Advanced Journal of Environmental Sciences
Volume.15, Number 12; December-2024;
ISSN: 2837-3928 | Impact Factor: 8.16
https://zapjournals.com/Journals/index.php/ajes
Published By: Zendo Academic Publishing

EFFECTS OF OYSTER SHELL POWDER AND CHEMICAL TREATMENT ON THE MECHANICAL PROPERTIES OF EXPANDED POLYSTYRENE/SAWDUST COMPOSITE.

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Article Info
Keywords: Polystyrene, sawdust, polymer, plastic composite, oyster shell powder.
DOI
10.5281/zenodo.14418025

Abstract
The global plastic waste menace has evolved over the years and has contributed to increased pollution rates. The lack of alternative uses for plastic waste results in mismanagement and landfilling. Hence, it is imperative that the circularity of the plastic value chain be investigated, and a strategy to close the loop be determined. Thus, we seek to develop a plastic/sawdust composite from expanded polystyrene and sawdust waste and explore the role of the sawdust fiber filler and oyster shell powder (OSP) additive in the enhancement of the composite's physical and mechanical properties. The bulk density and water absorption of the composites were determined conventionally. The tensile strength, modulus of elasticity, and rupture were measured. The analyzed data indicate that different OSP loadings enhanced the physical and mechanical properties. The treatment of the sawdust enhanced the tensile strength more than the OSP loading, with the best performing composite being without OSP loadings. Therefore, the life cycle of polystyrene waste can be prolonged through the secondary use in plastic/ sawdust composite whose physical and mechanical properties can be enhanced by the addition of 0.5% or 0.7% OSP loadings and the tensile strength can be improved by the chemical treatment of sawdust fibers.

1. Introduction

The growing global demand for materials such as wood, metals, glass, and plastics has resulted in the exploitation of natural reserves with consequential effects on the climate.(Kulmer et al., 2020). Composite materials form a promising alternative resource to the naturally occurring ones,(Maiti et al., 2022) and act as ecofriendly sources of raw materials.(Elfaleh et al., 2023)

Composites are generally man-made materials that are prepared from a binder and a reinforcing unit.(Rajak et al., 2019) The binder is called a matrix, and the reinforcement is the filler.(Ambrosio et al., 2016) The components

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have different physical properties, which synergistically form the properties of the composite.(Egbo, 2021) For instance, cement concrete has cement binders and gravel fillers.(Egbo, 2021) The hard brittle gravel filler provides additional strength to the concrete, while the cement is easy to mold and hold the gravel in place for stronger bulk material in construction applications.(Egbo, 2021) Composites are classified based on the type of the matrix.(Egbo, 2021) Hence, the types include polymer, ceramic, and metal composites.(Egbo, 2021)

Polymer composites have either thermoplastic or thermosetting polymers as the matrix with fillers being organic, mineral, or metallic.(Hsissou et al., 2021) Common polymer matrices include polyether imide, polycarbonate, polyethylene terephthalate, poly hexamethylene sebacic, polyether sulfone, polyether ether ketone, polyether ketone, polyurethane, phenoplasts, and epoxy resin.(Hsissou et al., 2021) The composites demonstrate enhanced properties such as enhanced mechanical strength, good thermal resistance, suitable fire behavior, premium impact resistance, and favorable rigidity.(Hsissou et al., 2021)

Polystyrene (PS) is a common thermoplastic polymeric material that is utilized in packaging(Ashby, 2013) due to its unique lightweight, insulation, and resistance to corrosion properties.(Gausepohl & Nießner, 2001). It provides shockproof to electronic devices and insulation to hot meals. It has been employed in composite preparation as the matrix or binding component due to its ease of processing and unique binding effect.(Gausepohl & Nießner, 2001). Among the fillers are durian husk fiber,(Chun et al., 2018) graphene,(Farouq, 2022) carbon nanofibers,(Moskalyuk et al., 2020), aluminum powder and clay,(Adeniyi et al., 2022) and Agave fiber(Singha & Rana, 2012). The composites demonstrated unique properties such as enhanced tensile strength, improved electrical conductivity, increased elastic modulus, favorable heat capacity, and thermal stability, respectively. These properties advance the application of polystyrene composites in construction, furniture, and electronics.(Gaidhani et al., 2023; Ramli et al., 2019)

Recent breakthroughs in recycling polystyrene, such as the pyrolysis of the waste into monomer-grade styrene, contribute to closing the value chain loop for the plastic material.(Reed et al., 2024). Even at the early stages, chemical recycling techniques have also been employed in an attempt to recycle polystyrene into valuable chemicals,(Huang et al., 2022), which will prolong the life cycle and save it from landfills and leakage into the environment. In light of the efforts to recycle polystyrene, our study repurposes polystyrene in the preparation of a composite to provide an alternative use for plastic, which enhances the circularity of plastic waste and limits its disposal. In this study, we employed polystyrene and wood waste to prepare a polymer composite for the first time. The PS formed the matrix while the sawdust was dispersed uniformly as the filler. Oyster shell powder has been predominantly employed in the improvement of the mechanical properties of cement mortar,(Liao, Fan, et al., 2022; Liao, Wang, et al., 2022), asphalt (Hu et al., 2023), and properties of poly(vinyl alcohol) (PVA),(Zhou et al., 2022), polypropylene (PP),(Shah et al., 2018)and poly(butylene succinate) (PBS),(Shen et al., 2024); however, it has yet to be utilized in polymer/sawdust composites. Therefore, we incorporated small ratios of oyster shell powder into the polystyrene/sawdust composite and measured the effects on the mechanical properties. Similarly, the sawdust fiber was chemically treated, and the effects on the composite properties were measured. Therefore, an alternative use for the waste materials; polystyrene foam, sawdust, and oyster shell powder was explored in the preparation of a polymer composite and its mechanical properties were determined.

