

Thermal Decomposition of Seashell Powder

Cinthya Alvarado, MSc¹, Hernán Alvarado-Quintana, PhD²

¹Universidad Privada del Norte, Perú, cinthya.alvarado@upn.edu.pe

²Universidad Nacional de Trujillo, Perú, halvarado@unitru.edu.pe

Abstract— In recent decades, the growth of the aquaculture industry has produced an increase in the production of seashells whose residual shells currently generate an environmental problem. The objective of this research was to review the fundamentals of the thermal decomposition of seashell powder. The first part defines what they are, how they were formed, and identifies which are the most produced. Then, thermal decomposition, microstructure, and the effect of particle size on phase transformations were analyzed. Finally, the main applications of both calcined powder and non-calcined powder were reviewed.

Keywords—Seashell powder; functionality; thermal decomposition; scallop shell; cockleshell

I. INTRODUCTION

In recent decades, the production of seashell waste has increased substantially, but the seashell waste is dumped into landfills, disposed of in the soil, or transferred to the ocean, causing great environmental pollution. Seashells are not biodegradable, their residues take a long time to degrade due to their properties, resulting in an increase in discharge areas and causing soil and water pollution [1]. Over time, seashells suffer microbial decomposition, producing compounds such as hydrogen sulfide, ammonia, and amines, and generating unpleasant odors [2], [3]. Figure 1 shows a quarry where shell waste has been dumped after removing the edible part, generating air and soil pollution due to intensive odor emissions during microbial decomposition.



Fig. 1 Seashells dumped in a quarry in Huarney (Peru).

The aquaculture industry produces some 6 million to 8 million tons of waste annually worldwide [2], [4]. The production of these large amounts of seashells represents an important economic activity for many countries. By species, bivalve mollusks production via aquaculture in 2015 consisted of 38% clams, cockles, and ark shells, 35% oysters, 14%

mussels, and 13% scallops and pectin [5]. Actually, oysters and scallops become the most cultivated shellfish in the world [6]. For every 1 kg of oysters or scallops consumed, about 370-700 g of waste shells are produced [7], [8]. For this reason, the researchers' efforts are focused on transforming this shell waste into a useful material for the development of products that are in accordance with a cleaner environment.

II. SEASHELL IN ORIGINAL CONDITION

A. Composition

All the shells are composed mainly of calcium carbonate (CaCO_3) in 95% to 98% by weight and other oxides in small proportions (potassium, silicon, iron, etc.) [5], [8]. Table I shows the chemical composition after being calcined of the two most-produced seashells in the world: Oyster shell [9]–[15] and Scallop shell [16].

TABLE I
CHEMICAL COMPOSITION OF SEASHELLS (% WEIGHT) [3]

OXIDE CONTENT	OYSTER SHELL	SCALLOP SHELL
CaO	48.0 – 77.81	53.70
SiO ₂	0.64 – 13.28	0.10
Al ₂ O ₃	0.05 – 0.64	0.10
MgO	0.01 – 0.94	0.18
Fe ₂ O ₃	0.03 – 0.20	0.03
Na ₂ O	0.23 – 0.93	0.50
K ₂ O	0.01 – 0.51	0.01
SO ₃	0.60 – 1.09	0.32
P ₂ O ₅	0.01 – 0.18	-
TiO ₂	0.02 – 0.11	-
SO ₄ ²⁻	0.43	0.01
Cl ⁻	0.01 – 2.92	0.01
LOI	42.83 - 51	44.40

Oyster shells have the most calcium carbonate (up to 98%) [5]. The basic composition of mollusks shells is similar regardless of the species and they have a percentage of calcium carbonate greater than 95% [5], [8].

Calcium carbonate (CaCO_3) has three natural anhydrous crystalline phases: calcite, which is thermodynamically stable under ambient conditions; aragonite, a high-pressure and low-temperature polymorph less stable than calcite; and vaterite, the least stable among the polymorphs [17].

B. Biomineralization

The biomineralization of mollusks is a phenomenon by which these organisms produce inorganic compounds in a controlled manner. Seashells are mainly composed of calcium carbonate that crystallizes by biochemical processes with alternate deposition of aragonite, calcite, or mother-of-pearl crystals embedded in an organic matrix made up of proteins,

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chitin, and polysaccharides, which do not exceed 1% by volume [18].

Although the matrix is quantitatively a minor constituent in the shell of mollusks (less than 5% w/w), it is, however, the major component that controls different aspects of the shell formation processes: synthesis of transient amorphous minerals and evolution to crystalline phases, choice of the calcium carbonate polymorph (calcite vs aragonite) and organization of crystallites in complex shell textures (microstructures) [19].

C. Microstructure

Bivalve shells can be divided into three layers: the outermost layer known as periostracum, a middle layer called the prismatic layer, and the inner layer designated as the nacre layer. The periostracum is secreted in the groove between the outer and middle layers of the mantle [5]. Figure 2 shows microphotographs obtained in a scanning electron microscope (SEM) of the structure of the external and internal part of a mussel shell, in which we can observe its prismatic shape (a), and of the structure of the internal part of a scallop shell, in which it is observed that it is laminar in shape (b).

