Research on the Transformation of Oyster Shells into a Green, Recyclable, Low Carbon Emission Building Material

Wen-Cheng Shao, Yu-Wei Dong, Jia-Wei Chen, Chao-Ling Lu, and Yun-Hsuan Lee

Abstract—**In response to climate change and sustainable environment, the "circular economy" that reduces energy development and waste reuse is an important carbon reduction strategy in addition to developing green energy. Based on the circular economy theory of local materials and local use, combines quenched blast furnace slag and geopolymer technology to convert waste oysters into building materials bricks for effective utilization. Our goal is to "recycle" oyster shell waste, "reduce" carbon emissions from the manufacturing, and achieve "recycling". Innovative high-pressure bricks that meet local building material standard.**

The experiment results show that: 1. The ratios of oyster shell and quenched blast furnace slag were 7:3 and 5:5 respectively, made under the pressure of 110kgf/cm². Curing 28 days later, the compressive strength was 27.5MPa and 38.4MPa, respectively. The bending strength was 3.6MPa and the abrasion test was 1.94mm. 2. Crushing the original high-pressure bricks made of oyster shells, added oyster shell powder and quenched blast furnace slag, remade them in a ratio of 7:3. Curing 7 days later, the compressive strength can reach 41.46 and 51.66MPa.3. Each high-pressure brick made of oyster shells will produce 0.206 to 0.219kg CO_2 emissions, which is 49% to 52% fewer carbon emissions than the 0.422kg CO_2 emitted by each high-pressure concrete brick. 4.The remade oyster shell high-pressure reformed bricks will produce 0.295 to 0.304kg CO_2 emissions, which is 28% to 30% lesser carbon emissions than each high-pressure concrete brick.

This result can prove that the oyster shell high-pressure bricks can pass Taiwan's CNS and Green-building materials standard, comply with the circular economy and achieve the goal of net-zero carbon emissions.

Index Terms—**Oyster shell, Geopolymer technology, circular economy, carbon reduction, high-pressure bricks.**

I. Introduction

The 2013 UN Panel on Climate Change (IPCC) report stated: "More than 95% probability that the increase in the concentration of carbon dioxide in the atmosphere will lead to an increase in the average temperature of the earth's surface. To control global warming, carbon dioxide emissions must first be reduced." The committee also adopted the Paris Agreement in 2015: "The global warming must be kept below 2 degrees Celsius by the end of this century", and then the IPCC released a new research report in 2018 that pointed out: "Carbon emissions must be reduced by 45% by 2030, and reach net-zero (carbon neutrality) by 2050". In addition, it pointed out that "resource efficiency improvement is an indispensable strategy to achieve climate goals".

In 2002, Professor Michael Braungart from the Department of Chemistry, University of Lüneburg, Germany, put forward the theory of circular economy, providing a new mode of economic operation of "reduce-reuse-recycle". The circular economy can be divided into two parts, the bio-cycle and the industrial cycle. Bio-cycle involves biodegradable raw materials that can be transformed into bio-cycle nutrients. Meanwhile, the industrial cycle includes recycled materials that can be reused or upgraded to make new products [1]. This has become an important carbon reduction strategy and policy for countries around the world in addition to developing green energy [2].

According to the 2020 report of the United Nations Environment Programme (UNEP), the construction industry accounted for 35% of the world's total energy consumption in 2019, and greenhouse gas emissions were as high as 38% of the total [3]. Therefore, reducing the energy consumption and carbon emissions of the construction industry could be an effective way to achieve net-zero emissions.

According to the 2020 Fishery Statistics Annual Report of the Taiwan Fisheries Administration [4], the annual production of oysters reaches 19,243 metric tons, and the oyster shells are 6 times heavier than oysters [5]. In other words, the annual waste of oyster shells will be as high as 115,458 metric tons, and most of them are discarded without processing, causing serious environmental problems.

Therefore, this study is based on the theory of the "reduce-reuse-recycle" of the circular economy. We used locally available waste material to reduce high-energy sintering and high carbon dioxide emissions from the manufacturing process of building materials. By combining waste oyster shells with Geopolymer technology, the waste is transformed into an innovative building material. Through this research method, the waste that should have been discarded can be recycled and used effectively and can be utilized as a sustainable, alternative construction material.

In order to realize the circular economy theory and the goal of reducing carbon emissions by using local resources through local production to create a material for local use, the innovative building materials in this study must also pass the local standard inspections including the "Republic of China National Standard (CNS)" and "Green Building Materials

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The authors are with National Taipei University of Technology, Taiwan (e-mail: wcshao@ntut.edu.tw, dan19710509@hotmail.com, t106859008@ntut.edu.tw, amylulu@mail.taivs.tp.edu.tw, sun95771@gmail.com).