2. Methodology

a. Preparation of raw materials.

The wood waste of eucalyptus was collected from Miro Forestry Plywood Company, Drobonso, in the Sekyere Afram Plain district of the Ashanti Region. After air drying the residue, it was milled in a hammer mill. The particle size was further reduced by employing a commercial blender. The particles obtained were sieved using five (5) sieves with standard numbers of 200, 160, 120, 80, and 40 corresponding to particles with sizes of 425, 180, 125, 97, and 75 microns.

To prepare the treated sawdust, acetone was added to the sawdust with a particle size of 425 m because it formed the bulk of the sawdust, and the sawdust was treated for 15 min with ultrasonic mixing. Afterwards, the acetone was decanted, and the residue was air-dried to obtain the treated sawdust. The obtained treated and untreated sawdust was stored separately in large ziplocks for the preparation of composite materials.

The expanded polystyrene foam waste was collected from electrical shops, washed with powered soap, rinsed in clean water, and air-dried. They were shredded into tiny flakes using a shredder and stored in clean large zip-lock polyethylene bags. Oyster shells were collected from the beach in Accra and thoroughly washed with distilled water to remove sand and salt residues, air-dried, and ground into granules. The granules were then ball-milled into powder. The ground particles were sieved to obtain a fine powder with a maximum particle size of 180 m and stored in ziplock polythene bags.

b. Preparation of the composite

Polystyrene (PS)/Sawdust (SD) composite samples were prepared by mixing different weights of polystyrene and sawdust in a mixing chamber. The components were mixed according to SD: PS ratios by weight (1:0.5, 1:0.7, 1:0.9, 1:1.1, 1:1.3, and 1:1.5. Solvent (500ml) was continuously stirred until a homogeneous mixture was obtained. The mixture was poured into a square mold and pressed under 300 psi to form composite boards. The board was removed from the mold and placed in an air-drying chamber for 14 days. The dried boards were stored for characterization.

Furthermore, a composite with oyster shell added was prepared separately. The composites were prepared as discussed earlier. These composites were prepared for both treated and untreated sawdust. Oyster shell powder was added to the treated and untreated composites at ratios: 0.3, 0.5 and 0.7 percent separately. The unfilled treated and untreated composites were prepared as reference materials.

c. Testing of composites.

The mechanical and physical properties were determined at the Wood and Furniture Testing Center (WFTC) of CSIR-FORIG. A universal testing machine (Inspekt table 50k/N) was used.

The Tensile strength of all composites was determined under ISO 527, while the modulus of elasticity (MOE) and modulus of rupture (MOR) were determined under EN 310. The water absorption test of the composites was conducted according to standard EN 317. The bulk densities of the composites were determined using standard methods EN 323.

3. *Results and Discussion*

a. Bulk Density

The bulk density measurements determined the compactness of the particle boards made from sawdust and polystyrene at different loadings. It was observed that the plastics effectively held sawdust particles together with increasing density from 0.5 to 1.3 loadings with densities of 0.51g/cm^3 to 0.78 g/cm^3, respectively (Figure 1. However, there was a decline in the compactness at 1.5 plastic loadings and a density of (0.71 g/cm^3) which can be attributed to self-adhesion between the plastic chains. As the plastic loading increased from 0.5 to 1.3, the density and compactness of the composites increased. This implies that composite 1:1.3 was the most compact and best-performing composite. Hence, the density of the composite increased with the increase in the proportion of plastic components. This observation is a reversal of the observation in polyethylene terephthalate (PET): Sawdust composite.(Rahman et al., 2013)

The effect of sawdust treatment and the addition of various loadings of oyster shell powder (OSP) on the composite bulk density was examined. Composite 1:1.3 was prepared with treated and untreated sawdust and 0.3–0.7 loadings of oyster shell powder. Figure 2 shows the measured density. According to the Figure, the bulk density of the composites with untreated sawdust fibers exceeded that of the composites with treated sawdust fibers with increasing OSP loading. The compactness of the untreated sawdust composites increased as the OSP content was increased from 0.3% to 0.7%. However, the composite of treated fibers was more compact at OSP loadings of 0.3% than that of untreated fiber composites. This indicates that the sawdust fiber treatment minimally affected the compactness of the composites. On the other hand, the oyster shell loadings significantly influenced the composite bulk density, with the highest density recorded at 0.7% OSP loading (1.03 g/cm^3. Hence, the density of the polystyrene/sawdust composite was enhanced by adding 0.7% OSP.

