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Sustainable Composite Fabrication Using Waste Oyster Shells Through Additive Manufacturing Technology

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Keywords：Green Additive Manufacturing, Recycle Oyster Shell, Green Supply Chain.

ABSTRACT

Sustainable resources are one of the important aspects in maintaining the stability of nature. Nowadays, one of the major concerns is the development of recycled materials as additives or even substitutes for raw materials. This research aims to examine the possibility of using recycled materials in additive manufacturing (AM) in order to reduce the environmental impact. In this regard, oyster shells are considered as one of the wastes that can be utilized as a sustainable resource in the AM process. The current study involves the use of oyster shells and recycled clay as the feeding material for the 3D printer. The results revealed that the quality of fabricated products from recycled oyster shell raw materials was comparable to products made from conventional raw materials. The average flexural strength and compression strength of products fabricated through recycled material are 19.06 MPa and 429.57 kPa, respectively. In addition, this study also examines the impact of using recycled oyster shells on the green supply chain and its contribution to the circular economy. The utilization of recycled raw materials in the AM processes also positively impacts cost efficiency.

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INTRODUCTION

Additive Manufacturing (AM), also known as 3D printing has become one of the most popular and widely developed manufacturing technologies in recent times. There are seven classifications of AM technologies according to ASTM International standards. The Fused Deposition Modelling (FDM) basically involves melting of the material through a heated nozzle, and depositing it layer by layer on to the print bed. FDM is one of the most popular AM process with several advantages such as low production costs, relatively easy operation, and flexibility in printing various sizes and shapes (Abeykoon, Sri-Amphorn et al. 2020, Rajan, Samykano et al. 2022). Plastic base materials such as PLA, ABS, and PETG are the most common materials used in the FDM method (Menderes and Ipekci 2021). With the advancement in AM technologies, the process has also been developed for various other kinds of raw materials such as ceramic (Romario, Bhat et al. 2024), metal (Jiang, Romario et al. 2023) and also clay.The advantages of these technologies drive significant improvements in both printing speed and precision (Jiang, Romario et al. 2023).

The fabrication process is carried out by adding clay material layer by layer to form the desired model. (Chaari, Abdelfatah et al. 2022, Alonso Madrid, Sotorrío Ortega et al. 2023). Thus, the recycled materials in the form of additives for clay can be used for fabrication. The use of recycled raw materials in the AM manufacturing process can provide benefits in terms of production efficiency and sustainability (Romani, Rognoli et al. 2021) but still has a high level of precision and product (Sanchez, Boudaoud et al. 2020).

Oyster shell waste is an organic waste, produced by the fishing industry and can be a source of environmental pollution. However, with the natural ingredients contained, oyster shells have the potential to be recycled materials which still have many benefits

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(H. Silva, Mesquita-Guimarães et al. 2019).

The addition of recycled oyster shell raw materials in clay can reduce waste, thereby reducing environmental impact and reducing production costs (de Alvarenga, Galindro et al. 2012, Liu, Zhang et al. 2022). In addition, the use of oyster shell waste can generate a circular economy and green supply chain. (Fellner and Brunner 2022, Ferreira, Oliveira et al. 2023) The use of oyster shell raw materials can also provide economic benefits in terms of 3D printed products. This study explores the use of oyster shells as a recycled raw material in FDM based products whose mechanical properties are being analyzed.

METHOD AND MATERIALS

FABRICATION METHOD

The research process for exploring the use of FDM additive manufacturing with a clay and recycled oyster shell mixture begins with material characterization as shown in Figure 1. It is followed by crushing and checking the diameter of the oyster shells to achieve the desired size. The size of the oyster shell must be below 0.3 mm to avoid nozzle clogging. The crushed oyster shells are then mixed with clay in the desired proportions before printing. The recycled oyster shell composition comprises 30% of its makeup, while the remaining 70% is made up of clay. The two materials require the addition of water for effective mixing. The quantity of water used affects the viscosity of the raw material. The ideal viscosity range for this 3D printing lies between 9000 Pa.s and 14000 Pa.s. (Gunduz, McClain et al. 2018).