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Specification" in Taiwan.

II. Materials and Methods

A. Geopolymer Technology

Geopolymer Technology was proposed by French scientist Davidovits in 1978, and its technical methods can be divided into two parts: 1) the inorganic polymerization process of mixing alkali metal solution and alkali metal aluminosilicate solution to form an alkaline solution and act on inorganic substances; and 2) the addition of water to the aluminosilicate inorganic solid material to produce inorganic polymerization. Both methods can be performed in a low-temperature environment. The permeation or chemical reaction first dissolves the aluminosilicate ions and covers the surface of the inorganic particles. Next, the aggregation expands which forms a silicon-oxygen tetrahedron and an aluminum-oxygen tetrahedron, and then bonds into a continuous three-dimensional framework network structure. After dehydration, drying, and hardening, a strong inorganic polymer material is formed, which is called an inorganic polymer precursor colloid [6]. Its reaction is shown in Fig. 1 [7].

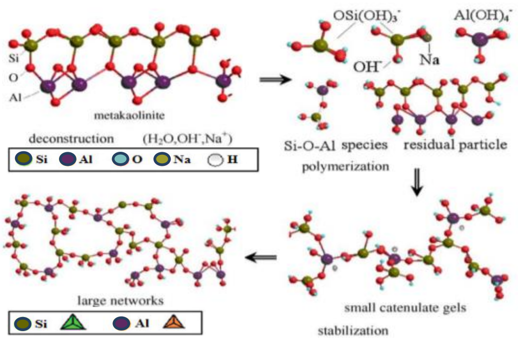


Fig. 1. Schematic diagram of Geopolymer reaction.

In order to avoid insufficient dissolution of aluminosilicate ions which results in poor link strength, the Geopolymer is made by mixing alkali metal solutions, alkali metal aluminosilicate solutions, and aluminosilicate solid materials. In addition to natural minerals, slag, incineration ash, and other wastes are all aluminosilicate solid materials. Further, Geopolymer can be combined with inorganic wastes (e.g., industrial waste, construction waste, and marine waste) to form Geopolymer materials to achieve waste recycling which is the purpose of utilizing and reducing environmental load. In addition to physical durability such as low thermal conductivity, wear resistance, high strength, and high electrical resistance, Geopolymer materials also have chemical durability, including acid and alkali resistance, metal corrosion resistance, sulfate resistance, etc. In Geopolymer production, carbon dioxide is released which effectively solves the problem of carbon emissions. Geopolymer has high early strength, which can reach 70% of the strength of curing for 28 days in a short period of four hours [8]. This excellent characteristic is regarded as a new generation of environmentally friendly materials with great potential for future development.

B. Oyster Shell

Oyster shell is a marine waste inorganic material that can be used to replace the fine aggregate in concrete after grinding without decreasing the compressive strength of the concrete [9]. The main chemical composition of oyster shells is calcium carbonate ($CaCO_3$) which is more than 90%. Its calcium content is 37.4% and contains other trace metals including sodium (0.594%), magnesium (0.269%), potassium (0.012%), iron (0.034%), etc. [10]. The density of an oyster shell is about 2.41 g/cm^3, greater than that of water [11]. Its surface is porous, and the shell is composed of skin, prism, and nacre from the outside to the inside. Moreover, it is resistant to acid, corrosion, heat, and pressure; therefore, oyster shells can be easily and effectively reused [12].

In this experiment, discarded oyster shells from the Penghu area of Taiwan were used; most of which were Pacific oysters (Crassotrea Gigas) of the family middle Ostreidae in the order Pterioida [13]. Before the experiment, the oyster shells were ground into a powder with a Hammer Mill. The median diameter (D50) was about 390μm and the moisture content was 5.8%.

C. Quenched Blast Furnace Slag

A quenched blast furnace slag is the molten iron of the steelmaking plant. The process of "quenching" smelting can be divided into quenched blast furnace slag or air-cooled blast furnace slag. The ingredients consist of magnesium oxide, calcium oxide, silicon oxide, aluminum oxide, and a small amount of iron oxide, which can be used as aluminosilicate solid materials during inorganic polymerization. Because of its low hydration heat, when used as a clinker for building materials production, it can reduce CO_2 discharge and can increase material bonding.

The blast furnace stone powder used in this study is the quenched blast furnace slag in the steelmaking plant and is the CNS1223 product produced by China United Resources Co., Ltd. Its main components are CaO, SiO_2, and Al_2O_3. The particle size distribution is between 0.6~135.7μm, and the median diameter (D50) is 12.3μm.

