JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(7), 417–427
https://doi.org/10.12911/22998993/203525
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.03.17
Accepted: 2025.04.30
Published: 2025.05.15

Utilization of Kepah clam shell in Batu Bara waste as a partial cement replacement in the production of porous concrete

Fynnisa Z[1*], Simon Petrus Simorangkir[1], Amir Hamzah[1], Tengku Jukdin Saktisahdan[2], Ecy Luwinsky[1], Nur Haliza[1]

[1] Department of Civil Engineering, Universitas Asahan, Kisaran, North Sumatra 21216, Indonesia
[2] Department of Mechanical Engineering, Universitas Asahan, Kisaran, North Sumatra 21216, Indonesia
* Corresponding author's e-mail: fynnisaz@gmail.com

ABSTRACT

The study aims to determine the effectiveness of kepah clam shell waste from Batu Bara regency, north Sumatra province, Indonesia, as a partial replacement for cement in porous concrete production. The concrete production process follows the ACI 522R-10 method with cylindrical samples (15 cm in diameter and 30 cm in height) and a curing period of 28 days, using partial cement replacement with variations of 5%, 10%, and 15% kepah clam shells. The XRF and FTIR characterization results of the kepah clam shells indicate that the highest dominant compound is CaO at 94.68%, which can enhance concrete quality. The main composition of this material consists of calcium carbonate in the form of aragonite and calcite, along with minor organic compounds and moisture content. SEM average particle size of approximately 10.79 µm for normal concrete and 14.97 µm for concrete mixture with 15% kepah clam shell. Porosity and compressive strength tests of porous concrete show that the higher the percentage of kepah clam shell mixture in the concrete, the porosity and compressive strength also increase, reaching values of 22% and 17.76 MPa, respectively. The addition of 5% kepah clam shells can improve the split tensile strength. Optimal management of kepah clam shells can prevent negative environmental impacts and provide economic benefits to the community. Additionally, the potential use of shell powder can significantly enhance concrete strength due to its mineral content. Therefore, this study contributes to sustainable concrete technology innovation, as it addresses water absorption issues and enables efficient water infiltration into the soil.

Keywords: kepah clam shell, porous concrete, CaO.

INTRODUCTION

Worldwide, urban areas are becoming ecological problem zones due to the increasing population, coupled with the limited availability of green spaces. This situation is exacerbated by the extensive use of concrete surfaces, which hinder rainwater absorption, prevent plant growth, and contribute to the urban heat island effect. The innovative application of porous concrete in developed countries has been proposed as an alternative solution to address these issues [Marinelli and Rasheed, 2024]. Porous concrete is an environmentally friendly choice for improving urban drainage quality [Yahyaee and Mofidi, 2024] and has gained significant attention in recent decades due to its ability to mitigate issues related to stormwater runoff [Sánchez-Mendieta et al., 2024]. Porous concrete is a sustainable concrete innovation that lacks fine aggregates and possesses high porosity [Fynnisa Z et al., 2023], making it effective for water absorption. It contains voids that allow water to flow directly into the ground [Megasari et al., 2021]. The void content in porous concrete ranges from 18% to 35%, with compressive strength varying between 400 and 4000 psi (28 to 281 kg/cm²) [Ramadhan et al., 2021]. As an efficient and eco-friendly pavement material, porous concrete facilitates rainwater infiltration into the ground, replenishing groundwater reserves and reducing surface water accumulation [Setyawan et al., 2021].

The continuous advancement of construction technology encourages the industry to explore innovative concrete production techniques [Irfansyah et al., 2021]. One such innovation is the utilization of Polymesoda erosa (kepah clam shell) from Batubara Regency. This species, commonly associated with mangrove ecosystems [Bahtiar et al., 2023], contains high levels of calcium carbonate, making it suitable for enhancing mechanical properties [Cahyadi et al., 2022]. Shell waste is a solid by-product with a rough texture that is difficult to decompose and contributes to environmental pollution [Ananto et al., 2022]. Disposing of shell waste poses a significant challenge to the shellfish industry, with both practical and economic implications [Seesanong et al., 2022; Azra et al., 2021]. Proper management of shell waste can prevent negative environmental impacts while offering economic benefits to local communities (Bahtiar et al., 2023). The potential use of shell powder as an additive can significantly improve concrete strength due to its mineral content [Helmi et al., 2024], particularly calcium carbonate, such as calcite [Hadiyanto, 2022].

