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Development and Characterization of a Composite Material Based on Recycled Polystyrene Reinforced with Coconut Fibers

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Abstract

Population growth is leding to an increase in waste generation in Côte d'Ivoire, particularly of coconut fibers and polystyrene waste. This study therefore proposes a solution for valorizing this waste by using it to create composite materials. To this end, coconut fibers were mixed with expanded polystyrene (EPS) resin in proportions ranging from 16.66% to 50%. The obtained samples were subjected to various characterization tests: drying time, density, water absorption, and flexural strength. The results show that the acetone evaporation rate increases with the EPS resin content. When this content increases from 16.66% to 50%, the density decreases slightly from 0.92 to 0.82 g/cm^3. Water absorption also decreases from 5.18% to 2.35% as the resin content rises from 16.66% to 50%. Bending strength increases from 16.9 MPa to 25.99 MPa as the EPS content varies from 16.66% to 33.33%, then decreases to 13.68 MPa at 50% EPS. This study shows that the developed composite is a promising solution for the valorization of coconut fibers and polystyrene waste, while offering properties suitable for certain applications in the construction industry.

Keywords

Composite, Waste, Expanded Polystyrene, Coconut Fibers

1. Introduction

Given the rapid growth of the global population, waste generation is currently one of the major environmental challenges facing modern societies. The accumulation of industrial waste, such as polystyrene, and agricultural waste, such as coconut

fibers, contributes to environmental pollution, thereby highlighting the need to develop effective waste valorization and recycling strategies.

The development of composite materials combining a polymer matrix with natural fibers therefore represents a promising approach for the valorization of these wastes. In this context, the present study aims to develop a composite material from waste-derived resources and to evaluate its main properties. This study thus aims to contribute to the simultaneous valorization of polystyrene waste and coconut fiber residues, while exploring their potential for the manufacture of composite materials intended for various applications.

2. Materials and Methods

2.1. Raw Materials

2.1.1. Coconut Fibers

Coconut fibers are derived from the mesocarp surrounding the coconut, the fruit of the coconut palm (Cocos nucifera). These fibers are obtained by processing coconut mesocarp. They were collected in the commune of Jacqueville (Ivory Coast). The mesocarp was first separated from the nut and then immersed in water for three weeks to facilitate fiber separation. After soaking, it was beaten with a piece of wood to release the fibers, which were subsequently extracted by combing. These fibers have a maximum length of 10 cm (Figure 1).



Figure 1. Coconut fiber.

2.1.2. Expanded Polystyrene

The expanded polystyrene (EPS) used in this study was collected from in front of home appliance stores in the municipality of Adjamé (Ivory Coast). It is used as

packaging for household appliances. After unpacking, it is discarded in the streets as waste, polluting the environment (Figure 2).



Figure 2. Polystyrene waste.

2.1.3. Acetone

Acetone is an organic solvent with the chemical formula C_3H_6O, produced by dehydrogenation of propan-2-ol in the liquid phase and by the fermentation of agricultural waste [1]. Due to the low health risks associated with acetone [2] [3] and its ability to dissolve numerous organic compounds and some plastics, acetone is widely used in the laboratory. For our work, we used commercial acetone to dissolve the polystyrene and obtain a resin.

2.2. Formulation

To prepare the materials, dried coconut fibers and polystyrene resin were mixed in varying proportions. The polystyrene resin was obtained by maintaining the ratio of EPS mass to acetone volume constant at 0.80 kg/L. The amount of EPS used to produce the materials ranges from 16.33% to 50%. It should be noted that consolidated samples are obtained starting at a PSE resin content of 16.33%. After mixing the EPS resin and coconut fibers in a container, the mixture was kneaded to obtain a homogeneous composite. After kneading, the resulting composite was placed in a mold to give it the desired shape. The material was then compacted by placing a 20 kg weight on the mold for 5 minutes. This operation helps compact the mixture, improve the contact between the constituents, and reduce voids. At the end of the compaction process, the sample was removed from the mold and then dried. Drying was carried out in a well-ventilated area at room temperature for 4 to 5 weeks. After drying, the samples were thermoformed at a temperature of 160˚C for 20 minutes to obtain the composites on which the characterization tests were performed. The methodology adopted for the preparation of the materials is summarized in Figure 3. For each formulation, five independent samples were prepared and subjected to the various analyses. The curves presented in the "Results" section represent the mean values obtained from the five samples corresponding to each formulation.