D. Alkaline Solution

When preparing Geopolymer materials, sodium hydroxide (NaOH), sodium aluminate solution, and sodium silicate solution are usually primed as alkaline solutions. Based on previous literature, the lye ratio of inorganic polymerized green concrete has a molar ratio of SiO_2/Na_2O of 1.28 (NaOH concentration of 6M), a molar ratio of SiO_2/Al_2O_3 of 50, and a liquid-solid ratio of 0.8. The compressive strength will increase with the curing time and can reach 65MPa in 365 days [14]. Therefore, in this study, the lye concentration in the literature was used for the experimental ratio, and because the high-pressure process was used in this study, the liquid-solid ratio was reduced to 0.2.

In this study, industrial-grade sodium hydroxide with 98% purity produced by Chengtai B Chemical Co., Ltd. was used. The sodium aluminate solution is produced by Taiwan Taiyou Chemical Co., Ltd., and the molar ratio of Al_2O_3/Na_2O is about 1.8. The sodium silicate solution uses sodium silicate with a composition of 9.5% sodium oxide (Na_2O) and 29% silicon dioxide (SiO_2), and is produced by Taiwan Rongxiang Co., Ltd.

III. Detection and Result

This research was carried out in two experimental stages: (1) the waste oyster shell powder and quenched blast furnace slag powder were mixed with different ash-sand ratios and the Geopolymer was added to make high-pressure bricks; then, the bricks were tested to assess their compressive strength, flexural strength, and wear resistance, and the Physical and Toxicity Characteristic Leaching Procedure (TCLP) detection analysis was also performed; (2) After crushing the high-pressure bricks made from the original oyster shells, oyster shell powder and quenched blast furnace slag powder were added in different proportions for recycling, and their compressive strength and physical properties were tested and analyzed.

TABLE I: Compressive Strength Test

Mold	Sample code*	Shell powder percentage (%)	Quenched blast furnace slag percentage (%)	Brick making pressure kgf/cm^2	Curing days & Stress test (MPa)		
					7 days	14 days	28 days
I	WCGP-7-3-70	70	30	70	13.00	16.60	20.7
II	WCGP-7-3-110			110	18.39	26.46	27.5
III	WCGP-5-5-70	50	50	70	20.15	22.13	27.3
IV	WCGP-5-5-110			110	32.90	39.57	38.4

* W= Oyster shells, C= High-pressure bricks, GP=Geopolymeric

A. *Waste Oyster Shell High-Pressure Brick*

After mixing the oyster shell powder and quenched blast furnace slag powder in a ratio of 7:3 and 5:5, an alkaline solution with a concentration of 6M in a liquid-solid ratio of 0.2 was added. Next, it was poured into a mold with a width of 10cm, a length of 20cm, and a height of 6cm. After high-pressure treatment, demolding curing followed. The production process, steps, time, and conditions are shown in Fig. 2.

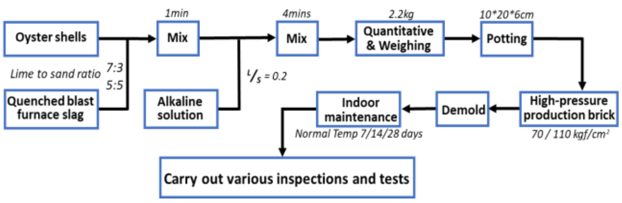


Fig. 2. Production conditions, steps, and time for oyster shell high-pressure bricks.

1) *Compressive strength test*

According to the high-pressure brick compression test specification, this study drilled holes on the oyster shell high-pressure brick, and took out a cylindrical specimen with a diameter of 50 mm for testing. The test results are shown in Table I.

Comparing the experimental results of WCGP-7-3-70 and WCGP-7-3-110, the compressive strength test data for 7 days, 14 days, and 28 days of curing shows that the compressive strength increased as the curing days increased. The compressive strength of WCGP-7-3-70 was lower than that of WCGP-7-3-110. Similarly, the compressive strength of WCGP-5-5-70 was also lower than WCGP-5-5-110. Therefore, it can be speculated that the curing days and manufacturing brick pressure directly affect the strength of the brick. Based on the results, the WCGP-5-5-110 passed the A-level brick standard (>32MPa) of Taiwan CNS13295 high-pressure brick specification; thus, it can be used for the road surface of super heavy-duty lanes. Meanwhile, WCGP-5-5-70 and WCGP-7-3-110 passed the B-level brick standard (>24MPa), which means that they can be used for small and medium-sized lanes, bicycles, and sidewalks.

2) *Bending strength test*

Since the current study's goal is to replace high-pressure concrete bricks and use them on bicycles and sidewalks, the WCGP-7-3-110, which has reached the B-level brick standard, was chosen to undergo the bending test conducted by the Taiwan SGS Company. The test method used was the Taiwan standard CNS1234. The test results in Table II show that the flexural strength was 3.6MPa, greater than the flexural strength standard of B-grade bricks (>3.42MPa).

