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Performance Evaluation of Novel Eco-Materials Composed of Millet Husks, Rice Husks, and Polystyrene

Paul Damien Amadji[1], Edem Chabi[2*], Valéry Kouandété Doko[1], Céphas Houndedji[1], Emmanuel Olodo[1]

[1]Laboratory of Applied Energy and Mechanics (LEMA), Polytechnic School of Abomey-Calavi, University of Abomey-Calavi, Abomey-Calavi, Benin
[2]Laboratory of Rural Engineering, School of Rural Engineering, National University of Agriculture, Kétou, Benin
Email: *edem.chabi@una.bj

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Abstract

Managing agricultural waste and expanded polystyrene (EPS) poses significant environmental and economic challenges. This study aims to create composites from millet husks, rice husks, and recycled EPS, using a manufacturing method that involves dissolving the polystyrene in a solvent followed by cold pressing. Various particle sizes and two binder dosages were investigated to assess their influence on the physico-mechanical properties of the composites. The mechanical properties obtained range from 2.54 to 4.47 MPa for the Modulus of Rupture (MOR) and from 686 to 1400 MPa for the Modulus of Elasticity in Bending (MOE). The results indicate that these composites have potential for applications in the construction sector, particularly for wood structures and interior decoration. Moreover, surface treatments could enhance their durability and mechanical properties. This research contributes to the valorization of agricultural and plastic waste as eco-friendly and economical construction materials.

Keywords

Bio-Based Composites, Millet Husk, Rice Husk, Expanded Polystyrene, Waste Valorization, Sustainable Construction

1. Introduction

Waste management is a critical issue on a global scale, affecting both natural ecosystems and economic resources. Among these wastes, those of agricultural origin, such as millet husks and rice husks, as well as plastic waste like polystyrene, pose particular challenges. These materials, often considered as by-products or waste, accumulate in the environment, contributing to various ecological problems.

In the construction sector, the urgency to find sustainable alternatives to traditional materials is increasingly felt. Although these materials are often considered waste, they have demonstrated utility in various research areas. For instance, rice husk ash, rich in silica, is commonly used as a partial substitute for cement due to its pozzolanic properties [1] [2] [3] [4]. There are also some exploratory studies on the use of millet husk ash in similar contexts [5] [6] [7].

Regarding the incorporation of these materials into polymer matrices, studies are scarce and diverse in terms of methodologies and outcomes. Gairola *et al.* [8] worked on polypropylene (PP) composites reinforced by husks of two types of millet: Finger Millet Husk (FMH) and Barnyard Millet Husk (BMH). Their composites were fabricated using an injection extrusion process with 10% weight of FMH and BMH. Wear properties were evaluated, and the results indicated a reduction in the specific wear rate, suggesting better adherence with the PP matrix. In another study, Hammajam *et al.* [9] examined the mechanical properties of high-density polyethylene (HDPE) composites reinforced by millet husk fibers. The fibers were pulverized into three different sizes, and the composites were prepared using an internal mixer, followed by a compression molding process. Various fiber loadings were studied, and it was found that tensile strength varied with fiber size and loading.

The use of expanded polystyrene as a polymer matrix is seldom documented. Abdulkareem et Adeniyi [10] developed plastic composites reinforced by rice husks from melted polystyrene waste in an unspecified solvent. The resulting composites showed improved mechanical properties, including a maximum Young's modulus of 365 MPa. Choi *et al.* [11] also worked on composites of rice husks and expanded polystyrene, using a styrene solution as a binder with the addition of Trimethylolpropane Trimethacrylate (TMPTMA) and Benzoyl Peroxide (BPO) as cross-linking agents and initiators, respectively.

Although some work has examined the employment of these wastes in polymer composites, their use remains relatively uncommon, particularly with expanded polystyrene as the matrix. The purpose of this study is to investigate the utilization of these agricultural wastes in a melted polystyrene matrix. We aim to study the influence of various parameters on the physico-mechanical properties of the composites, with a view to offering an eco-friendly and economical alternative to conventional construction materials.

2. Materials and Methods

2.1. Millet Husks and Rice Husks

Millet husks and rice husks serve as the primary reinforcement elements in the fabrication of millet husk-rice husk-polystyrene composite panels. To prepare these materials for incorporation, several processing steps were performed. First, the millet husks and rice husks were ground using a mechanical grinder to achieve a suitable particle size. Then, the ground materials were dried in an oven at a controlled temperature to eliminate any residual moisture. After drying, the materials were sieved to separate them into different granular classes. Table 1 shows the different granular classes obtained after this sieving process.