In the fabrication process, nozzle speed and material extrusion speed are important parameters that need optimization to ensure the best print quality. Once fabricated, the printed part will be left to dry in the air for 24 hours to remove residual water content. After drying, the part is sintered. The sintering process is conducted at a constant temperature of 1250°C. The process starts with an initial ramp-up phase, during which the temperature gradually increases to the desired sintering temperature of 1250°C. Once the target temperature is reached, it is maintained for two hours to allow for the densification and bonding of the particles. After the sintering duration, the furnace is gradually cooled down to room temperature to increase the part's strength and durability. Figure 1 shows the fabrication flowchart for this research.

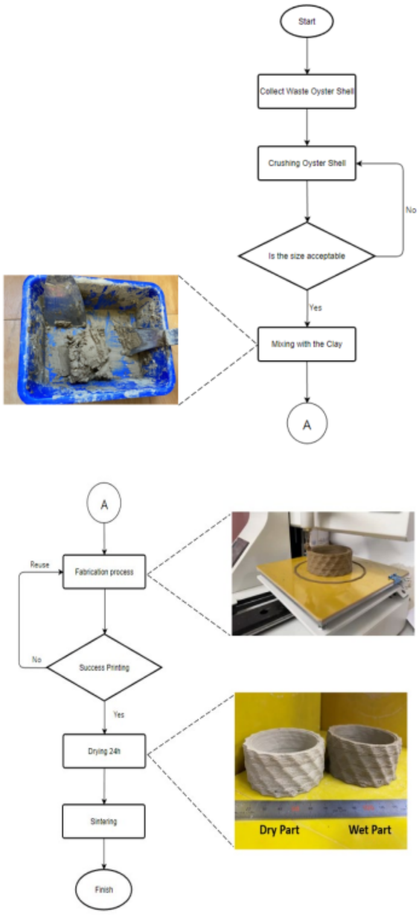


Fig. 1. Fabrication process flowchart.

MICROSTRUCTURAL ANALYSIS

The measurement of the recycled oyster shell size after ball milling, and the observation of the microstructure of the printed part after sintering are conducted using a field emission scanning electron microscope (FE-SEM JSM-7610F, Tokyo, Japan).

MECHANICAL PROPERTY OF SINTERING PART

The flexural strength and compression strength of the sintered part are measured using three-point bending and compression test, respectively. To comply with the ASTM standards, five specimens with dimensions of 2 mm x 1.5 mm x 25 mm are used, and the span length is set to 20 mm. The pressure probe moves down at a speed of 0.1 mm/min. Equation (1) is used to measure the flexural strength of the sintered part. where F is the load at a point, L is the span length, and b and d represented the width and depth of the material.

$$\sigma = \frac{3FL}{2bd^2} \qquad (1)$$

In this study, a universal testing machine (Universal Testing Machine CY-20, Chun-Yen Co., Taichung, Taiwan) is used to conduct compression tests and the flexural strength analyzes. Five specimens of sintered parts, each with a diameter of 12.7 mm and a height of 25.4 mm are used for compression test. The test was conducted at a loading speed of 0.5 mm/min to ensure consistent loading conditions.

TOTAL COST ANALYSIS

Cost analysis is an important and necessary analysis to determine the impact of recycled oyster shells on production cost. Total additive manufacturing production cost includes several aspects such as the cost of raw materials, equipment, labor, energy, and maintenance (Hopkinson and Dicknes 2003). Equation (2) is used to calculate the total cost analysis of additive manufacturing.

$$C_{am} = C_m + C_l + C_e + C_{eq} \qquad (2)$$

where C_{am}, C_m, C_l, C_e, and C_{eq} are the cost of additive manufacturing, material cost, labor cost, energy cost, and equipment cost, respectively.