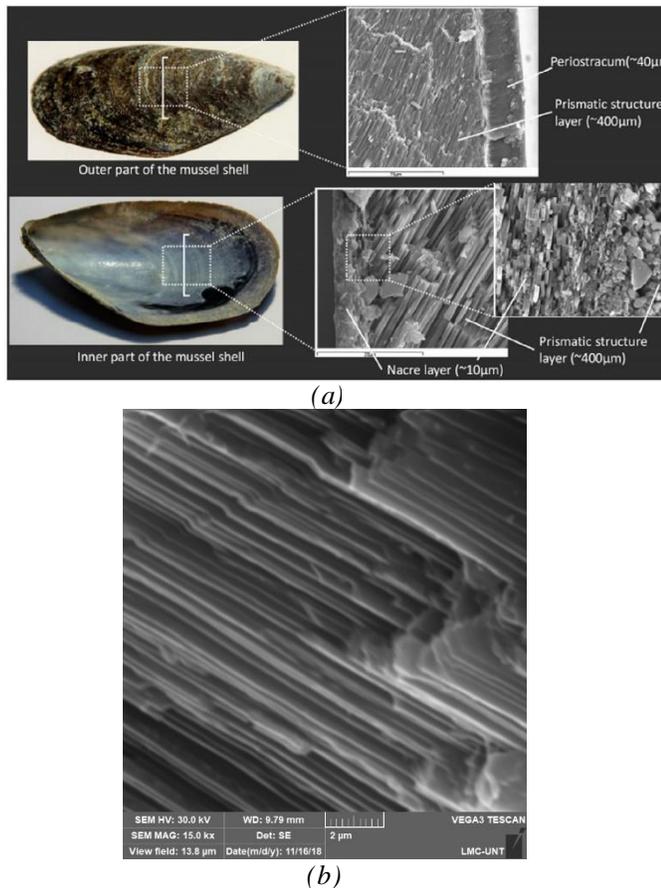


Fig. 2 SEM micrographs of (a) Mussel shell structure [5]. (b) Scallop shell structure.

The scanning electron microscope used was TESCAN Vega 3 XMU.

Shell matrix proteins (SMPs) are synthesized in the epitaxial cells of different regions of the mantle of mollusks. SMPs that are synthesized in the outer part of the mantle have been associated with the formation of calcite, while the dorsal region is related to the formation of aragonite [20].

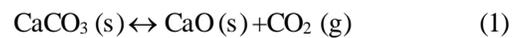
In most mollusks, the outer layer or periostracum is composed of organic compounds and is not calcified [21]. The inner layers are made up of polymorphs of aragonite and/or calcite [18]. In this way, different complex microstructures are formed that contribute to improving resistance by providing functions such as structural support and/or protection for the organism.

The biomineralization process comprises four stages: 1) Assembly of the matrix (SMPs) 2) Formation phase of amorphous calcium carbonate (ACC) 3) Nucleation of individual aragonite plates and 4) Growth of the plates to form a mature tissue (shell). Calcium carbonate polymorphs grow vertically until they meet a chitin plate. Subsequently, the crystal begins to grow laterally. During this process, acidic matrix proteins are incorporated between each generated plaque. [18], [22]

III. THERMAL DECOMPOSITION OF SEASHELL POWDER

A. Decomposition of calcium carbonate

Equation 1 represents the thermal decomposition process of the seashell, which is denoted by the decomposition of CaCO_3 and is known as calcination.



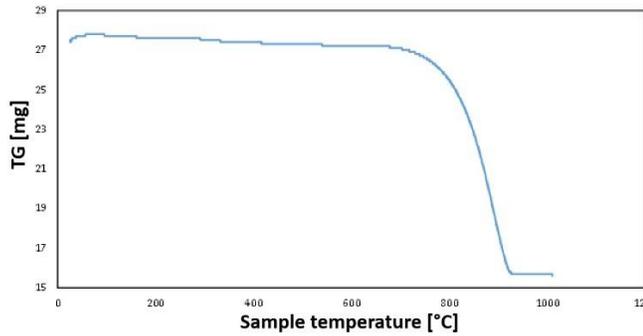
Lime is an inorganic material with predominant calcium oxide or calcium hydroxide compounds. Limestone, composed predominantly of calcite, is the most common carbonated rock from which calcitic lime is obtained [17].

Thermal analyses were performed to determine phase changes using a simultaneous thermal analyzer - Setaram Instrumentation - Setsys Evolution.