Table 1. Granular classes of materials.

Particle Size	Coarse Mixture	Fine Mixture
Retained on 1.250 mm sieve	40%	10%
Retained on 0.630 mm sieve	30%	20%
Retained on 0.315 mm sieve	20%	30%
Retained on 0.160 mm sieve	10%	40%

2.2. Expanded Polystyrene

The expanded polystyrene (EPS) used in this study was sourced from recovered packaging materials. This choice is motivated by the fact that EPS is frequently neglected and discarded in landfill sites or natural settings, thus posing significant environmental challenges. The use of EPS waste as a matrix in the composites aims to valorize this material while helping to mitigate challenges related to its waste management.

2.3. Binder Preparation

For the making of composites, a binder is prepared by dissolving expanded polystyrene in an organic solvent, specifically gasoline in this study. The process revolves around the gradual incorporation of polystyrene into the solvent, followed by mixing until a homogeneous adhesive material is obtained.

The optimal amount of solvent needed to dissolve the polystyrene is defined by the ratio k, which is formulated as follows:

$$k = \frac{\text{mass of solvent}}{\text{mass of polystyrene}}$$

This ratio was optimized through a series of experiments. An amount of solvent was weighed and mixed with the polystyrene until the complete evaporation of the solvent. The mass of the dissolved polystyrene was noted, and the ideal k ratio determined is 1.4.

The viscosity of the binder is closely linked to the value of k. A k less than 1.4 results in an insufficient amount of solvent for the complete dissolution of polystyrene, resulting in a pasty binder, high viscosity, and the presence of polystyrene residues. Conversely, a k greater than 1.4 results in an excess of solvent, which decreases the viscosity of the binder and compromises its effectiveness in holding the reinforcement particles in place.

2.4. Composite Formulation

In this study, two specific binder proportions were selected from preliminary experimental cycles. These proportions are expressed in terms of dosage *d*, formulated as follows:

$$d = \frac{\text{mass of binder}}{\text{mass of rice husk}}$$

The selected dosage values are 0.8 and 1. These proportions were adjusted to minimize structural defects such as crumbling while maximizing the homogeneity of the composites.

It's important to note that each composite is made up of 50% millet husk and 50% rice husk in terms of the total mass of the reinforcement. Thus, the final composite is a combination of millet husk, rice husk, and expanded polystyrene.

To facilitate references in this study, composites will be coded according to their dosage and the granulometry of the rice husks, as per **Table 2**.

Table 2. Composite coding based on granulometry and dosage.

Mixture	Code	Dosage
Fine	MF0.8	0.8
	MF1	1
Coarse	MG0.8	0.8
	MG1	1

2.5. Composite Implementation

- **Preparation of millet husks and rice husks**

The raw materials, millet husks and rice husks, are first dried in an oven until a constant mass is obtained. Different granular classes are then weighed to form fine and coarse mixes based on experimental needs.

- **Mixing**

Mixing is a key step to ensure a uniform distribution of rice husks and millet husks in the polystyrene polymer matrix. Effective mixing is necessary to obtain a homogeneous composite.

- **Specimen fabrication**

To fabricate the composite plates, a cold compaction process is used. The mixture of millet husks and rice husks, previously prepared, is combined with the polystyrene-based binder. This mixture is then poured into a metallic mold specially designed for this study.

The compaction is carried out using a hydraulic press. This method ensures a uniform distribution of pressure across the entire mixture, crucial for obtaining a homogeneous composite. The pressure is gradually increased to avoid complications such as the leakage of the polymer matrix or compromising the structural integrity of the composite. Once a stable pressure level is reached, it serves as an indicator that the mixture has reached satisfactory homogeneity (**Figure 1**).

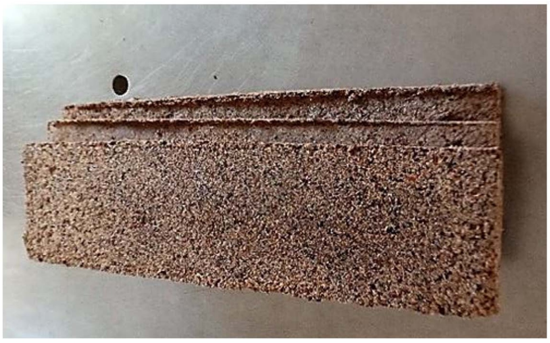

Figure 1. Plate obtained after compaction.