TABLE II: Bending Strength Test

Test items	Unit	CNS 1234(2018)	Test Results	Pass or None
Bending strength	MPa	A-level：3.9 B-level：3.4 C-level：3.2	3.6	Comply B-level standard

3) *Abrasion resistance test*

Since the research goal is to replace high-pressure concrete bricks and use them on bicycles and sidewalks, the WCGP-7-3-110, which has reached the B-level brick standard, was selected to undergo the abrasion test conducted by Taiwan SGS Company. Based on the Taiwan standard CNS13297, which was the test method used, the average thickness wear shall not exceed 3mm and the test result shall be 1.94mm, while the wear volume loss shall not exceed 15cm ^{3}/ 50cm ^{2}and the test result shall be 9.72cm ^{3}/ 50cm ^{2} As shown in Table III, these values were all satisfied by the WCGP-7-3-110.

TABLE III: Abrasion Resistance Test

Abrasion resistance Test items	Unit	CNS13297 (2018)	Test Results	Pass or None
Thickness wear Average value	mm	3	1.94	Approve
Abrasion volume Loss value	cm^3 /50cm^2	15	9.72	Approve

4) *Physical test*

Using Archimedes' principle, the test results in Table IV shows that the bulk density of different ratios was between

1.55 to 1.7 and the apparent specific gravity was about 2.47.

Further, it can be observed that the porosity and water absorption increased with the curing days, showing an upward trend. The porosity rate was between 0.31% to 0.38% and the water absorption rate was between 0.18% to 0.25%.

5) Toxicity characteristic leaching procedure (TCLP)

Based on the Taiwan Green Building Materials Specification, this study selected the sample number WCGP-7-3-110 to conduct a toxic dissolution test through the Taiwan SGS Company. The test results showed that the extract had a total silver test value of ND<0.014 mg/L, a total arsenic test value of ND<0.033 mg/L, a total cadmium test value of ND<0.010 mg/L, a total hexavalent chromium test value <0.02 mg/L, a total copper test value of ND<0.017 mg/L, a mercury test value of ND<0.0004 mg/L, and a total lead test value of ND<0.016 mg/L. All of which are in line with the Taiwan Green Building Materials Standard. The test values are summarized in Table V.

TABLE IV: PHYSICAL TEST

Mold	Sample code	Curing days	Bulk density	Apparent gravity	Porosity (%)	Water absorption (%)
I	WCGP-7-3-70	7	1.52	2.43	38	25
		14	1.52	2.46	38	25
		28	1.58	2.33	32	20
II	WCGP-7-3-110	7	1.59	2.55	38	24
		14	1.62	2.44	33	21
		28	1.57	2.46	36	23
III	WCGP-5-5-70	7	1.61	2.49	36	22
		14	1.61	2.52	36	23
		28	1.54	2.47	37	24
IV	WCGP-5-5-110	7	1.68	2.43	31	18
		14	1.70	2.46	31	18
		28	1.67	2.59	36	21

TABLE V: TOXICITY CHARACTERISTIC LEACHING PROCEDURE (TCLP)

Test items	Testing method	Green Building Materials standard	Unit	Test Results	Pass or Non
Toxicity of industrial waste Characteristic dissolution procedure	NIEA R201.15C	-	-	-	-
Total ″Ag″ in extract	NIEA R306.13C/M104.02C	0.050	mg/L	ND<0.014	Approve
Total ″As″ in extract	NIEA R306.13C/M104.02C	0.300	mg/L	ND<0.033	Approve
Total ″Cd″ in extract	NIEA R306.13C/M104.02C	0.300	mg/L	ND<0.010	Approve
Total ″Cr^{6+} ″ in extract	NIEA R309.12C	1.500	mg/L	ND <0.02	Approve
Total ″Cu″ in extract	NIEA R306.13C/M104.02C	0.150	mg/L	ND<0.017	Approve
Total ″Hg″ in extract	NIEA R314.12C	0.005	mg/L	ND<0.0004	Approve
Total ″Pb″ in extract	NIEA R306.13C/M104.02C	0.300	mg/L	ND<0.016	Approve

TABLE VI: COMPRESSIVE STRENGTH TEST

Mold	Sample code	Waste brick pellets percentage (%)	Oyster shell powder percentage (%)	Quenched blast furnace slag percentage (%)	Brick making pressure(kgf/cm^2)	Curing days & Stress test (MPa) 7 days
V	CCGP-703-110	70	0	30	110	51.66
VI	CCGP-755-110	70	15	15		41.46

B. Oyster Shell High-Pressure Remade Brick

After crushing the high-pressure brick made from the original WCGP-7-3-110 oyster shell, it was mixed with the oyster shell powder and quenched blast furnace slag powder with 0:1 and 1:1 ratio respectively. Next, they were mixed in a 7:3 ratio and an alkaline solution with a concentration of 6M at a liquid-solid ratio of 0.2 was added. The mixture was then poured into a mold with a width of 10cm, a height of 20cm, and a length of 6cm, and underwent high-pressure treatment and demolding maintenance. The production process, including the steps, time, and conditions required are shown in Fig.3.