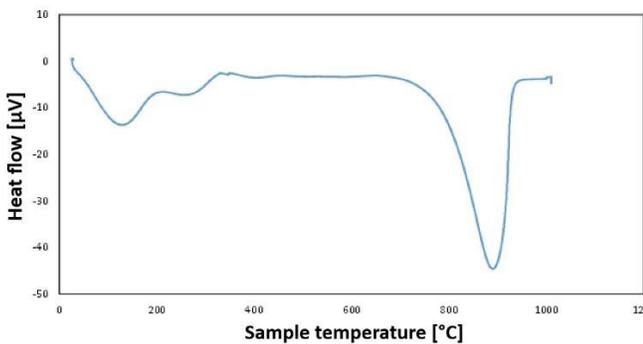
Thermal gravimetric analysis (TGA) of scallop shell powder (Fig. 3a) shows that weight losses can be divided into two general steps. In the first stage, thermal stability is observed up to 650 °C. After this temperature in the second stage between 650 °C and 940 °C, the loss of mass (42%) is evidenced as the temperature increases. As expected for calcium carbonate-based materials, the main weight loss that occurred in the last stage is due to the release of CO_2 .

Differential thermal analysis (DTA) of the scallop shell powder (Fig. 3b) shows small endothermic peaks at 125 °C and 270 °C that can be first attributed to the release of residual absorbed moisture and the second to the release of residual absorbed moisture. of the organic matter present in the scallop shells. In addition, a large endothermic peak can be observed at

a temperature of 922 °C, which indicates a possible change in phase and characteristics of the study sample. Both thermal analyzes were done with a particle size of 325 mesh.



(a)



(b)

Fig. 3 Thermal analysis of scallop shell powder (a) Gravimetric thermal analysis (TGA). (b) Differential thermal analysis (DTA).

B. X-ray diffraction analysis (XRD)

X-ray analyses were performed for the identification of the mineralogical phases in the scallop shells at room temperature and after being heated to 1000°C. For this purpose, an X-Ray Diffractometer – MiniFlex, Rigaku – was used.

Figure 4 shows the X-ray diffraction of the scallop shell powder at room temperature, in which 100% calcium carbonate (calcite, CaCO₃) is displayed.

Figure 5 shows the X-ray diffraction of the scallop shell powder heated to 1000°C, in which an almost total of 100% of calcium hydroxide (Ca(OH)₂) is displayed, with the exception of a slight small amount of less than 1% of calcium carbonate (CC); this shows a high reactivity of the fan shell powder, calcined at high temperature.

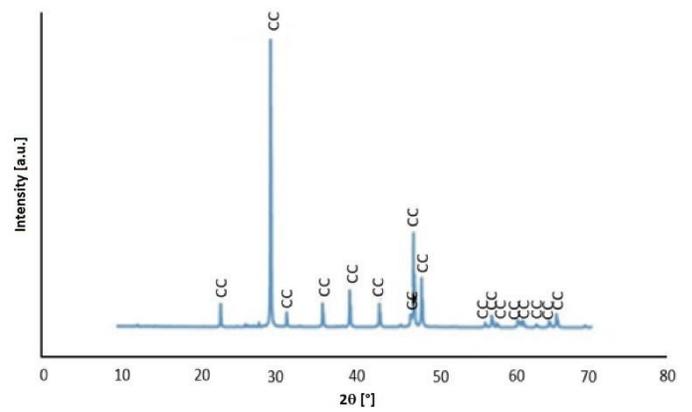


Fig. 4 X-ray diffraction analysis of scallop shell powder at room temperature CC: Calcite (CaCO₃)

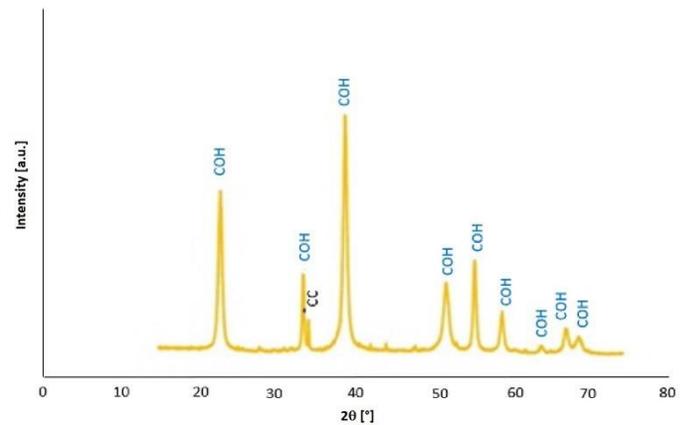


Fig. 5 X-ray diffraction analysis of scallop shell powder heated to 1000°C. COH: Calcium hydroxide CC: Calcite

C. Energy dispersive spectroscopy (EDS)

Energy dispersive spectroscopy analyses were performed to verify changes in chemical composition in scallop shells at room temperature and after heating to 1000°C. The detector for Energy Dispersive Spectroscopy (EDS) used was of the Oxford brand.

Figure 6 shows the energy dispersive spectroscopy analyses of the scallop shell powder at room temperature, in which it is verified with elemental analysis that its chemical composition corresponds to calcium carbonate.

