A study for a class of flame-retardant systems based on thermal, optical and mechanical analysis. *Sci. Bull., Series A*, 81, (4): 272-285
- Asyraf, M., Ishak, M., Syamsir, A., Nurazzi, N., Sabaruddin, F., Shazleen, S., Norrahim, M., Rafidah, M., Ilyas, R., and Abd Rashid, M. Z. (2021). Mechanical properties of oil palm fibre-reinforced polymer composites: A review. *Journal of Materials Research and Technology*.
- Bakhtiar, B., Rahim, A., & Sahrani, F. (2020). Mechanical properties of polymer composites. *Journal of Materials Science Research*, 9(2), 1-12. doi: 10.5539/jmsr.v9n2p1
- Chen, H.-J. C. (2023). Mass Spectrometry Analysis of DNA and Protein Adducts as Biomarkers in Human Exposure to Cigarette Smoking: Acrolein as an Example. *Chemical Research in Toxicology*.
- Davis, G., & Song, J. H. (2006). Biodegradable packaging based on raw materials from crops and their impact on waste management. *Industrial Crops and Products*, 23(2), 147-161.
- Edem C, Valéry K.D, Sena P.H, Paul D.A, Emmanuel O., (2024). Study of Rice Husks and Expanded Polystyrene Composites for Construction Applications. *Journal of Civil Engineering*, 14(2): 456-468. DOI: 10.4236/ojce.
- Gupta, B. (2023). Polymer Rheology-Effect of Various Parameters. In *Rheology Applied in Polymer Processing* (pp. 117-177): CRC Press.
- He, J., Li, Z., & Wang, Q. (2019). Polymer composites: Properties, applications, and future directions. *Journal of Composite Materials*, 53(11), 1575-1585. doi: 10.1177/0021998319865147
- Liu J, Li H, Chang H, He Y, Xu A, Pan B (2019). Structure and thermal property of intumescent char produced by flame - retardant high - impact polystyrene/expandable graphite/microencapsulated red phosphorus composite. *Fire Mater* 43:971-980. doi: 10.1002/fam.2758
- Madueke, C. I., Mbah, O. M., & Umunakwe, R. (2023). A review on the limitations of natural fibres and natural fibre composites with emphasis on tensile strength using coir



- as a case study. *Polymer Bulletin*, 80(4), 3489-3506.
- Nagasawa, A., Watanabe, K., Suga, K., and Nagao, D. (2023). Independent control over sizes and surface properties of polystyrene-based particles using multiple comonomers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 656, 130376.
- Rizal, S., Gopakumar, D. A., Thalib, S., Huzni, S., and Abdul Khalil, H. (2018). Interfacial compatibility evaluation on the fiber treatment in the Typha fiber reinforced epoxy composites and their effect on the chemical and mechanical properties. *Polymers*, 10(12), 1316.
- Shuaibu, M. A., Mamza, P. A. P., 1Hamza, A. & Isa, M. T. (2020). Mechanical properties of ficus polita seeds powder and calcium carbonate filled polypropylene, polystyrene and polyvinylacetate blends. *Nigerian Research Journal of Chemical Sciences*, 8, 2, pp. 172-186.(ISSN:2682-6054)
- Trinh, B. M., Chang, B. P., & Mekonnen, T. H. (2023). The Barrier Properties of Sustainable Multiphase and Multicomponent Packaging Materials: A Review. *Progress in Materials Science*, 101071.
- Uşurelu, E. M., & Panaitescu, D. M. (2023). Impact strength of polymer composites reinforced with hybrid fillers. *Journal of Composite Materials*, 57(11), 1575-1585. doi: 10.1177/00219983231193457
- Et alg, Z.; Chen, X.; Lu, S.; Wang, Z.; Li, J.; Liu, B.; Fang, X.; Ding, T.; Xu, Y. (2023). Synergistic Flame Retardant Properties of Polyoxymethylene with Surface Modified Intumescent Flame Retardant and Calcium Carbonate. *Polymers*, 15, 537. <https://doi.org/10.3390/polym15030537>
- Zhang X, Huang Z & Huang Y (2020a). Preparation of a novel EPDM modified polystyrene high impact material. *Yunnan Chemical* 47:74-78.
- Zhang Y, Wang X, Wang B, Yao L, Zhang X, Wang X (2020b). Development of Halogen-free flame retardant toughened PBT. *Engineering Plastics Application* 48:51-55.

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There are no competing financial interests in this research work.

Ethical considerations

Not applicable

Data availability

The microcontroller source code and any other information can be obtained from the corresponding author via email.

Author contributions

S.M.A. conceived and supervised the study, designed the experiments, and analyzed data. A.S. contributed to sample preparation and mechanical testing. M.A.B. assisted in data interpretation and manuscript drafting. S.U.A. coordinated research logistics and literature review. A.S.M. supported composite formulation. A.A.B. performed experimental validation. J.M.B. contributed to data analysis and final manuscript editing.