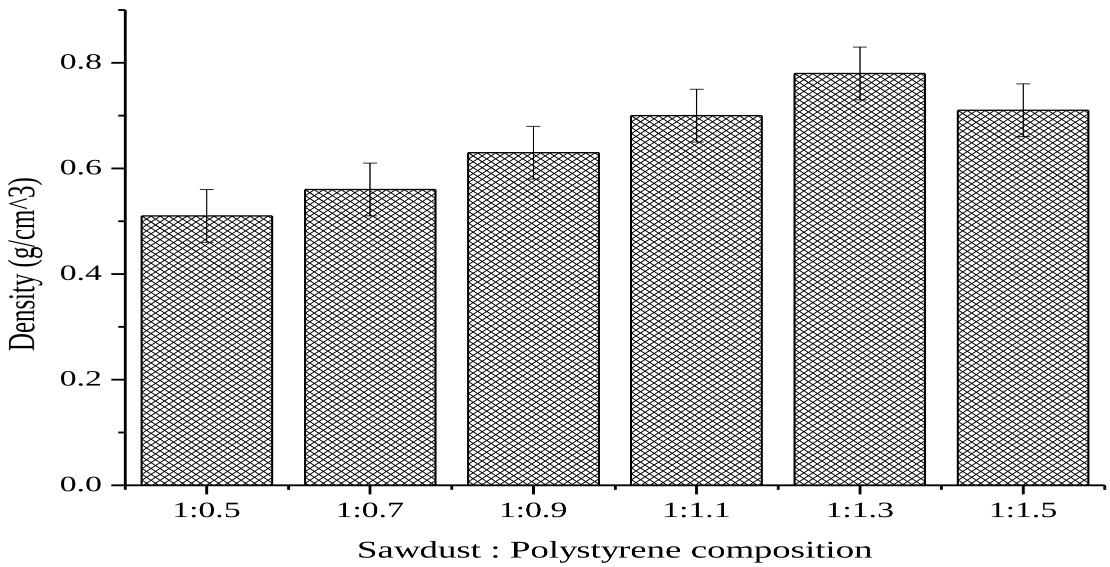

Figure 1. Bulk density of the PS/SD composites.

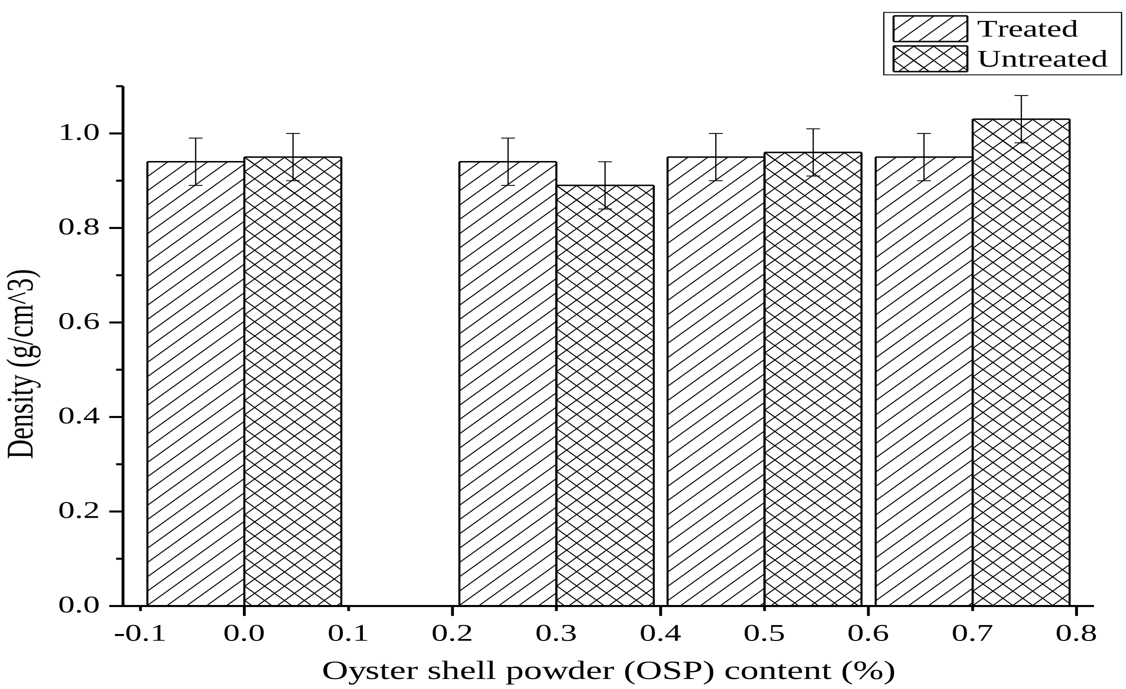

Figure 2. Bulk density against OSP loadings.

b. Water absorption

The composites exhibit varied resistance to water (Figure 3. The most water-resistant composition was 1:1.3 (4% and 8% at 2 and 24 hrs respectively), while the 1:0.5 composite displayed stronger water absorbance (48% and 66% at 2 and 24 hours respectively). The longer the composites remained in water, the more water they absorbed. The amount of absorbed water was doubled at 1:1.1 and 1:1.3 from 2 to 24 h. Furthermore, the dissimilarity in the water absorption rate was attributed to the different densities of the composites. An observation between density and water absorption (Figures 1 and 3) demonstrates that voids in less dense composites trapped more water than their denser counterparts with stronger matrix-filler affinity. Hence, composite 1:1.3 absorbed less water due to its denser properties. Additionally, the composites with minimal ratios of plastics absorbed more water than those with increased polystyrene content (Figure 3), which is consistent with the behavior of wood/plastic composites.(Bhaskar et al., 2021)

The effect of sawdust treatment and OSP addition on the water absorption of the composite was also investigated (Figure 4. The water absorption of the composite materials varied with the sawdust fiber treatment and the oyster shell powder. There was no pattern in the absorption at different OSP ratios; however, the significant absorption for the untreated composite at 0.3% OSP loadings corresponds to poor packing of constituents, which indicates that the porousness of the composite and availability of voids provided room for the absorption of more water. On average, minimal porosity is observed from 0.3% to 0.7% OSP loading for the treated composite material with a low water absorption of 13.31% compared to the average absorption of the untreated composite at from 0.3% to 0.7% loading. This indicates that the treatment of the sawdust and OSP loadings generally reduced the water absorption of the composites, which is consistent with polyethylene/sawdust composites.(Kamel et al., 2008). The best performing composite was recorded at 0.5% OSP loading (Figure 4), which implies that it is the ideal composition to resist decomposition by water particles during outdoor applications.(Khan et al., 2019)