Figure 7 shows the energy dispersive spectroscopy of the scallop shell powder heated to 1000°C, in which it is verified with elemental analysis that its chemical composition corresponds to calcium oxide.

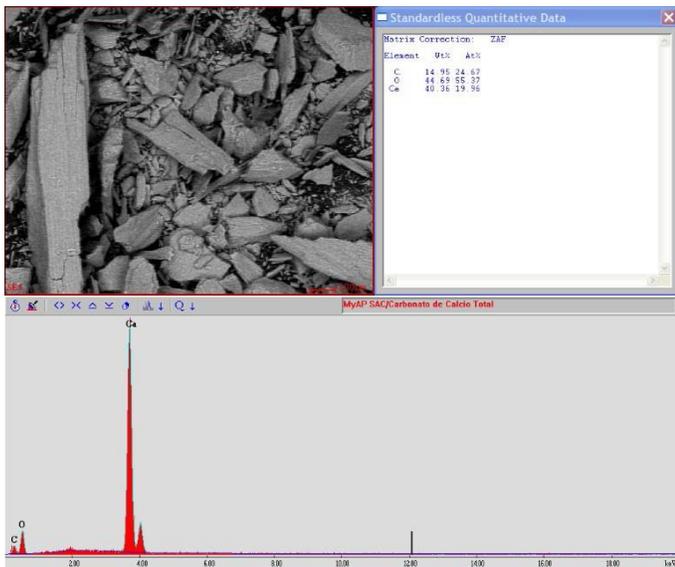


Fig. 6 Energy dispersive spectroscopy analyses of the scallop shell powder at room temperature.

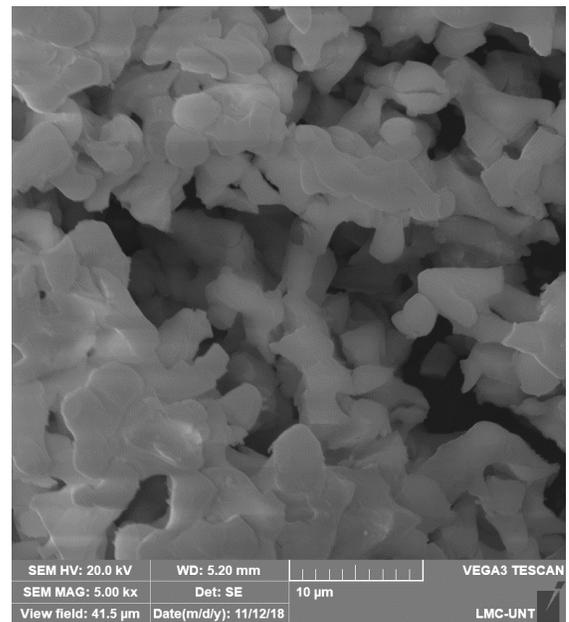


Fig. 8 SEM micrographs of scallop shell powder heated to 1000 °C.

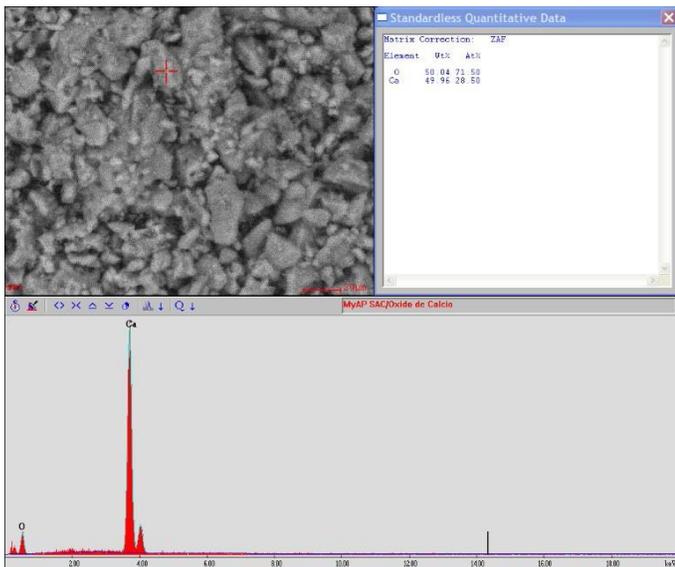


Fig. 7 Energy dispersive spectroscopy analyses of the scallop shell powder heated to 1000° C.

With the analyses carried out, the thermal decomposition of calcium carbonate in scallop shells is demonstrated.

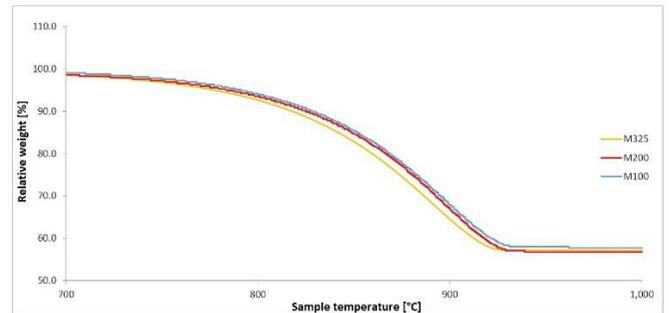
D. Microstructure

A Tescan Vega 3 XMU scanning electron microscope was used to observe the morphology of scallop shell powder heated to 1000 °C.