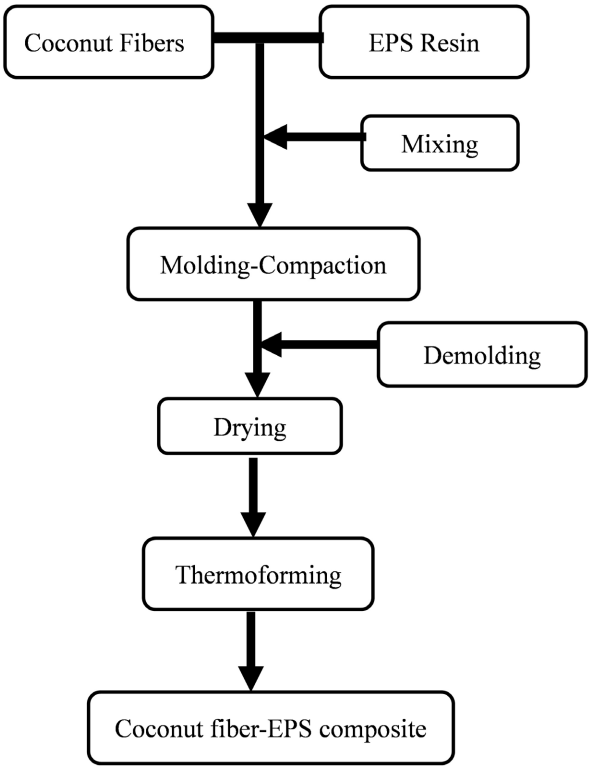

Figure 3. Composite manufacturing process.

The composites obtained are shown in **Figure 4**.

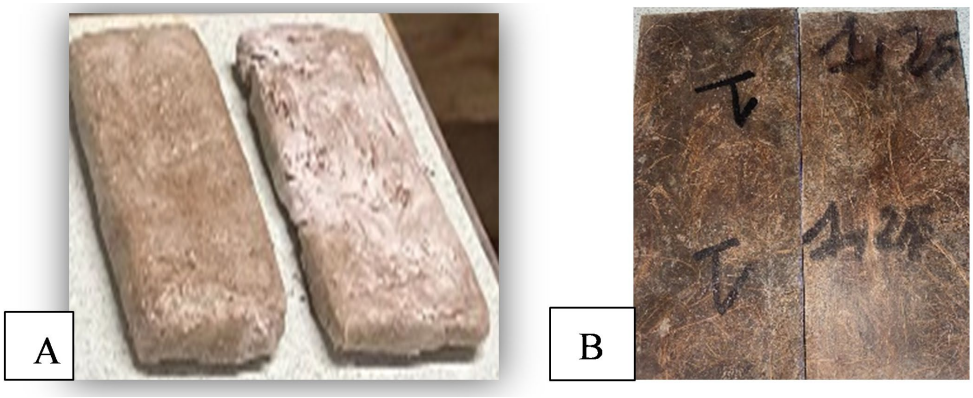

Figure 4. Materials obtained (A: Before thermoforming; B: After thermoforming).

2.3. Characterization of Composites

2.3.1. Determination of the Drying Rate

During drying, part of the acetone contained in the wet material evaporates. The departure of acetone causes a loss of mass in the sample. To control the departure of acetone from the composites and understand the influence of the resin and coconut fibers on the drying kinetics, daily variations in the mass of the composites were determined until a constant mass was obtained. The evaporation rate is then calculated using the formula 1:

$$E = \frac{w_j - w_s}{w_s} \times 100 \quad (1)$$

where:

E = evaporation rate (%); w_j = weigth of the sample on day j; w_s = weigth of the dry sample.

2.3.2. Density

After thermoforming, the samples are weighed. The dimensions are measured using a precision caliper with 0.01 mm resolution. The volume of the samples is calculated from their dimensions (length, width, thickness). The density is calculated using the following formula (2):

$$\rho = \frac{W}{V} \quad (2)$$

where: ρ is the density (g/cm^3), W is the weigth of the sample (g), and V is the volume of the sample (cm^3).