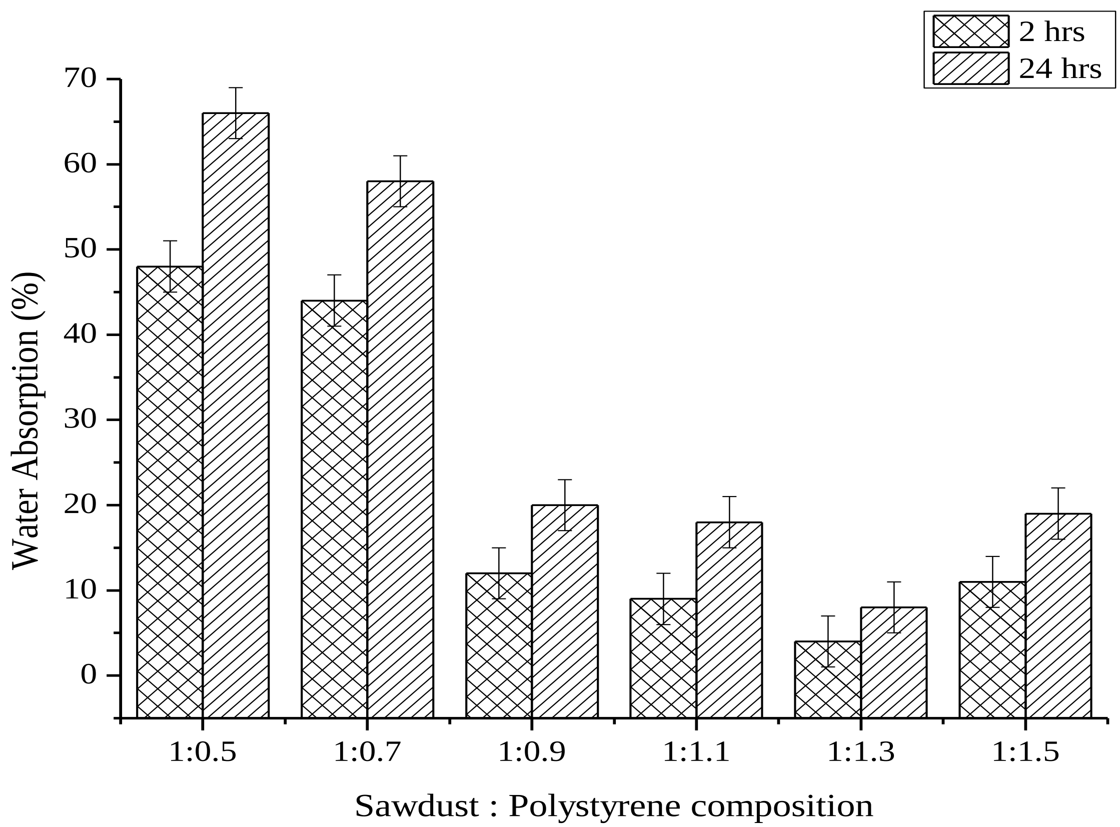

Figure 3. Water absorption by the PS/SD composites.

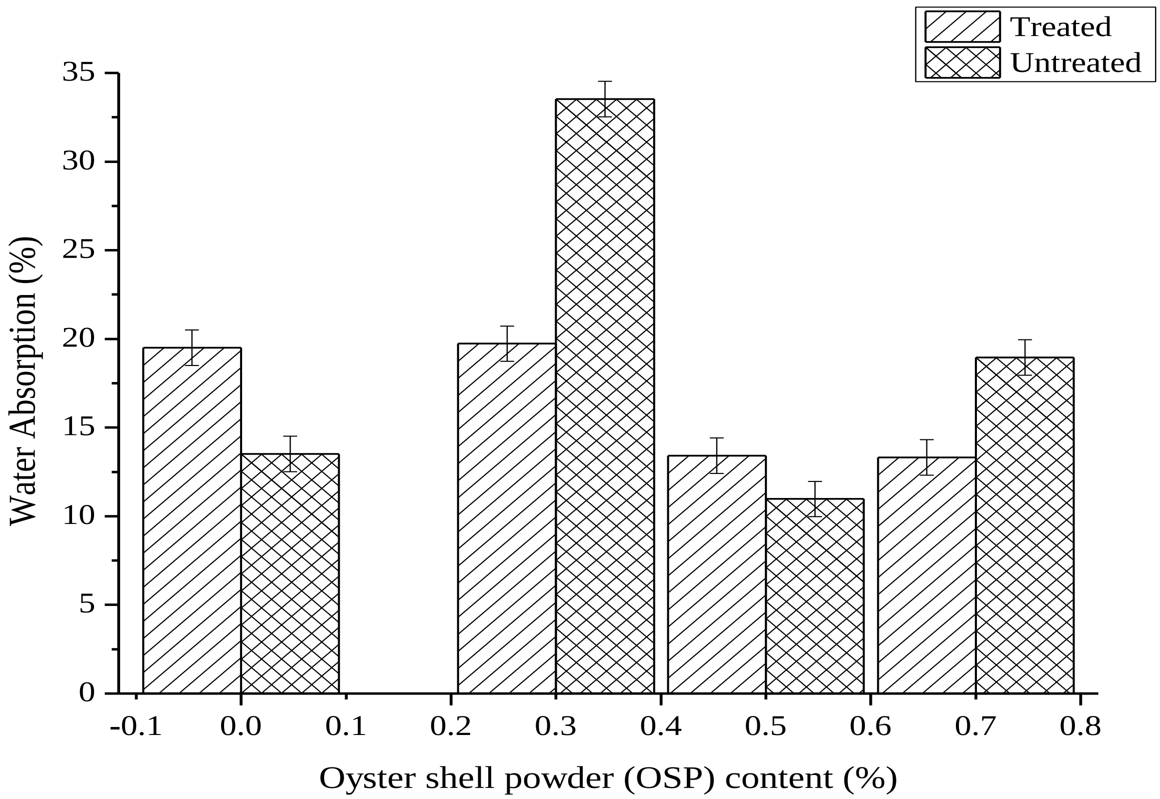

Figure 4. Water absorption against OSP loadings.