Table 1. Calculation of additive manufacturing cost

Subject		Cost of Additive Manufacturing	
		Variable	Obtained by
Total part per platform		N	Possible printing part in platform
Total build time		T	Total time to build part
Material Cost	Material per part (kg)	PW	Part weight
	Material cost per kg (NTD)	CP	Quote
	Total Material cost per part (NTD)	Cm	PW x CP
Labour Cost	Operator cost per hour (NTD)	Op	Minimum wage
	Set up time (hour)	St	Time to Set up
	Post processing time (hour)	Pot	Time to Post process
	Labour cost per part	Cl	((St+Pot) x T x Op) / N
Energy Cost	Cost/ Kwh (NTD)	Ck	Electric cost
	Energy consumption per hour (watt)	W	Machine specification
	Total cost Energy per part (NTD)	Ce	Ck x W
Equipment Cost	Production rate per hour	Pr	N/T
	Production volume total per year	Pv	(5*52*24*80%)*Pr
	Machine Cost (NTD)	Mc	Machine purchase cost
	Depreciation per year (NTD)	D	Mc/8
	Maintenance cost per year (NTD)	Mt	Mc*5%
	Total machine cost per part (NTD)	Ceq	(D+Mt)/Pv
Total Cost per part (NTD)		Cam	Cm + Cl + Ce + Ceq

Table 1 shows all the variables that are required to calculated the cost of additive manufacturing. Material cost is the combination of all materials used in the manufacturing process. In this research the cost comes from the price of clay mixed with oyster shell. Regarding the labor cost, the average standard hourly cost for unskilled workers in Taiwan is NT$172/ hour. In this research, minimum labor wage is considered while evaluating the cost of additive manufactured components. This is because the workers are only required to set up machines as well as to scrap out objects that have been fabricated. For energy cost, the total cost of energy needed for the fabrication process is calculated. Equipment costs include the costs incurred to prepare the tools needed in the production process such as 3d printing machine, and other tools. The maintenance cost is considered by calculating 5% of the price of the machine.

The percentage of cost efficiency shown in equation (3) is calculated by comparing the total cost of product fabrication by traditional method with the total cost by additive manufacturing.

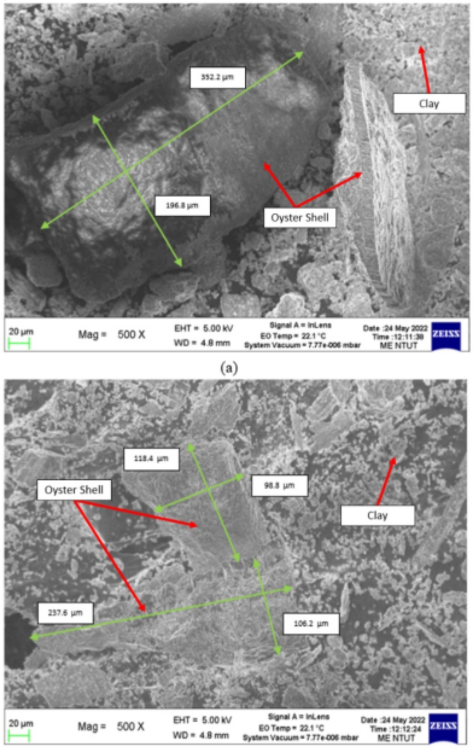
$$C_{ef} = \frac{C_{am} - C_{gam}}{C_{am}} \times 100\% \qquad (3)$$

where C_{ef} is cost efficiency and C_{gam} is the cost of the green additive manufacturing.

RESULTS AND DISCUSSION

RECYCLE OYSTER SHELL MEASUREMENT

The results of the SEM analysis showed a significant reduction in the size of the recycled oyster shell particles after ball milling. Figure 2a shows the initial dimension of the oyster shell particles after rough crushing. However, after ball milling, the particle size was reduced below 300µm. The reduction in particle size is attributed to the impact of the milling balls on the oyster shell particles, resulting in the fragmentation and breakdown of the shell into smaller particles.



(a)

(b)

Fig. 2. SEM images of the recycled oyster shell: (a) after rough crushing (b) after ball milling

Small particle sizes can cause agglomeration and increase packing density, thereby improving the mechanical properties of the printed product (Hu, Zhong et al. 2023). Furthermore, the small particle size can also prevent clogging of the nozzle. Therefore, choosing the nozzle diameter is very important to ensure smooth printing of the product.

COMPRESSION AND FLEXURAL STRENGTH

The compression and flexural tests were conducted to evaluate the mechanical properties of the recycled oyster shell material. Figure 3 shows the compression result of the clay-recycle oyster shell. The average compression strength obtained from the five specimens was 429.57 kPa, which is relatively high compared to previous research (Khan, Azam et al. 2014, Wang, Xue et al. 2021). The compressive strength of pure clay can vary depending on factors such as clay content and the addition of strengthening materials. Therefore, the compression test result indicates that the recycle oyster shell has effect on the clay nature strength.