2.3.3. Water Absorption Test

Water infiltration into a material occurs through absorption. This absorption affects the durability of the material and is responsible for various types of damage, including mold and staining. The immersion water absorption test conducted in this study was carried out in accordance with the NBN B 15-215:1989 (2013) [4] standard. After thermoforming, the samples are weighed to obtain the dry weigth (w_s). The samples were then immersed in water for 24 hours (**Figure 5**). After 24 hours of immersion, the sample was weighed (w).

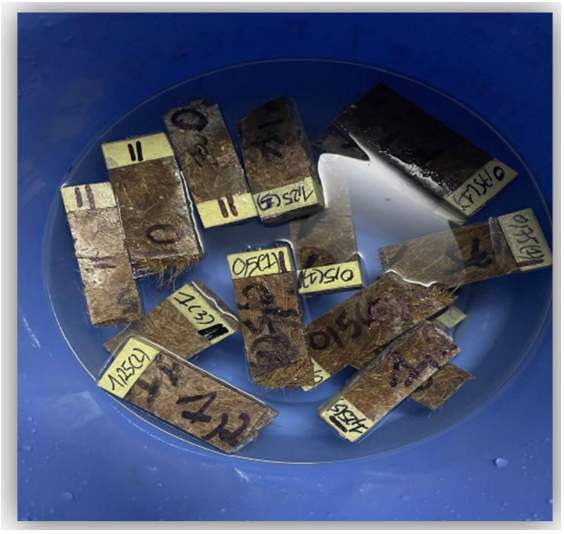

Figure 5. Samples immersed in water.

Water absorption by immersion is expressed as a percentage and is calculated using the following relationship (3):

$$w_{abs} = \frac{w_h - w_s}{w_s} \times 100 \quad (3)$$

where: w_{abs} is the rate of water absorption (%), m_h is the wet weigth after immersion (g), and m_s is the dry weigth (g).

2.3.4. Three-Point Bending Strength Tests

Knowledge of these properties is essential for structural applications where the material is subjected to bending loads. The bending test was performed on specimens measuring 20 × 10 × 1.9 cm^3 using a hydraulic press, in accordance with the NF B 51-008 (2017) [5] standard. The specimens to be characterized were placed on two simple supports separated by a distance L (Figure 6). A third support was positioned on the upper surface, midway between the two supporting points. Then, a progressive load was applied to the specimen using the press until failure occurred. The breaking load F is recorded. Bending strength is expressed in MPa and is given by Equation (4).

$$Rf = \frac{3FL}{2be^2} \tag{4}$$

where F = load measured at failure (N)

L = distance between the two support points (mm)

b = sample width (mm)

e = sample thickness (mm)



Figure 6. Bending test setup.

3. Results and Discussion

3.1. Acetone Evaporation during Drying

Figure 7 shows the variation in the acetone evaporation rate as a function of drying time. It shows that the evaporation rate varies over time, but also with the composition of the coconut fiber-polystyrene material.

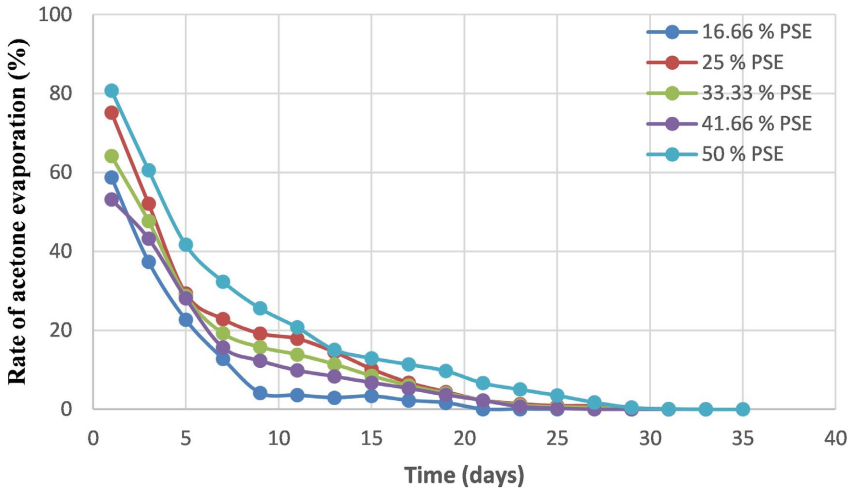

Figure 7. Evaporation rate as a function of time.