c. Tensile Strength

The tensile strength of the composites increased as the polystyrene content increased to 1:1.3 (Figure 5. The best-performing composition was 12.1 N/mm^2 for composite 1:1.3 compared to 1.39 N/mm^2 for composite 1:0.5. Hence, it can be implied that an increase in the plastic content enhances the resistance of the composite to stress load, which is consistent with the observation in sawdust/rPET composite.(Allaf et al., 2020) This gives the composite an improved functionality in applications such as partitioning walls whose 0.8N/mm^2 standard benchmark according to IS3087 lies below that of composite 1:1.3.(Ohijeagbon et al., 2020) On the other hand, the anomaly observed in the composite 1:1.5 demonstrates the failure in the material as the plastic content increased beyond 1.3 loadings. This can be attributed to the weak adhesion between plastic and sawdust particles at 1.5 polystyrene content. Hence, further experimentation was carried out on the best-performing composition 1:1.3, Figure 5.

The changes in the tensile strength with the treatment of sawdust and the addition of OSP are displayed in Figure 6. The treated composite exhibited improved resistance to stress compared to the untreated at 0.0%, 0.5%, and 0.7% OSP loadings. This is due to the availability of the fiber surface area to bond with the polystyrene chains, which is a similar observation in sawdust/HDPE composite.(Murugapoopathi et al., 2023). Generally, the treatment of sawdust fiber enhanced the tensile strength more than the OSP additive (Figure 6. The best-performing composite was obtained at 0.0 OSP with a tensile strength of 0.43 N/mm^2. This shows that the tensile strength of a polystyrene/sawdust composite can be best improved by treating the sawdust fiber.

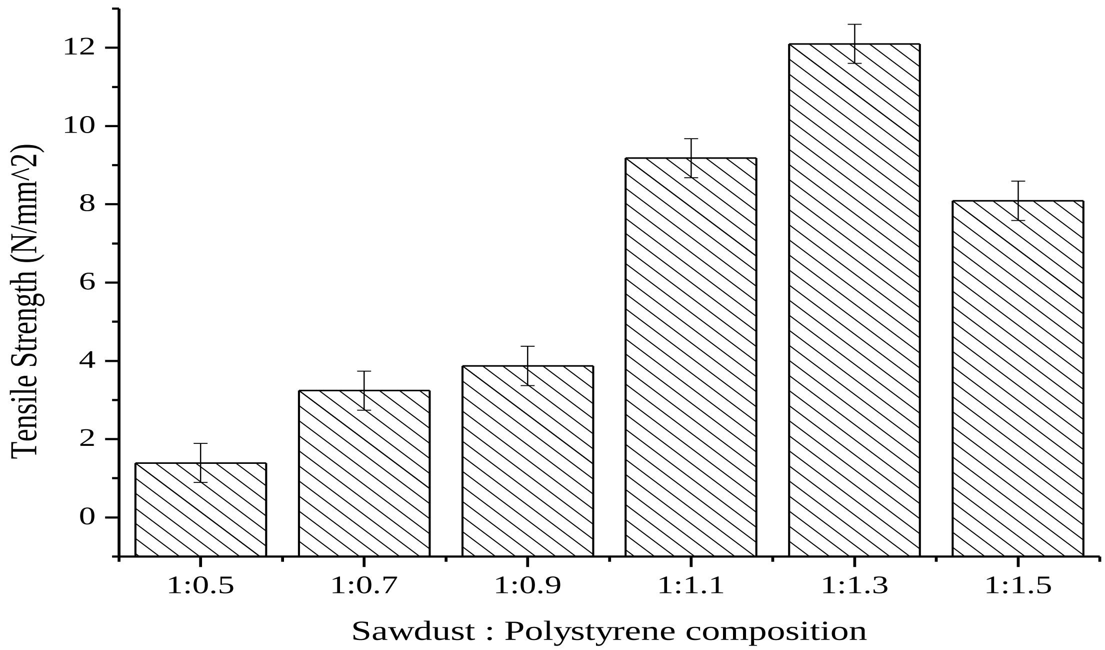

Figure 5 PS/SD composites.