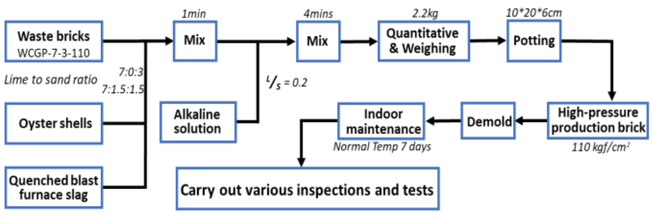


Fig. 3. Production process, steps, time, and conditions required for making the oyster shell high-pressure bricks.

1) Compressive strength test

Based on the high-pressure brick compression test specification, holes were drilled on the high-pressure remanufactured bricks mixed with oyster shells, and a cylindrical specimen with a diameter of 50 mm was taken for testing. The test results are shown in Table VI.

According to the results, the compressive strength of CCGP-703-110 and CCGP-755-110 were 51.66MPa and 41.46MPa respectively after 7 days of recycling and curing; both of which passed the A-level brick standard of Taiwan CNS13295 high-pressure brick specification (>32MPa). This study believes that the reason for these results is that after using WCGP-7-3-110 with a compressive strength of 27.5MPa, the strength is further improved as the degree of cementation between the quenched blast furnace slag powder and alkaline solution increased. Comparing the experimental results of CCGP-703-110 and CCGP-755-110, it can be seen that the proportion of the quenched blast furnace slag powder was reduced, but the compressive strength increased. However, the compressive strength of the remanufactured oyster shell high-pressure bricks were better than that of the original oyster shell high-pressure bricks.

TABLE VII: COMPRESSIVE STRENGTH TEST

Mold	Sample code	Curing days	Bulk density	Apparent gravity	Porosity (%)	Water absorption (%)
V	CCGP-703-110	7	1.71	2.54	0.33	0.19
VI	CCGP-755-110	7	1.79	2.59	0.3	0.17

TABLE VIII: ANALYSIS OF CARBON REDUCTION BENEFIT OF WCGP-7-3

Sample type	Concrete high pressure brick		Oyster shell high-pressure brick **WCGP-7-3(2.2kg)**				Decrease
CO_2 source	Concrete	water	Oyster shell powder	quenched blast furnace slag	Na_2SiO_3	NaOH	
Percentage	20%	8%	70%	30%	L/S=0.2		-
Usage (kg)	0.440	0.180	1.283	0.55	0.31	0.057	
CO_2 produced per kilogram (kg)	0.880	0.195	0.013	0.048	0.50	3.000	
	0.387	0.035	0.017	0.026	0.155	0.005	0.219
Total CO_2 (kg)	0.422		0.203				

TABLE IX: CARBON REDUCTION BENEFIT ANALYSIS OF WCGP-5-5

Sample type	Concrete high pressure brick		Oyster shell high-pressure brick **WCGP-5-5(2.2kg)**				Decrease
CO_2 source	Concrete	water	Oyster shell powder	quenched blast furnace slag	Na_2SiO_3	NaOH	
Percentage	20%	8%	50%	50%	L/S=0.2		-
Usage (kg)	0.440	0.180	0.916	0.916	0.31	0.057	
CO_2 produced per kilogram (kg)	0.880	0.195	0.013	0.048	0.50	3.000	
	0.387	0.035	0.012	0.044	0.155	0.005	0.206
Total CO_2 (kg)	0.422		0.216				

TABLE X: CARBON REDUCTION BENEFIT ANALYSIS OF CCGP-703

Sample type	Concrete high pressure brick		Remade Oyster shell high-pressure brick **CCGP-703(2.2kg)**					Decrease
CO_2 source	Concrete	water	Oyster shell high-pressure brick	Oyster shell powder	quenched blast furnace slag	Na_2SiO_3	NaOH	
Percentage	20%	8%	70%	0%	30%	L/S=0.2		-
Usage (kg)	0.440	0.180	1.283	0	0.550	0.31	0.057	
CO_2 produced per kilogram (kg)	0.880	0.195	0.092	0.013	0.048	0.50	3.000	
	0.387	0.035	0.118	0	0.026	0.155	0.005	0.118
Total CO_2 (kg)	0.422		0.304					

2) Physical test

Based on Archimedes' principle, the test results in Table VII shows that the bulk density of different ratios was about 1.7, the apparent specific gravity was about 2.55, the porosity was about 0.3%, and the water absorption rate was about

0.18%.