The evaporation rate during drying decreases regardless of the resin content of the EPS. The curve can be divided into three distinct regions:

- The first part is linear and corresponds to a rapid decrease in acetone content during the first five days.
- The second part, extending from the 5th to the 25th day, corresponds to the concave portion of the curve, where acetone evaporation gradually decreases over time.
- The third part, extending from the 25th to the 31st day, is characterized by a nearly zero slope and remains constant. Acetone evaporation is negligible, indicating that the samples are dry.

The drying curves exhibit three (3) phases, with different durations depending on the composition of the mixture. Drying is faster for samples with a low resin content. During the preparation of these samples, the low amount of resin was insufficient to properly impregnate the material, resulting in the formation of voids (pores). These voids provide pathways through which the acetone can escape during the drying process. This results in rapid evaporation of the acetone. As the resin content increases, the coconut fibers are better coated, making the material less porous. The acetone therefore remains trapped within the matrix and between the resin and the fibers, which slows down its evaporation. This explains the longer evaporation time observed for resin-rich samples.

From the 23rd day, some samples can be considered dry. However, the samples with a resin content of 16.66% require 25 days of drying, those with 25% require 29 days, while those with resin contents ranging from 33.33% to 50% require between 31 and 35 days of drying.

Similar results were obtained by some authors [6], who showed that the drying time of wood-EPS composites increases with increasing resin content.

3.2. Influence of EPS on the Density of the Composite

Figure 8 summarizes the results of the variation in the density of the composite

as a function of the EPS content.

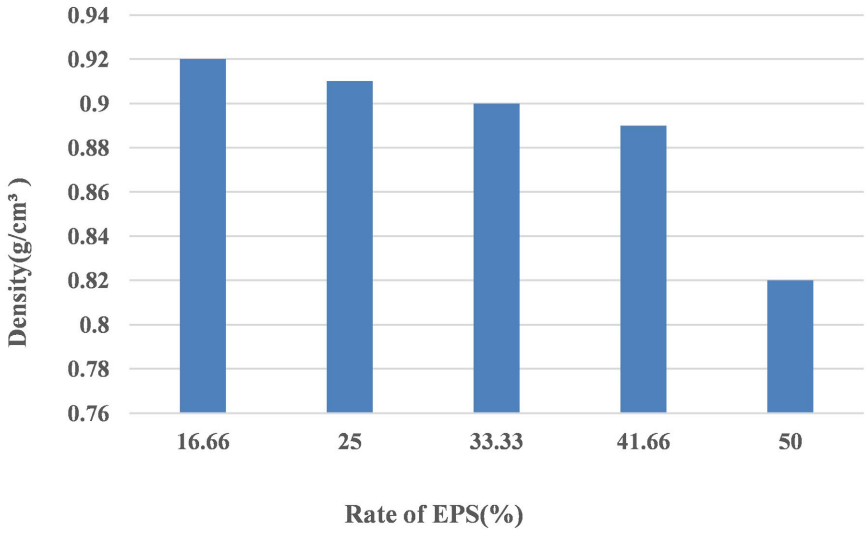

Figure 8. Density as a function of EPS resin.

This figure shows a gradual decrease in the density as the EPS resin content increases (from 16.66% to 50%). As the polystyrene resin content increases from 16.66% to 50%, the density decreases from 0.92 to 0.82 g/cm^3.

This decrease in the density of the composite is due to an increase in the EPS resin content (from 16.67% to 50%) in the mixture. Indeed, the density of the composites tends to approach that of the binder (EPS), which has a low density (0.75 g/cm^3). These results are similar to those of some authors [7] from their studies on composite materials based on fabric waste and EPS. He showed that the density of the material decreases as the binder content in the mixture increases.

The slight decrease in the density of the materials can be explained by the fact that the proportion of EPS resin (16.67% to 41.66%) is not sufficient to completely coat the coconut fibers in the mixture. The adhesion between the fibers is therefore limited, which promotes the formation of small voids within the material. The presence of these voids increases the volume of the composite without proportionally increasing its weigth, resulting in a slight decrease in the density of the material. Hence, the observed decrease in density is relatively small. The significant decrease in the density of the material from 41.66% to 50% EPS content is due to the higher resin content in the material, which makes it lighter.