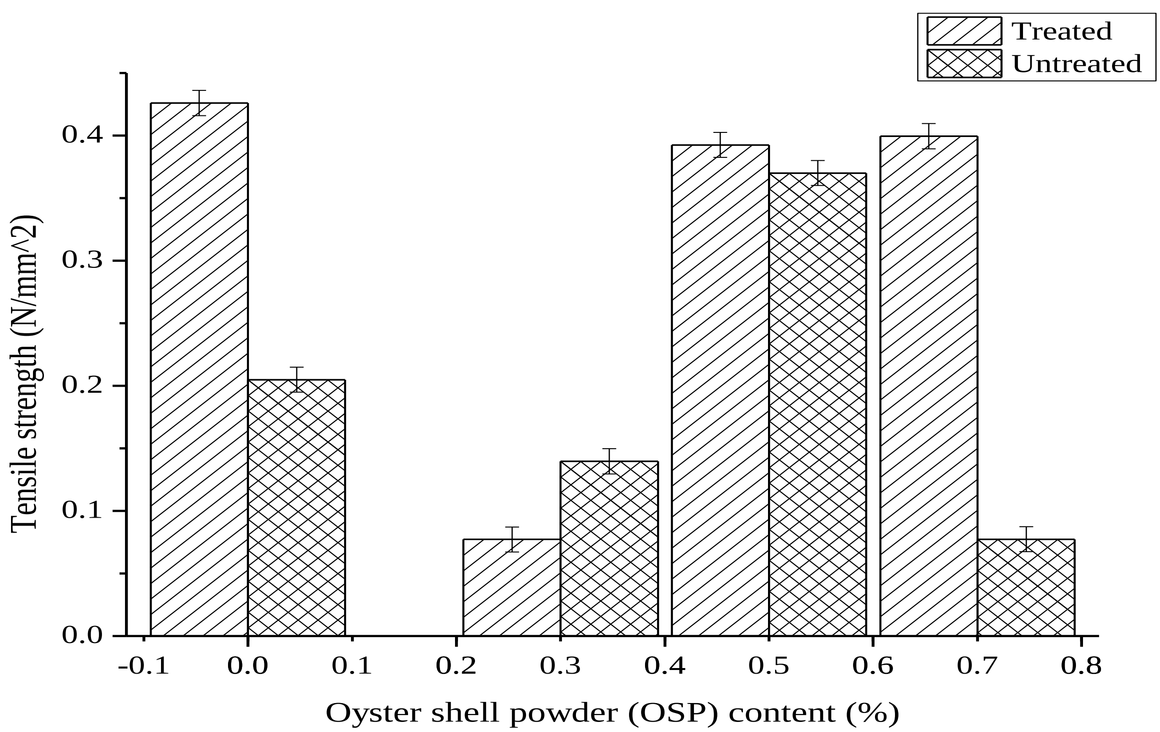

Figure 6. Tensile strength against OSP loadings.

d. Flexural Strength (Modulus of Elasticity and Modulus of rupture)

A general increase in the MOR of composites with increasing polystyrene component. This is similar to observations in other plastics and sawdust composite.(Jian et al., 2022). However, the MOE of composites with increasing polystyrene content did not follow a similar pattern. The modulus of rupture (MOR), which determines the miscibility between plastic and sawdust components of the composite, displayed the best mean value of 2.36 N/mm^2 in the 1:1.5 composition with a corresponding mean modulus of elasticity (MOE) of 1220.55 N/mm^2 compared to the 1:0.9 composition whose MOE was 1156.07 N/mm^2 and MOR of 1.62 N/mm^2, Figures 7 & 8. This indicates that the composition 1:1.5, which has the optimal plastic ratio, demonstrated good miscibility with the sawdust fiber with the best MOR and MOE, which is consistent with observations in sawdust/LDPE composite.(Sofina & Islam, 2015)

Furthermore, the effect of the chemical treatment of the fiber and the addition of OSP on the flexural properties was explored (Figures 9 & 10. The untreated composite exhibited the best MOR at 0.7% OSP loading, with a value of 0.77 N/mm^2. The MOR of the untreated sawdust composites increased with increasing OSP loading from 0.3% to 0.7%. Similarly, there was an improvement in the treated composites compared with the untreated composites from 0% to 0.7% OSP loading. This result demonstrates that the material's strength before rupture depends on both the OSP loading ratio and the surface treatment of the sawdust fiber.

Additionally, the composites exhibited various MOEs with OSP loadings and chemical treatment of the sawdust fiber. The flexible materials were observed under 0.5% OSP loading for both treated and untreated composites. The best composite was the untreated one at 0.5% OSP loading with a value of 215.67 N/mm^2. Although the treatment of sawdust fibers improved their elasticity at no OSP loading, the effect diminished at OSP loadings of 0.3%. This indicates that OSP loading has a superior influence on the elasticity of the fiber surface during the surface treatment. Hence, OSP at different loadings affected the elasticity of the composite more than the surface treatment of the sawdust fiber.