C. Analysis of Carbon Reduction Benefit of Oyster Shell High Pressure Brick

In the process of converting raw meal into clinker during the manufacturing of cement, it needs to be fired at 1450℃ to 1500℃ to a semi-molten state, and then cooled in a cooler. According to previous research, the production of 1kg of cement emits 0.88kg of CO_2. Meanwhile, the production of 1kg of quenched blast furnace slag powder carbon dioxide produces an emission amount of 0.048kg which is the energy consumption during grinding. Moreover, the production of 1kg of sodium silicate solution and sodium hydroxide solution produces 0.5kg and 3kg of carbon emissions respectively [14]. The carbon emission of oyster shell powder comes from the Hammer Mill, which can crush 75kg of oysters using 3.3 kWh of electricity in 1 hour, and using 0.0235 kWh of electricity to crush 1kg of shell powder. A total of 0.533kg of carbon emission can be produced. Therefore, 1kg of oyster powder will produce 0.013kg of carbon emissions.

TABLE XI: CARBON REDUCTION BENEFIT ANALYSIS OF CCGP-755

Sample type	Concrete high pressure brick		Remade Oyster shell high-pressure brick **CCGP-703(2.2kg)**					Decrease
CO_2 source	Concrete	water	Oyster shell high-pressure brick	Oyster shell powder	quenched blast furnace slag	Na_2SiO_3	NaOH	
Percentage	20%	8%	70%	15%	15%	L/S=0.2		-
Usage (kg)	0.440	0.180	1.283	0.275	0.275	0.31	0.057	
CO_2 produced per kilogram (kg)	0.880	0.195	0.092	0.013	0.048	0.50	3.000	
	0.387	0.035	0.118	0.004	0.013	0.155	0.005	
Total CO_2 (kg)	0.422		0.295					0.127

The WCGP-7-3-110 and WCGP-7-3-70 had the same amount of materials. After calculation of the WCGP-7-3 series oyster shell high-pressure bricks, it was found that each block could produce 0.203kg of carbon dioxide emissions which reduces the carbon content to 0.219kg. This leads to a carbon reduction benefit that is 52% lower than the high-pressure concrete brick carbon. The test values are shown in Table VIII.

WCGP-5-5-110 and WCGP-5-5-70 had the same amount of materials. After calculation of the WCGP-5-5 series oyster shell high-pressure bricks, it was found that each block could produce 0.216kg of carbon dioxide emissions, reducing the carbon content to 0.206kg. This leads to a carbon reduction effect about 49% lower than the high-pressure concrete brick carbon. The test values are shown in Table IX.

After calculation, it was found that the sample CCGP-703 oyster shell high-pressure remade brick could produce a carbon dioxide emission of 0.304kg, with a carbon reduction amount of 0.118kg. This leads to a carbon reduction effect that is 28% lower than the high-pressure concrete brick carbon. The values are shown in Table X.

After calculation, it was found that the sample CCGP-755 oyster shell high-pressure remade brick could produce a carbon dioxide emission of 0.295kg with a carbon reduction amount of 0.127kg. This leads to a carbon reduction effect that is about 30% lower than the high-pressure concrete brick carbon. The values are shown in Table XI.

IV. DISCUSSION AND CONCLUSIONS

Oyster shells are considered marine waste. If they can be effectively recycled and reused, they will reduce environmental pollution and create huge potential value in the circular economy. According to the results of this study, the oyster shell waste combined with inorganic Geopolymer technology to create an innovative building material met the circular economy theory and carbon emission reduction goals. The oyster shell high-pressure bricks are innovative materials that can be made into different proportions, formulations, and specifications for varied uses and goals. The experimental data results confirmed that the material meets the specifications of Taiwan CNS and green building materials. Therefore, waste oyster shells can be recycled. The experimental results are described in detail below.

1) The oyster shell wastes that were made into bricks by Geopolymer Technology through pressure molding are in line with Taiwan CNS high-pressure brick specifications as shown in Fig. 4.

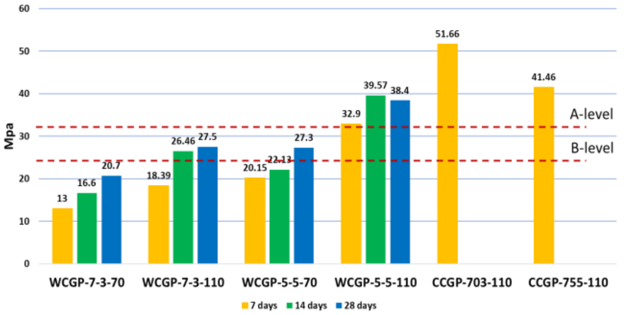


Fig. 4. Compression value and comparison specifications.