The results of this study are consistent with those reported by some authors [8], who showed in his research that, during the production of eco-materials, the density decreases as the resin content increases.

3.3. Influence of EPS Resin on Water Absorption

Figure 9 shows the variation of water absorption as a function of the EPS resin content.

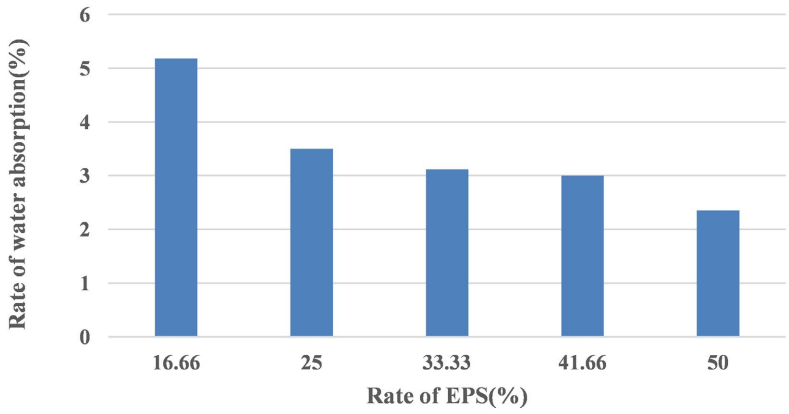

Figure 9. Evolution of absorption as a function of the EPS resin.

Increasing the resin content reduces the water absorption rate of the material. This decrease is related to the reduction in the number of pores in the material as the resin content increases. At a binder content of 16.66%, the material absorbs a large amount of water, approximately 5.1%. When the binder content increases from 16.66% to 25%, the water absorption rate decreases rapidly to 3.18%. From 25% to 50% binder content, the water absorption rate decreases from 3.18% to 2.35%. This trend can be explained by the hydrophilic nature of the plant fibers (coconut fibers) and the hydrophobic nature of the EPS resin. At a low resin content (16.66%), water absorption is high, and porosity is also high because the material is more porous and contains a large amount of fibers that attract water. Between 25% and 41.66% resin content, the resin better coats the fibers and fills the pores of the composite, making water penetration more difficult and reducing water absorption. Beyond 41.66%, as the resin content increases, the fibers become better coated, leading to a decrease in the porosity of the composite and consequently reducing its water absorption capacity. These results are consistent with the findings of some authors [9] [10], who demonstrated in their studies that water absorption depends on acetone evaporation, which generates voids within the material structure.

Some authors [11] [12] also confirmed these results in their studies, demonstrating that composite absorption increases significantly with the proportion of natural fibers used.

According to ASTM D570-22 (2022) [13], a material can be used as a partition or coating material if its water absorption is low and below 15%. Based on this standard, the composite obtained in this study can be used as a partition or coating material, since the water absorption values obtained in the test ranged from 2.35% to 5.18%. Similarly, according to the NF EN 14342(2013) [14] standard, the materials obtained can be used as floor coverings (parquet flooring), as this standard requires water absorption to be below 15%.

3.4. Influence of EPS Resin on Three-Point Bending Strength

Figure 10 shows the variation of strength as a function of the EPS content. This

curve shows that the strength increases with the resin content up to a certain threshold, after which it decreases. The strength increases from 16.9 MPa to 25.99 MPa as the EPS resin content increases from 16.66% to 33.33%. Then, it decreases from 25.99 to 13.68 MPa as the polystyrene content increases from 33.33% to 50%.