After compaction, the plates are removed from the mold and left to dry at room temperature. They are weighed every 8 hours until a constant mass is reached, indicating their maturity and the complete evaporation of residual solvents.

The plates are then machined to dimensions of 11 mm in thickness, 76 mm in width, and 314 mm in length, as shown in **Figure 2**. These specimens will then be used for three-point bending tests to determine the modulus of elasticity and the stress at static bending failure [12].

3. Results and Discussions

3.1. Physical Properties of the Composites

Table 3 below presents the results of the physical tests performed on the composites. The data shows notable variations between the composites, suggesting that the particle size and binder dosage could have a significant impact on the physical properties of these materials.

3.1.1. Mass Loss of Composites

The analysis of mass loss in the composites shows a complex dynamic influenced by particle size and binder dosage (**Figure 3**). Most of the mass loss occurs in the first 48 hours, reaching 80% of the total loss. After 96 hours, the mass of the composites no longer varies, or very little, indicating that the mass loss process has reached a stable state.

Fine-grain composites show a higher total mass loss, despite initially slower loss rates. This observation is not entirely explained by solvent evaporation and could involve other chemical or physical interactions that require further investigation. Coarse-grain composites lose weight more quickly in the first 24 hours, possibly due to their lesser ability to retain the solvent.

As for the effect of binder dosage, it is interesting to note that although the variations between different dosages are not drastic, they are nevertheless present. A slight increase in mass loss is observed when the binder dosage increases from 0.8 to 1. This variation, although limited in this study, could be due to better material cohesion, which allows for more controlled evaporation of volatile components.

Figure 2. Machined plates.

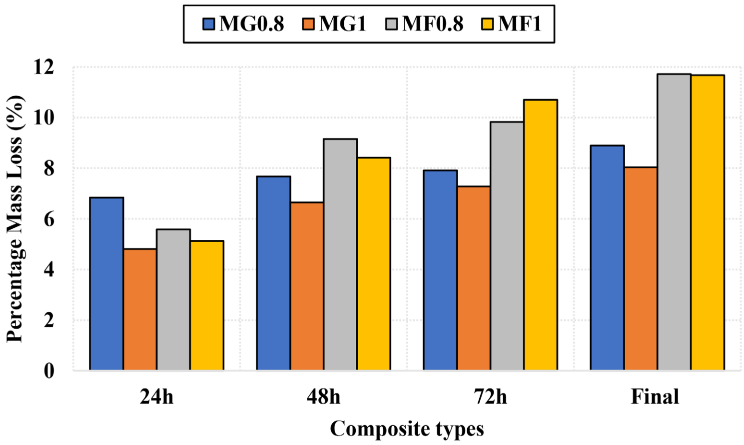

Figure 3. Mass loss of composites over time.

Table 3. Physical properties of the composites.

Composites	Mass loss (%)	Density (kg·m^{-3})	Water absorption	Swelling (%)			
				Thickness	Length	Width	Volumetric
MG0.8	8.89	0.731 ± 0.006	62.15	13.16	3.34	3.14	20.61
MF0.8	11.72	0.851 ± 0.010	66.60	22.80	3.82	3.02	31.53
MG1	8.03	0.903 ± 0.009	65.65	19.30	3.98	3.01	30.30
MF1	11.68	0.934 ± 0.012	69.88	38.60	3.47	3.02	48.23

Understanding these mechanisms is crucial for the future optimization of these materials, with a view to minimizing losses and improving durability.

3.1.2. Density of the Composites

Figure 4 above illustrates the variations in composite density based on particle size and binder dosage. Significant differences are observed depending on particle size and binder dosage. The density increases with the addition of binder,

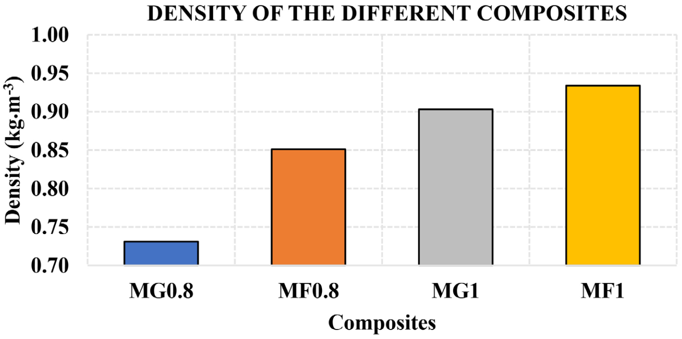

Figure 4. Variation in density based on composite type.