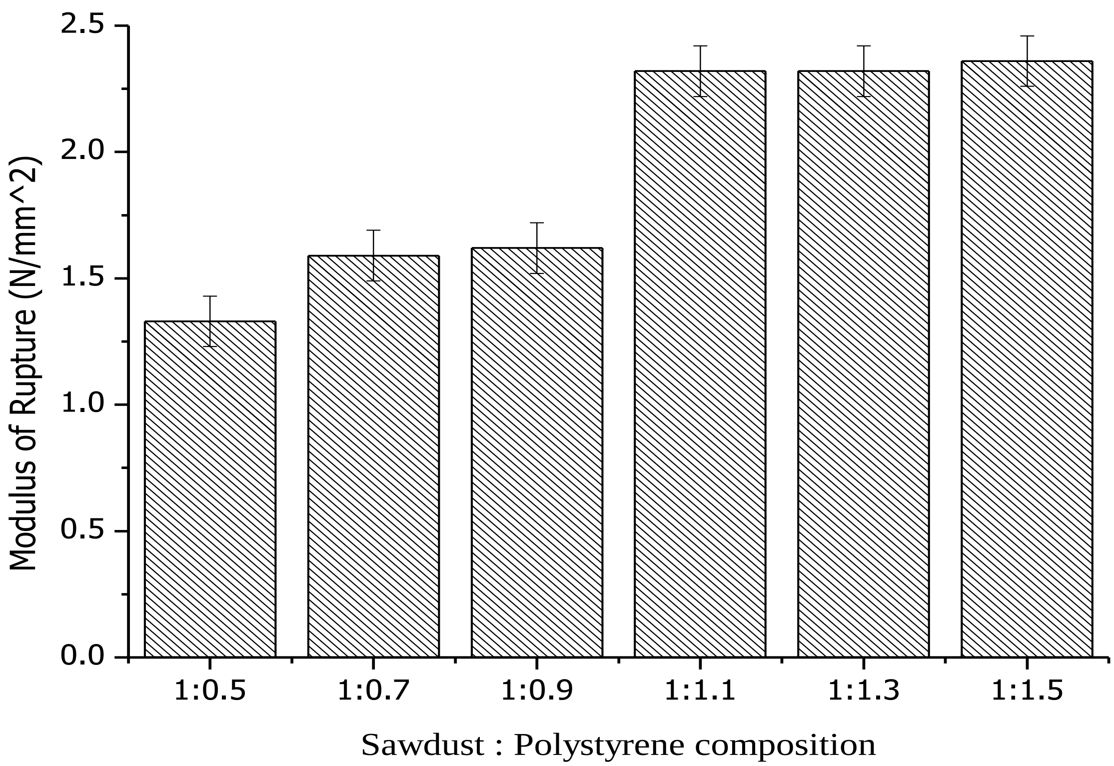

Figure 7. Modulus of rupture in PS/SD composites.

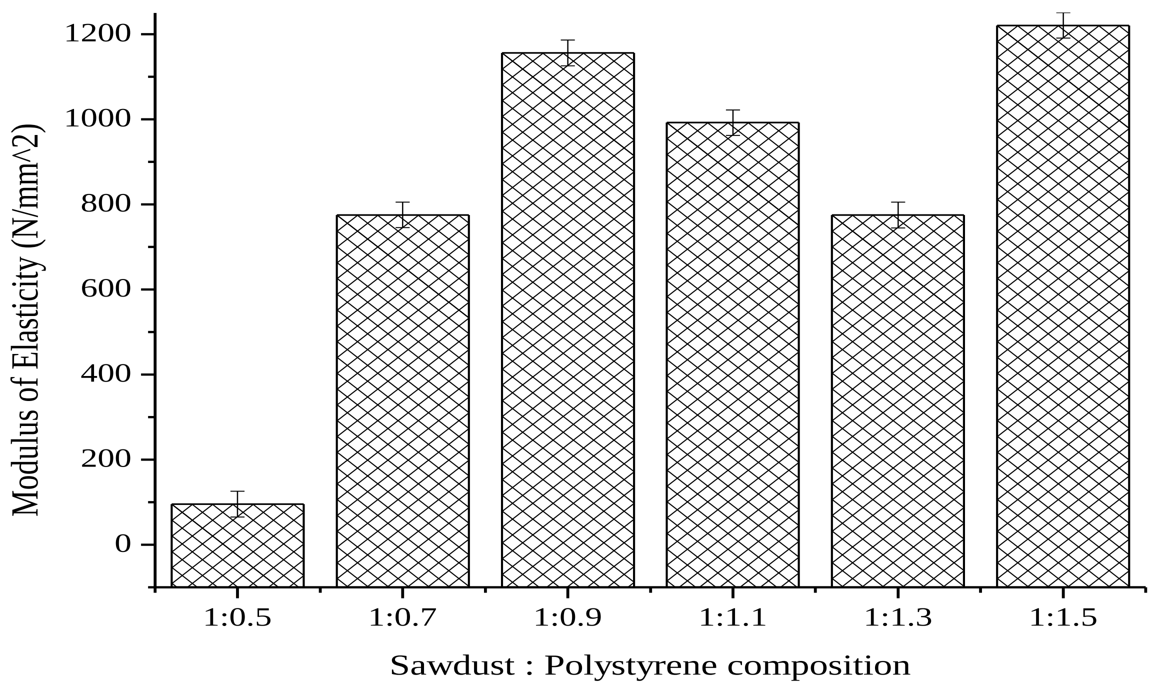

Figure 8. Modulus of elasticity of PS/SD composites.