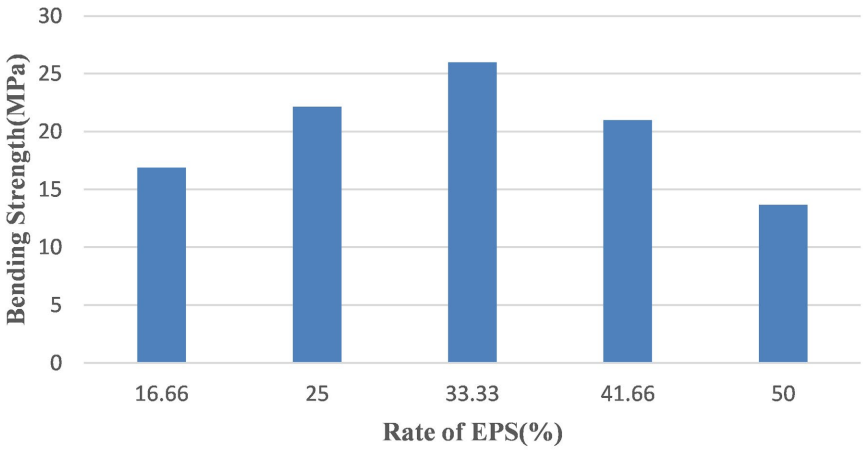

Figure 10. Variation of strength as a function of EPS.

Since the polystyrene resin content is low in the composite, it is difficult for the resin to adequately coat all the coconut fibers, resulting in the low strength observed at 16.33%. Poor or weak adhesion between the coconut fibers and the resin results in low material strength.

Increasing the EPS resin content in the material promotes better coating of the coconut fibers and progressively enhances the cohesion between the coconut fibers and the EPS resin, resulting in an increase in the strength of the composites.

The low strength observed at a resin content of 16.66% is consistent with the results reported by some authors [15] [16], who showed that a high fiber content makes wetting more difficult, resulting in reduced mechanical performance.

The increase in strength with increasing resin content is consistent with the results reported by some authors [17]-[19], who showed in their studies that bending strength increases with increasing binder content.

The decrease of bending strength between 33.33% and 50% EPS content can be attributed to the excess resin in the material. The resin increasingly surrounds the coconut fibers, reducing their reinforcing role. The load is then mainly borne by the resin, which is less resistant, thereby resulting in a decrease in the strength of the composite. These results are consistent with those reported by some authors [17] [20]-[23], who observed an increase of bending strength up to a certain threshold, followed by a decrease in strength as the LDPE content increased in the material.

According to the ASTM D790-07 (2008) [24] standard, a material can be used as a partition or coating material if its bending strength is greater than 5 MPa. Based on this standard the composite obtained can be used as a partition or cov-

ering material because the results obtained during the bending test are between 16.9% and 25.99%.

Furthermore, according to the NF EN 14342 (2013) [14] standard, a material may be used as flooring (parquet) if its flexural strength exceeds 15 MPa. Also based on this standard, the composite can be used as a partition or covering material because the results obtained during the bending test are between 16.9% and 25.99%.

4. Conclusions

With the aim of reducing environmental pollution caused by polystyrene and coconut fiber waste, this study was conducted by proposing a method for recycling these waste materials. In this study, coconut fibers and polystyrene were mixed in varying proportions to produce samples. The samples were prepared using a simple molding process, followed by thermoforming after drying.

The experimental results obtained in this study demonstrated that:

- the acetone evaporation rate increases with the EPS content.
- the density of the composites decreases as the resin content increases (from 0.92 g/cm^3 to 0.82 g/cm^3).
- water absorption gradually decreases from 5.18% to 2.35% as the EPS content ranges from 16.66% to 50%.
- bending strength increases from 16.9 to 25.99 MPa as the EPS content rises from 16.66% to 33.33%, then drops from 25.99 to 13.68 MPa as the PSE content increases from 33.33% to 50%.

The incorporation of coconut fibers into polystyrene therefore represents a promising solution for recycling coconut fibers and expanded polystyrene (EPS), thereby contributing to environmental improvement and promoting a healthier living environment. Furthermore, based on the results obtained, the polystyrene-fiber composite can be used as a construction material.

Author Contributions

Conceptualization: Brahiman TRAORE, Serge Pacome Kaho and Souleymane Sie SANOGO.

Methodology: Brahiman TRAORE, Serge Pacome KAHO, Souleymane Sié SANOGO, and Conand Honoré KOUAKOU.

Validation: Brahiman TRAORE, Serge Pacome KAHO, Conand Honoré KOUAKOU and Moro Olivier BOFFOE.

Supervision: Conand Honré KOUAKOU, Moro Olivier BOFFOUE and Edjikémé EMERUWA.

Conflicts of Interest

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

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