going from 0.731 kg·m^{-3} for MG0.8 to 0.903 kg·m^{-3} for MG1, and from 0.851 kg·m^{-3} for MF0.8 to 0.934 kg·m^{-3} for MF1. This increase is likely due to a larger amount of binder material, contributing to a denser composite structure by filling the interstitial spaces between the reinforcing particles.

Moreover, fine-grain composites exhibit higher density than coarse-grain composites. This difference could be attributed to the better compacting ability of fine particles, resulting in higher density.

3.1.3. Swelling of the Composites

The objective of this swelling test on composites is to understand how these materials react when exposed to water. This is particularly important for assessing their durability and applicability in environments where they may come into contact with moisture or water. Swelling can indicate water absorption, which in turn could affect the mechanical properties and structural stability of the composite.

Thickness Swelling: The swelling in thickness is significantly greater than the swelling in length and width for all tested composites. This could be explained by the structure of the composites: millet husks and rice hulls are generally aligned in the thickness direction during the manufacturing process, which could facilitate water absorption in this direction.

For the fine-grained composites, the increase in thickness swelling is even more pronounced. A finer particle size results in a larger specific surface area, which could increase water absorption. The relationship between water retention, absorption, and swelling is tight: better water retention can lead to greater absorption and thus greater swelling.

Length and Width Swelling: The swelling in length and width is relatively low for all composites, regardless of particle size or binder dosage. The orientation of particles in the composite could influence these swelling dimensions.

Influence of Binder Dosage: Contrary to initial intuition that more binder would result in less swelling due to better adhesion, the data shows an increase in swelling with higher binder dosages. Although polystyrene itself is not hydrophilic, this trend could be explained by changes in the composite structure, such as the size of the spaces between particles. Microstructure analyses could help confirm or refute this hypothesis.

Overall Interpretation: The MG composites seem to absorb more water, which could be due to a more porous structure, allowing water to penetrate more easily and cause more significant swelling. On the other hand, the MF composites seem to be less affected by water immersion, suggesting a denser polymer matrix or better adhesion around the fine particles, thereby limiting absorption.

Figure 5 provides a clear and concise visual representation of these results, greatly facilitating their understanding.

3.2. Mechanical Properties of the Composites

Table 4 presents the results of the mechanical tests conducted on the composites. The mechanical properties of the composites are evaluated in terms of Modulus of Rupture in Bending (MOR), Flexural Rigidity Coefficient (K), and Modulus of Elasticity in Bending (MOE).

For a more detailed graphical analysis, the mechanical properties of the composites are represented in Figure 6, where variations in MOR and MOE for different composites can be observed.

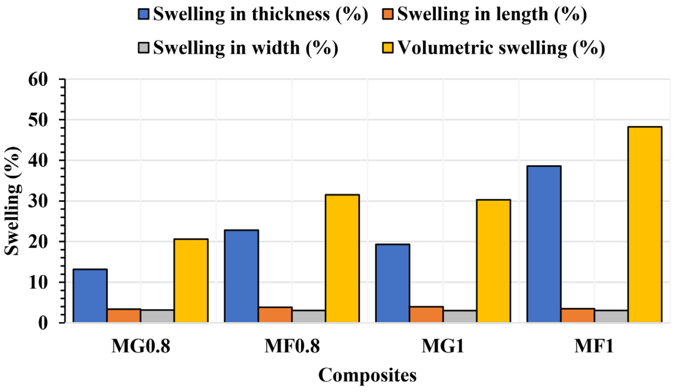

Figure 5. Swelling behavior of composites after 24-hour water immersion.