Of oyster shell high-pressure bricks After 28 days of curing, the high-pressure bricks made of waste oyster shells combined with Geopolymer Technology (WCGP-5-5-110) had a compressive strength of 38.4 Mpa. This means that it had passed the A-level brick standard (>32MPa), indicating that can be used for super-heavy road pavements. Meanwhile, the compressive strengths of WCGP-5-5-70 and WCGP-7-3-110 were 27.3 MPa and 27.5 MPa respectively; both have passed the B-grade brick standard (>24MPa), indicating that they can be used on small and medium-sized lanes, bicycle lanes, and sidewalks. Further, after 7 days of recycling and curing, because of the increase in cementation, the CCGP-703-110 and CCGP-755-110 obtained a compressive strength of 51.66MPa and 41.46Mpa respectively, which passed the A-level brick standard (>32MPa). In addition, the flexural strength test of WCGP-7-3-110 was 3.6MPa, and the wear test result was only 1.94 mm. The above experimental results are in line with the CNS13295 high-pressure brick specification.

2) Oyster shell high-pressure bricks conform to Taiwan's green building materials standards, increasing their value in the circular economy; thus, they have high future application development as a building material.

Based on the restricted substance analysis of the Taiwan Green Building Materials Specification, the WCGP-7-3-110 sample was subjected to the Toxicity Characteristic Leaching Procedure (TCLP). The experimental results were all within the safety standard value and in line with the evaluation project of recycled green building materials of Taiwan. Also, it passed the five-star rating of the innovative green building materials evaluation system. According to the circular economy framework, oyster shell high-pressure bricks conform to the industrial cycle of "reduce-reuse-recycle", and their performance is optimized after remanufacturing. Currently, the developers of the oyster shell high-pressure bricks have applied for the German Cradle-to-Cradle certification classification, and they are hoping to obtain a "Silver Grade" mark certification.

3) The carbon reduction benefits of oyster shell high-pressure bricks contribute to the development of important carbon reduction strategies other than green energy, in line with the UN goal of net-zero carbon emissions as shown in Fig. 5.

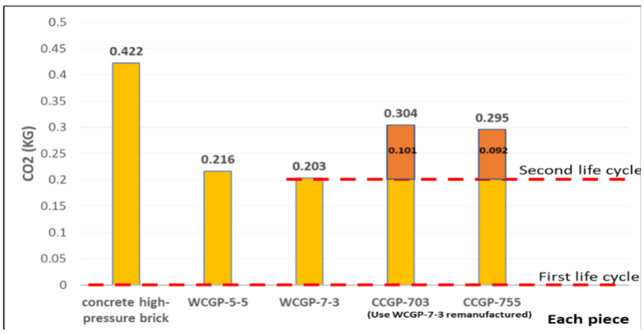


Fig. 5. Carbon reduction benefits of oyster shell high-pressure bricks.

Each oyster shell high-pressure brick could produce 0.203kg to 0.216kg of CO_2 emissions which is 49% to 52% fewer carbon emissions than those emitted by each high-pressure concrete brick (0.422kg of CO_2). Moreover, two life cycles of oyster shell high-pressure recycled brick could produce 0.295kg to 0.304kg of carbon emissions, which is 28% to 30% lower than those emitted by each high-pressure concrete brick in a life cycle (0.422kg of CO_2). The above experimental results provide carbon emission reduction strategies other than green energy development, and are more in line with the net-zero carbon emission goal of the United Nations sustainable development.

4) Based on the results of this study, the effects of different formulation ratios, particle sizes, and lye concentrations on the performance and carbon emissions can be further explored in future studies. It would be interesting to know how to further optimize oyster shell high-pressure bricks. These are the target directions in the next stage of this study.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

Conceptualization, Resources, Review and supervision, by Author Shao and Author Chen; Experiment, by Author Lee; Methods, by Author Lu; Formal analysis, by Author Dong; Data planning, Writing and Editing, by Author Chen.

References

[1] ©EPEA Intl.Umweltforschung Gmbh Taiwan Branch. (June 2020). Cradle to Cradle® Platform Message. [Online]. Available: http://www.c2cplatform.tw/c2c.php?Key=1.

[2] ©Column, Circular Taiwan Network, Circular Foundation. (Dec. 2021). [Online]. Available: https://circular-taiwan.org/2021/12/30/%E5%9C%8B%E9%9A%9B%E5%BC%B7%E8%AA%BF%E5%BE%AA%E7%92%B0%E7%B6%93%E6%BF%9F%E5%B0%8D%E6%B7%A8%E9%9B%B6%E6%8E%92%E6%94%BE%E7%9A%84%E9%87%8D%E8%A6%81%E6%80%A7/

[3] I. Hamilton, "Global status report for buildings and construction," *Copyright © United Nations Environment Programme*, 2020. pp. 4-8.