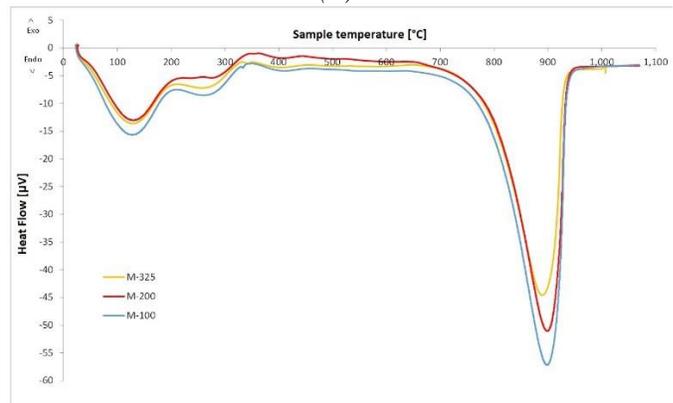
Figure 8 shows SEM micrographs of the scallop shell powder heated to 1000°C, in which you can see a particulate powder whose approximate particle size is 2 µm.

E. Effect of particle size

Thermal analyses were performed to determine the effect of particle size on phase transformations using a simultaneous thermal analyzer - Setaram Instrumentation - Setsys Evolution.



(a)



(b)

Fig. 3 Thermal analysis of scallop shell powder at different particle sizes (a) Gravimetric thermal analysis (TGA). (b) Differential thermal analysis (DTA).

Thermal gravimetric (TGA) and differential thermal (DTA) analyses of scallop shell powder are presented in Figures 9(a) and 9(b) respectively. These curves show that the particle size does influence the phase transformation process. With a smaller particle size, a higher decomposition rate is observed in a shorter time and at a lower temperature, compared to larger particle size.

IV. APPLICATIONS

For non-calcined powder, the construction industry is the major user of waste shells, particularly for concrete aggregate as either fine or coarse aggregate [3], [6]. It has also been used as cement clinkers [8], [23], as a soil stabilizer [7], as raw material for lime, and as an additive to ceramics [6].

The calcined powder has been used to remove heavy metals [24]–[32], for catalysis [33]–[38], as a bactericide [24]–[32], [39]–[49], as a coagulant [50], as an odor remover [51] and as a hygroscopic coating [52].

V. CONCLUSION

Scallop shells containing calcium carbonate as calcite thermally decompose at the temperature of 1000°C and convert to calcium oxide as a particulate powder with a size of 2 micrometers. SEM photographs reveal that scallop shells have a brick-like microstructure held together by organic material (SMPs), and this hierarchical microstructure explains the superior strength and toughness of inorganic calcium carbonate. The powder of calcined scallop shells is very active, as confirmed by XRD, the calcium oxide quickly transforms to calcium hydroxide in a humid environment.

Through thermogravimetric and differential thermal analysis, scallop shells begin to decompose at 650 °C and the temperature of calcination is 922 °C. The findings confirmed that particle size influenced the process. A sample with a smaller particle size demonstrates a higher decomposition rate in a shorter time and at a lower temperature compared to larger particle size.

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REFERENCES

[1] H. N. Ruslan, K. Muthusamy, S. M. Syed Mohsin, R. Jose, and R. Omar, "Oyster shell waste as a concrete ingredient: A review," in *Materials Today: Proceedings*, 2021, vol. 48, pp. 713–719. doi: 10.1016/j.matpr.2021.02.208.

[2] B. Peceño, B. Alonso-Fariñas, L. F. Vilches, and C. Leiva, "Study of seashell waste recycling in

fireproofing material: Technical, environmental, and economic assessment," *Science of The Total Environment*, vol. 790, p. 148102, Oct. 2021, doi: 10.1016/J.SCITOTENV.2021.148102.

[3] U. G. Eziefule, J. C. Ezeh, and B. I. Eziefule, "Properties of seashell aggregate concrete: A review," *Construction and Building Materials*, vol. 192, pp. 287–300, Dec. 2018, doi: 10.1016/j.conbuildmat.2018.10.096.

[4] N. Yan and X. Chen, "Sustainability: don't waste seafood waste," *Nature*, vol. 524, no. 7564, pp. 155–157, 2015, doi: https://doi.org/10.1038/524155a.

[5] C. Martínez-García, B. González-Fonteboa, D. Carro-López, and F. Martínez-Abella, "Recycled mollusc shells," in *New Trends in Eco-efficient and Recycled Concrete*, Elsevier, 2018, pp. 191–205. doi: 10.1016/B978-0-08-102480-5.00008-7.