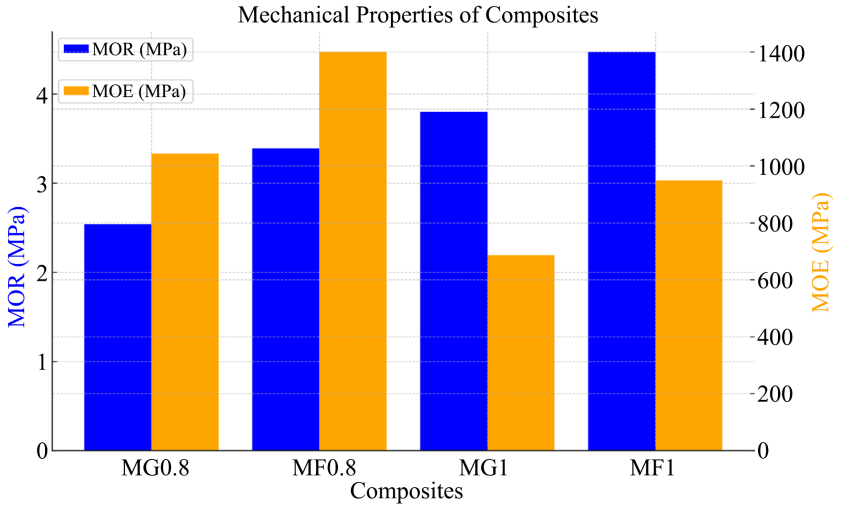

Figure 6. Comparision of mechanical properties of the composites.

Table 4. Mechanical properties of the composites.

Composite	MOR (MPa)	K (N/mm)	E (MPa)
MG0.8	2.54 ± 0.07	22.97 ± 0.47	1044.22 ± 40.70
MF0.8	3.39 ± 0.08	30.80 ± 0.77	1400.11 ± 53.89
MG1	3.80 ± 0.08	15.15 ± 0.27	686.37 ± 28.49
MF1	4.47 ± 0.10	20.92 ± 0.60	948.74 ± 27.33

Fine-grained composites display a higher Modulus of Rupture in Bending (MOR) and Modulus of Elasticity in Bending (MOE) compared to those with coarse grain sizes. This can be attributed to better adhesion and distribution of the fine particles within the matrix, thereby increasing rupture resistance. However, this trend is not necessarily reflected in the Flexural Rigidity Coefficient (K), indicating that other factors may be at play.

As for the influence of binder dosage, special attention must be given to this parameter's impact, even if the variations are not drastic. Composites with a binder dosage of 1 generally show higher MOR and MOE compared to those with a dosage of 0.8. This observation could be explained by better cohesion of particles at higher binder dosages. However, this trend is limited to the dosages examined in this study.

When comparing the composites in this study with those available in the literature, the MOR and MOE values are generally lower. The composites studied here have MOR values ranging from 2.54 to 4.47 MPa and MOE values from 686 to 1400 MPa. These values are lower than those reported in the literature for composites based on wood chips, bagasse, chili stems, and others [13]-[18], where MOR values can reach up to 35.84 MPa and MOE up to 3343.2 MPa.

Several factors can explain these differences. First, the type of binder used in this study, namely melted polystyrene, could have different adhesion properties compared to more commonly used resins such as Urea Formaldehyde or Phenol Formaldehyde. It should be noted that some commonly used binders, such as formaldehyde, pose health and environmental risks. Second, the cold manufacturing method could also influence the mechanical properties.

Despite these more modest mechanical properties, these composites have potential applications in construction, especially for woodwork like ceilings and interior decoration. Using laminated coatings or other forms of surface treatment, the mechanical properties and durability of these composites could be significantly improved, thus expanding their utility in carpentry for elements such as furniture and doors.

4. Conclusions

Effective management of agricultural waste and plastics is a contemporary environmental and economic issue. This study examined the potential of millet and rice husks as reinforcements in composites based on melted polystyrene for applications in the construction sector.

The mechanical properties of the composites vary according to the particle size and binder dosage, with Modulus of Rupture in Bending (MOR) values ranging from 2.54 to 4.47 MPa and Modulus of Elasticity in Bending (MOE) values ranging from 686 to 1400 MPa. These variations indicate that particle size and binder dosage are factors to consider for composite optimization.

These results contribute to the global effort to valorize waste in the context of sustainable development and materials engineering. The observed properties open up perspectives for the use of composites in construction sectors such as interior decoration and certain types of woodwork. It should be noted that surface treatments such as coating and veneering can be applied to improve the durability and mechanical properties of these composites.

For future research, a more in-depth analysis of the long-term durability of the composites would be useful, as well as the exploration of other types of binders and manufacturing methods to further optimize the properties of the composites.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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