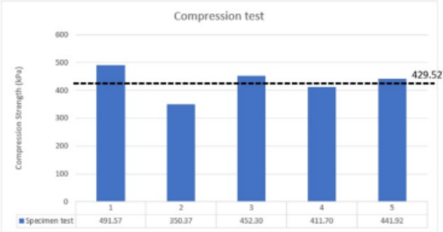


Fig. 3. Compression test result

Figure 4. shows the flexural strength of the samples fabricated with clay-recycled oyster shell material. The average result of the flexural strength is 19.06 MPa. The addition of recycled oyster shells to clay contributes to an increase in the mechanical properties of the printed material compared to pure clay. This strength enhancement is because of oyster shells which contain calcium carbonate (Hu, Zhong et al. 2023). The results indicate that the use of recycled oyster shells is not only environmentally friendly but also helps to improve the mechanical properties of the printed material.

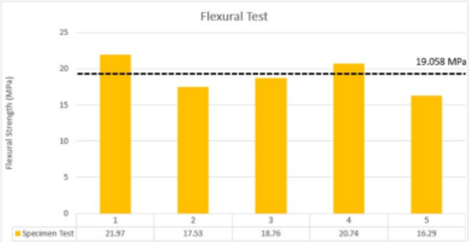


Fig. 4. Flexural test result

POTENTIAL USE OF CLAY OYSTER SHELL

The study showed that the flexural strength and compression properties of the 3D printed parts using recycled oyster shell and clay mixture were promising. These mechanical properties make the printed parts suitable for various applications, such as architectural structures, construction, and decorative purposes (Sangiorgio, Parisi et al. 2022).

Fig. 5. Printed parts of the recycle oyster shell and clay

The use of this waste material can reduce the demand for virgin resources, and minimize the amount of waste sent to landfills. By utilizing waste material as a resource, additive manufacturing can reduce the environmental impact associated with traditional manufacturing processes (Yang and Zhao 2021). Additive manufacturing using recycled oyster shell as a raw material can contribute to the circular economy, which aims to keep resources in use for as long as possible (Ponis, Aretoulaki et al. 2021) .

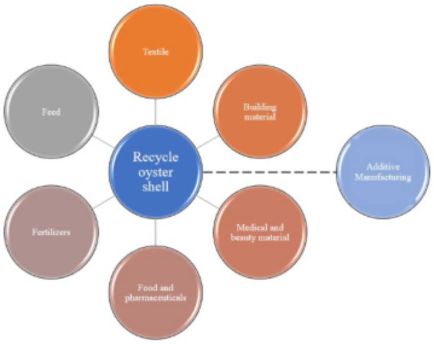


Fig. 6. Circular economy diagram of recycle oyster shell

The use of recycled oyster shells in additive manufacturing has the potential to create a closed-loop system, where waste from one industry becomes a resource for another. In this case, the oyster shells have several benefits and positive impacts on the circular economy. Figure 6 shows that the use of recycled oyster shell raw materials can be used as textile materials, animal feed, fertilizers, building materials, additives in medicines, and cosmetics (H. Silva, Mesquita-Guimarães et al. 2019). In this study the use of oyster shells as a raw material for additive manufacturing fabrication is proposed. Furthermore, the circular economy can also generate economic benefits. The use of recycled oyster shells can lower the cost of raw materials and reduce waste management costs.

ANALYSIS OF COST EFFICIENCY

Table 2, Table 3, and Table 4 presents a comprehensive analysis comparing various parameters and fabrication costs for both additive manufacturing (using only clay) and green additive manufacturing techniques (using clay and oyster shell waste).