[6] A. Hart, "Mini-review of waste shell-derived materials' applications," *Waste Management and Research*, vol. 38, no. 5, pp. 514–527, May 2020, doi: 10.1177/0734242X19897812.

[7] Z. Yao, M. Xia, H. Li, T. Chen, Y. Ye, and H. Zheng, "Bivalve shell: Not an abundant useless waste but a functional and versatile biomaterial," *Critical Reviews in Environmental Science and Technology*, vol. 44, no. 22, pp. 2502–2530, Nov. 17, 2014. doi: 10.1080/10643389.2013.829763.

[8] K. H. Mo, U. J. Alengaram, M. Z. Jumaat, S. C. Lee, W. I. Goh, and C. W. Yuen, "Recycling of seashell waste in concrete: A review," *Construction and Building Materials*, vol. 162, pp. 751–764, Feb. 2018, doi: 10.1016/j.conbuildmat.2017.12.009.

[9] H. Ez-Zaki, A. Diouri, S. Kamali-Bernard, and O. Sassi, "Composite cement mortars based on marine sediments and oyster shell powder," *Materiales de Construcción*, vol. 66, no. 321, Jan. 2016, doi: 10.3989/mc.2016.01915.

[10] J. H. Jung, H. Shon, K. S. Yoo, and K. J. Oh, "Physicochemical Characteristics of Waste Sea Shells for Acid Gas Cleaning Absorbent," *Korean J. Chem. Eng.*, vol. 17, no. 5, pp. 585–592, 2000.

[11] W. ten Kuo, H. Y. Wang, C. Y. Shu, and D. S. Su, "Engineering properties of controlled low-strength materials containing waste oyster shells," *Construction and Building Materials*, vol. 46, pp. 128–133, 2013, doi: 10.1016/j.conbuildmat.2013.04.020.

[12] P. Lertwattanaruk, N. Makul, and C. Siripattarapratvat, "Utilization of ground waste seashells in cement mortars for masonry and plastering," *Journal of Environmental Management*, vol. 111, pp. 133–141, Nov. 2012, doi: 10.1016/j.jenvman.2012.06.032.

[13] B. G. de Oliveira Maia, S. Arcaro, M. T. Souza, A. P. Novaes De Oliveira, T. M. Novais De Oliveira, and J. B. Rodrigues Neto, "Characterisation of sand casting and oyster shells as potential sources of raw material for the production of soda-lime glasses," *Chemical*