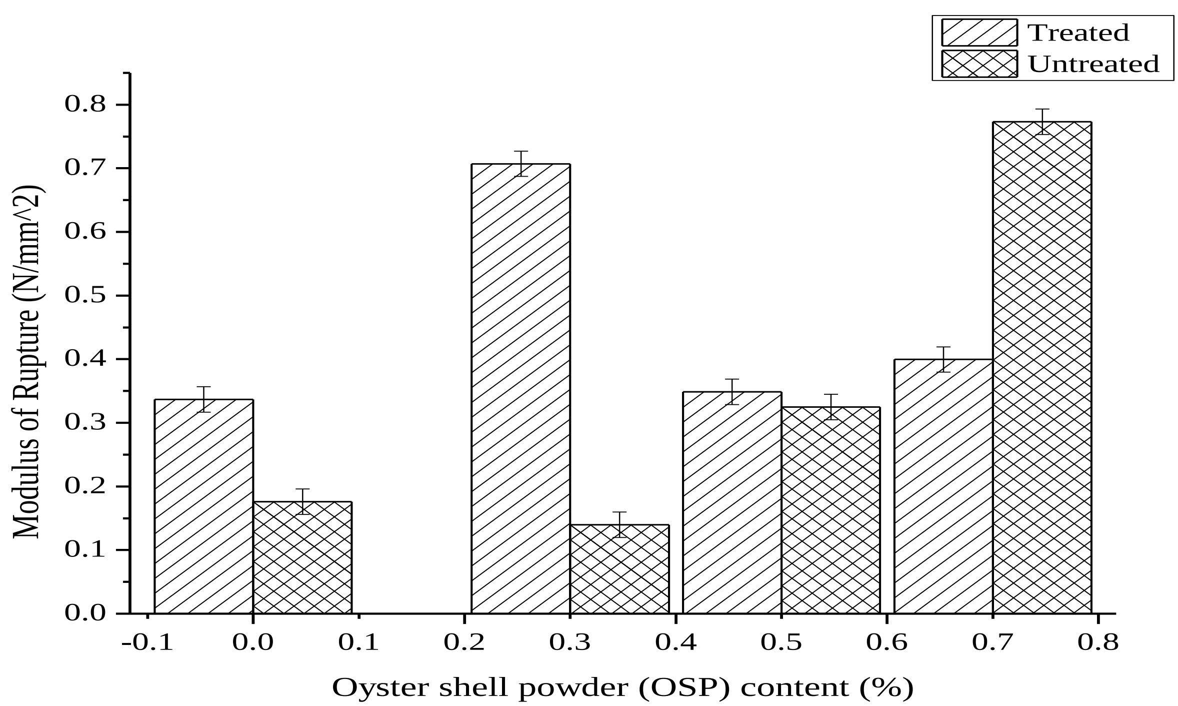

Figure 9. The rupture modulus against OSP loadings.

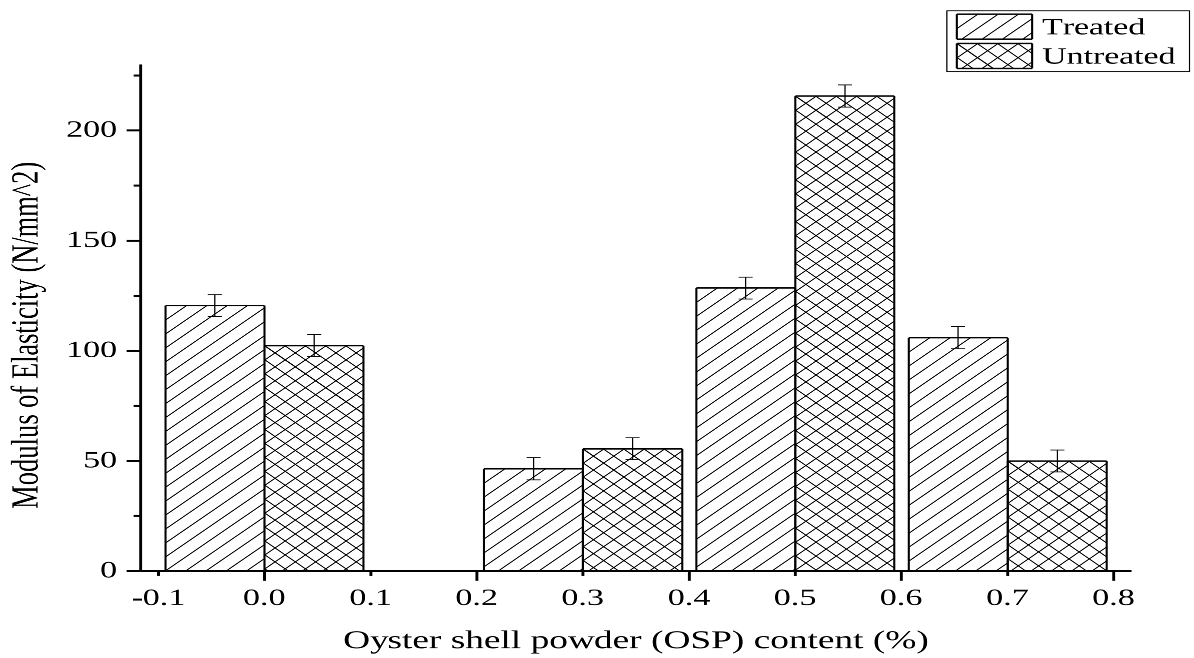

Figure 10. Modulus of elasticity against OSP loadings.

4. Conclusion

The preparation of composites from polystyrene plastic and sawdust was conducted for the first time. Different combinations of polystyrene and sawdust were prepared and the physical and mechanical properties were determined. Combination 1:1.3 demonstrated superior physical and mechanical properties compared to the counterparts. The best performing composite was further modified with oyster shell powder to enhance its properties. Physical and mechanical characterization was carried out to determine the influence of the preparation conditions on the material properties. The conditions included the use of sawdust fibers of the same particle size but with different chemical treatments. The first portion was left untreated, and the second portion was treated. The composites were further filled with oyster shell powder at ratios of 0.3%, 0.5%, and 0.7%. Hence, composites with untreated and treated sawdust components were separately filled with oyster shell powder at different ratios. The bulk density and water absorption of the composites were measured in the physical property determination. The tensile strength, rupture modulus, and elasticity were determined to determine the mechanical properties of the composites.

The data indicate that the treatment of the composites has a positive influence on the tensile strength, with the best tensile strength recorded at no OSP loading. It did not influence water absorption, Bulk density, modulus of rupture, or elasticity. Furthermore, the OSP loadings affected the material behavior in the measured properties. It enhanced the water absorption and modulus of elasticity at 0.5% loading and the bulk density and modulus of rupture at 0.7% loading; however, it marginally weakened the tensile strength of the treated and untreated composites compared to the best performing tensile strength at no OSP loading. The addition of OSP to the composite material is key to enhancing its physical and mechanical properties, even though it must be added at small proportions relative to the weight of the filler component of the composite.

Statements and declarations

Not applicable

Ethical considerations

Not applicable

Consent to participate

Not applicable

Consent to publish the study

Not applicable

Declaration of conflict of interest

The authors declare no potential conflicts of interest with respect to research, authorship, and publication of this article.

Funding statement

The authors disclose receipt of the following financial support for the research in this article: This work was supported by the CSIR-Research Grant [grant number 001/2022].

Data availability

The authors are willing to share the data if requested.

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