Table 2. Detail cost breakdown for part A

Part	Subject		Additive Manufacturing	Green Additi Manufacturi
A  **dimension** **68 mm x 65 mm x 78mm**	Total part per platform		4	4
	Total build time		1.03	1.03
	Material Cost	Material per part (kg)	0.13	0.13
		Material cost per kg (NTD)	60	42
		Total Material cost per part (NTD)	7.70	5.39
	Labour Cost	Operator cost per hour (NTD)	172.00	172.00
		Set up time (hour)	0.08	0.08
		Post processing time (hour)	0.03	0.03
		Labour cost per part (NTD)	5.18	5.18
	Energy Cost	Cost/ Kwh (NTD)	3.10	3.10
		Energy consumption per hour (watt)	96.00	96.00
		Total cost Energy per part (NTD)	0.08	0.08
	Equipment Cost	Production rate per hour	3.87	3.87
		Production volume total per year	19323.87	19323.87
		Machine Cost (NTD)	14500.00	14500.00
		Depreciation per year (NTD)	1812.50	1812.50
		Maintenance cost per year (NTD)	725.00	725.00
		Total machine cost per part (NTD)	0.13	0.13
	Total Cost per part (NTD)		13.10	10.78

Table 3. Detail cost breakdown for part B

Part	Subject		Additive Manufacturing	Green Additive Manufacturing
B  **dimension** **28 mm x 28 mm x 45 mm**	Total part per platform		6	6
	Total build time		1.23	1.23
	Material Cost	Material per part (kg)	0.06	0.06
		Material cost per kg (NTD)	60	42
		Total Material cost per part (NTD)	3.81	2.66
	Labour Cost	Operator cost per hour (NTD)	172.00	172.00
		Set up time (hour)	0.08	0.08
		Post processing time (hour)	0.03	0.03
		Labour cost per part (NTD)	4.12	4.12
	Energy Cost	Cost/ Kwh (NTD)	3.10	3.10
		Energy consumption per hour (watt)	96.00	96.00
		Total cost Energy per part (NTD)	0.06	0.06
	Equipment Cost	Production rate per hour	4.86	4.86
		Production volume total per year	24285.41	24285.41
		Machine Cost (NTD)	14500.00	14500.00
		Depreciation per year (NTD)	1812.50	1812.50
		Maintenance cost per year (NTD)	725.00	725.00
		Total machine cost per part (NTD)	0.10	0.10
	Total Cost per part (NTD)		8.10	6.95

Table 4. Detail cost breakdown for part C

Part	Subject		Additive Manufacturing	Green Additive Manufacturing
C  **dimension** **42 mm x 42 mm x 25 mm**	Total part per platform		8	8
	Total build time		1.35	1.35
	Material Cost	Material per part (kg)	0.05	0.05
		Material cost per kg (NTD)	60	42
		Total Material cost per part (NTD)	2.77	1.94
	Labour Cost	Operator cost per hour (NTD)	172.00	172.00
		Set up time (hour)	0.08	0.08
		Post processing time (hour)	0.03	0.03
		Labour cost per part (NTD)	3.39	3.39
	Energy Cost	Cost/ Kwh (NTD)	3.10	3.10
		Energy consumption per hour (watt)	96.00	96.00
		Total cost Energy per part (NTD)	0.05	0.05
	Equipment Cost	Production rate per hour	5.93	5.93
		Production volume total per year	29582.22	29582.22
		Machine Cost (NTD)	14500.00	14500.00
		Depreciation per year (NTD)	1812.50	1812.50
		Maintenance cost per year (NTD)	725.00	725.00
		Total machine cost per part (NTD)	0.09	0.09
	Total Cost per part (NTD)		6.30	5.46

The results reveal that the total cost associated with green additive manufacturing is marginally lower, compared to additive manufacturing methods. The cost efficiency in part A, B, and C is 17.64%, 14.10 %, and 13.2 %, respectively. This cost efficiency can be primarily attributed to the implementation of recycled oyster shells, which effectively reduces the overall expense of clay usage. Moreover, by enhancing the operational efficiency of the machine, it is possible to further optimize the production rate, leading to a more substantial reduction in costs.

CONCLUSIONS

This study proposes the use of recycled oyster shells as an additive in AM fabrication processes. The composition of oyster shells and clay is optimized to get the best printing results. The following summarizes the results of the experiments:

1. Recycled oyster shells as additives have the potential to improve the mechanical properties of clay, with high flexural and compressive strengths.
2. The use of recycled oyster shells as an additive does not affect the printability of the mixture.
3. This study also highlights the positive impact of the use of recycled oyster shells on the green supply chains and cost efficiency.

Further research in this area could focus on optimizing the composition of oyster shell clay mixtures and exploring the potential of this material for wider applications in various industries.

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