- Engineering Transactions*, vol. 43, pp. 1795–1800, 2015, doi: 10.3303/CET1543300.
- [14] E. I. Yang, S. T. Yi, and Y. M. 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, Nov. 2005, doi: 10.1016/j.cemconres.2005.03.016.
- [15] Z. Y. Bin-Yang ZHOU Qiang CHAN Chang-Feng Yan, “Structure and Property Characterization of Oyster Shell Cementing Material ①,” *Chinese J. Struct. Chem*, vol. 31, no. 1, pp. 85–92, 2012.
- [16] C. Varhen, S. Carrillo, and G. Ruiz, “Experimental investigation of Peruvian scallop used as fine aggregate in concrete,” *Construction and Building Materials*, vol. 136, pp. 533–540, Apr. 2017, doi: 10.1016/j.conbuildmat.2017.01.067.
- [17] E. Ferraz, J. A. F. Gamelas, J. Coroado, C. Monteiro, and F. Rocha, “Recycling Waste Seashells to Produce Calcitic Lime: Characterization and Wet Slaking Reactivity,” *Waste and Biomass Valorization*, vol. 10, no. 8, pp. 2397–2414, Aug. 2019, doi: 10.1007/s12649-018-0232-y.
- [18] C. Rivera Pérez and N. Y. Hernández Saavedra, “¿Cómo se forma la concha de moluscos?,” *Recursos Naturales y Sociedad*, vol. 6, no. 1, pp. 24–39, May 2020, doi: 10.18846/renaysoc.2020.06.06.01.0007.
- [19] F. Marin, G. Luquet, B. Marie, and D. Medakovic, “Molluscan Shell Proteins: Primary Structure, Origin, and Evolution,” in *Current Topics in Developmental Biology*, vol. 80, 2007, pp. 209–276. doi: 10.1016/S0070-2153(07)80006-8.
- [20] C. Zhang and R. Zhang, “Matrix proteins in the outer shells of molluscs,” *Marine Biotechnology*, vol. 8, no. 6, pp. 572–586, Dec. 2006, doi: 10.1007/s10126-005-6029-6.
- [21] A. G. Checa, E. M. Harper, and A. González-Segura, “Structure and crystallography of foliated and chalk shell microstructures of the oyster Magallana: The same materials grown under different conditions,” *Scientific Reports*, vol. 8, no. 1, Dec. 2018, doi: 10.1038/s41598-018-25923-6.
- [22] L. Addadi, D. Joester, F. Nudelman, and S. Weiner, “Mollusk shell formation: A source of new concepts for understanding biomineralization processes,” *Chemistry - A European Journal*, vol. 12, no. 4, pp. 980–987, Jan. 2006, doi: 10.1002/chem.200500980.
- [23] S. Her, T. Park, E. Zalnezhad, and S. Bae, “Synthesis and characterization of cement clinker using recycled pulverized oyster and scallop shell as limestone substitutes,” *Journal of Cleaner Production*, vol. 278, Jan. 2021, doi: 10.1016/j.jclepro.2020.123987.
- [24] J. Sawai, K. J. Nagasawa, and M. Kikuchi, “Ability of heated scallop-shell powder to disinfect *Staphylococcus aureus* biofilm,” *Food Science and Technology Research*, vol. 19, no. 4, pp. 561–568, 2013, doi: 10.3136/fstr.19.561.
- [25] N. Shimamura, F. Irie, T. Yamakawa, M. Kikuchi, and J. Sawai, “Heated scallop-shell powder treatment for deactivation and removal of *Listeria* sp. biofilm formed at a low temperature,” *Biocontrol Science*, vol. 20, no. 2. Society for Antibacterial and Antifungal Agents Japan, pp. 153–157, 2015. doi: 10.4265/bio.20.153.
- [26] J. Sawai, “Antimicrobial characteristics of heated scallop shell powder and its application,” *Biocontrol Science*, vol. 16, no. 3. pp. 95–102, 2011. doi: 10.4265/bio.16.95.
- [27] D.-H. Bae, J.-H. Yeon, S.-Y. Park, D.-H. Lee, and S.-D. Ha, “Bactericidal Effects of CaO (Scallop-Shell Powder) on Foodborne Pathogenic Bacteria,” 2006. [Online]. Available: <http://apr.psk.or.kr>
- [28] R. Xing, Y. Qin, X. Guan, S. Liu, H. Yu, and P. Li, “Comparison of antifungal activities of scallop shell, oyster shell and their pyrolyzed products,” *Egyptian Journal of Aquatic Research*, vol. 39, no. 2, pp. 83–90, 2013, doi: 10.1016/j.ejar.2013.07.003.
- [29] T. Watanabe, R. Fujimoto, J. Sawai, M. Kikuchi, S. Yahata, and S. Satoh, “Antibacterial Characteristics of Heated Scallop-Shell Nano-Particles,” 2014.
- [30] M. S. Jeong, J. S. Park, S. H. Song, and S. B. Jang, “Characterization of antibacterial nanoparticles from the scallop, *Ptinopecten yessoensis*,” *Bioscience, Biotechnology and Biochemistry*, vol. 71, no. 9, pp. 2242–2247, 2007, doi: 10.1271/bbb.70228.
- [31] A. Tsuruma, Y. Nomoto, M. Nishio, M. Ishikawa, and J. Sawai, “Efficacy of sorbitol-coated heated scallop-shell powder for the antimicrobial treatment of fresh vegetables,” *Food Control*, vol. 110, Apr. 2020, doi: 10.1016/j.foodcont.2019.106972.
- [32] G. Aydin and A. Kalemantas, “Antibacterial Properties of Scallop Shell Derived Calcium Hydroxide Powders,” *Material Science Research India*, vol. 18, no. 1, pp. 56–65, Apr. 2021, doi: 10.13005/msri/180107.
- [33] A. Buasri, N. Chaiyut, V. Loryuenyong, P. Worawanitchaphong, and S. Trongyong, “Calcium oxide derived from waste shells of mussel, cockle, and scallop as the heterogeneous catalyst for biodiesel production,” *The Scientific World Journal*, vol. 2013, 2013, doi: 10.1155/2013/460923.
- [34] M. Kaewpanha, S. Karnjanakom, G. Guan, X. Hao, J. Yang, and A. Abudula, “Removal of biomass tar by steam reforming over calcined scallop shell supported Cu catalysts,” *Journal of Energy Chemistry*, vol. 26, no. 4, pp. 660–666, Jul. 2017, doi: 10.1016/j.jechem.2017.03.012.
- [35] G. Guan *et al.*, “Catalytic steam reforming of biomass tar over iron- or nickel-based catalyst supported on calcined scallop shell,” *Applied Catalysis B: Environmental*, vol. 115–116, pp. 159–168, Apr. 2012, doi: 10.1016/j.apcatb.2011.12.009.
- [36] N. Chaihad *et al.*, “Catalytic pyrolysis of wasted fishing net over calcined scallop shells: Analytical Py-