[4] Fishery Statistics Annual Report - Fisheries Department, Council of Agriculture, Executive Yuan, R.O.C. Taiwan. [Online]. Available: https://www.fa.gov.tw/cht/PublicationsFishYear/content.aspx?id=35&chk=6c7f7242-297c-47d1-8bb1-51e7c8a5961c.

[5] N. C. Ye, T. Y. Gao, and H. Q. Lin, "Agricultural science news, © agricultural global information network of the council of agriculture," *Executive Yuan*, no. 343, pp. 125-128, 2021.

[6] W. Sun, Y. Zhang, W. Lin and Z. Liu, "In situ monitoring of the hydration process of K-PS geopolymer cement with ESEM," *Cement and Concrete Research*, vol. 34, no. 6, pp. 935-940, 2004.

[7] X. Yao, Z. Zhang, H. Zhu, and Y. Chen, "Geopolymerization process of alkali–metakaolinite characterized by isothermal calorimetry," *Thermochimica Acta*, vol. 493, no. 1-2, pp. 49-54, 2009.

[8] D. Zheng, "Development, application and review of inorganic polymerization technology," *Mining and Metallurgy*, vol. 54, no. 1, pp. 140-157, 2012.

[9] E. Yang, S. Yi, and Y. Leem, "Effect of oyster shell substituted for fine aggregate on concrete characteristics: Part I. Fundamental properties," *Cement and Concrete Research*, vol. 35, no. 11, pp. 2175-2182, 2005.

[10] H. Kwon, C. Lee, B. Jun, J. Yun, S. Weon, and B. Koopman, "Recycling waste oyster shells for eutrophication control," *Resources, Conservation and Recycling*, vol. 41, no. 1, pp. 75-82, 2004.

[11] H. Yoon, S. Park, K. Lee, and J. Park, "Oyster shell as substitute for aggregate in Mortar," *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 22, no. 3, pp. 158-170, 2004.

[12] N. C. Ye, L. W. Xu, and H. J. Cai, "High-value application of oyster shells," *Water Test Newsletter*, vol. 64, pp. 16-19, 2018.

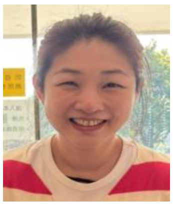
[13] M. H. Liang, "Growth and seedling of oyster cultured in cloth bags research," M.S. thesis, Institute of Zoology, National Taiwan Univ., Taipei, 1981.

[14] Z. H. Wang, "Research on the durability of inorganic polymer green cement and green concrete," M.S. thesis, Institute of Resource Engineering, National Taipei University of Technology, Taipei, 2016.

Wen-Cheng Shao was born in Taiwan in 1964. He received is doctoral degree at the College of Architecture in National Cheng Kung University, Taiwan. He is currently an associate professor and Department head at the National Taipei University of Technology in the Department of Architecture. He Hosted the Innovative Green Building Materials R&D Center and Health Environment Laboratory, NTUT, Taiwan. He has expertise in intelligent building, indoor environment control, architectural design and construction, physical environment, green building. He was also a review committee in national standards of the Republic of China and Architecture Science and Ministry of Education Sustainable Campus and Sick House and Green Building, Taiwan.

Yu-Wei Dong was born in Taiwan in 1971. He finished his master's degree in the Department of Architecture & Urban planning at Chung Hua University, Taiwan. Currently, he is a doctoral student in College of Design at National Taipei University of Technology. He is also a lecturer at Chung Hua University and CEO of Z.J. Interior Design Company. He has expertise in architectural design and construction, physical environment, green building and working with the Environmental Medicine Modulation Technology License E.P.A. Taiwan.

Jia-Wei Chen was born in China in 1981. She finished her master's degree in School of Arts of Chongqing University, China. She worked as a lecturer at Lingnan normal University in Guangdong, China from 2007 to 2020. Currently, she is a doctoral student in College of Design at National Taipei University of Technology. She has expertise in interior design, industrial design, IAQ strategy and certification system, health building.



Chao-Ling Lu was born in Taiwan in 1973. She finished her master's degree in Department of Architecture at National Taiwan University of Science and Technology, Taiwan. Currently, she is a doctoral student in College of Design at National Taipei University of Technology. She is also a architecture and a teacher who work at Taipei Municipal Da-An Vocational High School. She has expertise in architectural design and construction, physical environment, green building and architecture education in Taiwan.

Yun-Hsuan Lee was born in Taiwan in 1995. She finished her master's degree in National Taipei University of Technology. She has expertise in architectural design, green building.