- GC/MS study,” *Journal of Analytical and Applied Pyrolysis*, vol. 146, Mar. 2020, doi: 10.1016/j.jaap.2019.104750.
- [37] M. Kouzu, A. Kajita, and A. Fujimori, “Catalytic activity of calcined scallop shell for rapeseed oil transesterification to produce biodiesel,” *Fuel*, vol. 182, pp. 220–226, Oct. 2016, doi: 10.1016/j.fuel.2016.05.111.
- [38] S. Sirisomboonchai *et al.*, “Biodiesel production from waste cooking oil using calcined scallop shell as catalyst,” *Energy Conversion and Management*, vol. 95, pp. 242–247, May 2015, doi: 10.1016/j.enconman.2015.02.044.
- [39] Y. Sato *et al.*, “Preparation and application of bioshell calcium oxide (BiSCaO) nanoparticle-dispersions with bactericidal activity,” *Molecules*, vol. 24, no. 18, Sep. 2019, doi: 10.3390/molecules24183415.
- [40] N. Koyama, K. Sasaya, T. Yoshida, C. Fukuhara, T. Kohirumaki, and S. Okuda, “Bionic Design of the Scallop Shell Development of New Products that Apply Its Functions,” *Recent Research Developments in Material Science*, vol. 4, no. Research Signpost, pp. 449–462, 2003.
- [41] J.-H. Han, R. Ahmed, and B.-S. Chun, “Evaluation of Antimicrobial Activity of Allyl Isothiocyanate (AITC) Adsorbed in Oyster Shell on Food-borne Bacteria,” *Clean Technology*, vol. 21, no. 4, pp. 241–247, Dec. 2015, doi: 10.7464/ksct.2015.21.4.241.
- [42] M. Kubo, Y. Ohshima, F. Irie, M. Kikuchi, and J. Sawai, “Disinfection Treatment of Heated Scallop-Shell Powder on Biofilm of *Escherichia coli* ATCC 25922 Surrogated for *E. coli* O157:H7,” *Journal of Biomaterials and Nanobiotechnology*, vol. 04, no. 04, pp. 10–19, 2013, doi: 10.4236/jbnb.2013.44a002.
- [43] N. Shimamura, T. Yamakawa, M. Kikuchi, and J. Sawai, “Heated Scallop-Shell Powder Treatment for Deactivation and Removal of *Listeria sp.* Biofilm Formed at a Low Temperature,” *Biocontrol Science*, vol. 20, no. 2, pp. 153–157, 2015.
- [44] J. Sawai, “Antimicrobial Characteristics of Heated Scallop Shell Powder and its Application,” *Biocontrol Science*, vol. 16, no. 13, pp. 95–102, 2011.
- [45] N. Gultekin, “Evaluation of Antimicrobial Activity of Scallop Shell Powder Against Staphylococci Species and Gram Negative Bacteria Isolated From Patients Intensive Care Units,” *Biomedical Journal of Scientific & Technical Research*, vol. 13, no. 4, Jan. 2019, doi: 10.26717/bjstr.2019.13.002445.
- [46] K. Takama *et al.*, “Inhibition of the Growth of Foodborne Disease-Causing Bacteria by Calcined Scallop Shell Powder,” *Bulletin of the faculty of the fisheries Hokkaido University*, vol. 50, no. 2, pp. 149–153, Aug. 1999, Accessed: Feb. 28, 2022. [Online]. Available: <http://hdl.handle.net/2115/24192>
- [47] A. Buasri, P. Worawanitchaphong, S. Trongyong, and V. Loryuenyong, “Utilization of Scallop Waste Shell for Biodiesel Production from Palm Oil – Optimization Using Taguchi Method,” *APCBEE Procedia*, vol. 8, pp. 216–221, 2014, doi: 10.1016/j.apcbee.2014.03.030.
- [48] J. Sawai, M. Satoh, M. Horikawa, H. Shiga, and H. Kojima, “Heated Scallop-Shell Powder Slurry Treatment of Shredded Cabbage,” 2001. [Online]. Available: http://meridian.allenpress.com/jfp/article-pdf/64/10/1579/1671670/0362-028x-64_10_1579.pdf
- [49] J. Sawai, H. Shiga, and H. Kojima, “Kinetic analysis of the bactericidal action of heated scallop-shell powder,” 2001. [Online]. Available: www.elsevier.com/locate/jfoodmicro
- [50] S. Zaman, A. Begum, K. S. Rabbani, and L. Bari, “Low cost and sustainable surface water purification methods using Moringa seeds and scallop powder followed by bio-sand filtration,” *Water Science and Technology: Water Supply*, vol. 17, no. 1, pp. 125–137, Feb. 2017, doi: 10.2166/ws.2016.111.
- [51] S. Abraham, S. Joslyn, and I. H. (Mel) Suffet, “Treatment of odor by a seashell biofilter at a wastewater treatment plant,” *Journal of the Air and Waste Management Association*, vol. 65, no. 10, pp. 1217–1228, Oct. 2015, doi: 10.1080/10962247.2015.1075918.
- [52] Z. Mao, H. Zhang, Y. Li, X. Wang, Q. Wei, and J. Xie, “Preparation and characterization of composite scallop shell powder-based and diatomite-based hygroscopic coating materials with metal-organic framework for indoor humidity regulation,” *Journal of Building Engineering*, vol. 43, Nov. 2021, doi: 10.1016/j.jobbe.2021.103122.