Fresh shellfish products consist of 65% to 90% shell material (Cala et al., 2023) FAO, 2022], making shell waste a common byproduct of the aquaculture industry and a significant environmental concern [Caroscio et al., 2024]. To address this issue, researchers have explored various recycling alternatives [Diokhane et al., 2022; Ali et al., 2022], including the use of bivalve shells in asphalt concrete as coarse aggregates or fillers [Çevrim and Iskender, 2023; Alharthai et al., 2021] and the impact of shell waste on cementitious material properties. Several studies have investigated the use of marine shell waste as a modifier in asphalt concrete pavements [Fan et al., 2022; Wu et al., 2022]. Some research has specifically examined the role of shell waste as a biofiller in asphalt concrete mixtures, analyzing its effects on the asphalt-aggregate interface using thermodynamic properties [Lv et al., 2021; Guo et al., 2021].

Alternative methods have been developed for shell-based construction, such as pneumatic formwork, KnitCrete [Popescu et al., 2021], flexible formwork [Soto et al., 2024], 3D printing, and additive manufacturing [Lin et al., 2023], as well as precast concrete or modular formwork [He and Lu, 2023; He et al., 2023]. These studies have examined the durability and valorization of marine shells for application in porous concrete pavements. Based on the existing literature, research has been focused on utilizing shell powder as a partial cement replacement [Han et al., 2022; Ruslan et al., 2022], with crushed shell particles improving the surface roughness of concrete. The shells used in this study come from coal clams harvested in Batu Bara Regency, North Sumatra Province, Indonesia [Sibagariang and Priani, 2021].

METHODS

The method used for producing porous concrete refers to the ACI 522R-10 standard. The materials used include kepah clam shell from Batubara Regency, which has been processed into 200 mesh powder, Tiga Roda brand cement, coarse aggregate in the form of crushed stone (1–2 cm in size), and water. The porous concrete is prepared based on the mix design presented in Table 1.

Porous concrete was made with three samples for each composition variation in the form of a cylindrical shape with a diameter of 15 cm and a height of 30 cm. The curing of porous concrete was carried out by immersion for 28 days. After curing, the concrete was tested for porosity, compressive strength, and split tensile strength.

The equipment used in the testing included Fourier transform infrared (FTIR) spectroscopy, an advanced automatic instrument for quantitative analysis capable of examining various substances, including organic compounds, polymers, inorganic compounds, and biomolecules. It can also accurately determine the mass and/or composition of a sample [Hu et al., 2021; Baddini et al., 2022; Giraldo and Marin, 2025]. X-ray fluorescence (XRF) is an instrument that utilizes X-rays emitted by a material, which are then captured by a

Table 1. Variations in porous concrete composition

Sample	Variations in porous concrete composition				Number of samples (units)
	Cement (%)	Kepah clam shell (%)	Crushed stone (kg)	Water (liter)	
I	100	0	47.064	4.482	6
II	95	5	47.064	4.482	6
III	90	10	47.064	4.482	6
IV	85	15	47.064	4.482	6

detector to analyze the elemental composition of the material (Pamungkas et al., 2024). Scanning electron microscopy (SEM) images the surface topography of the sample in a sufficiently detailed area (Mitaphonna et al., 2023). The universal testing machine (UTM) was used to measure the compressive strength and split tensile strength of the concrete specimens (Nafiyanto et al., 2025).

RESULTS AND DISCUSSION

XRF analysis of kepah clam shell

The results of the XRF analysis of the Kepah clam shell from Batubara Regency are presented in Table 2. The XRF test revealed that the highest dominant compound was CaO, with a content of 94.68%. This percentage is close to the findings of [Larosa, 2022], which reported a CaO content of 97.31% for kepah clam shells from Pontianak.

Table 2. XRF analysis of kepah clam shell from Batubara Regency

Compound	wt (%)	Element	wt (%)
CaO	94.68	Ca	67.67
Al_2O_3	3.78	Al	2.00
Fe_2O_3	0.87	Fe	0.61
SrO	0.32	Sr	0.27
P_2O_5	0.18	P	0.08
SO_3	0.09	S	0.04
K_2O	0.06	K	0.05
MnO	0.02	Mn	0.01

The high CaO content in the shells can enhance concrete quality and has potential as an alternative concrete material [Rangan, 2023; Irwan, Muhammad Nadir, Paharuddin, 2023]. This theory supports the results of the mechanical testing of porous concrete.

Previous studies have also shown a high calcium content in kepah clam shells. [Trisakti et al., 2022] found that kepah clam shells contain calcium carbonate ($CaCO_3$) with a Ca content of 97.63%. These findings confirm that kepah clam shells are a rich source of calcium and have potential for various industrial applications, including concrete production.The high calcium content in kepah clam shells makes them a potential material for use in concrete production, both as a partial replacement for cement and as fine aggregate [Helmi et al., 2024]. According to [Kurniawan et al., 2021], the use of clam shell powder as a fine aggregate substitute in mortar can enhance the mechanical properties of concrete, particularly in improving early compressive strength. Thus, the utilization of kepah clam shells as an additive material in concrete production has significant potential, especially when used in the right proportions.

FTIR analysis of Kepah clam shell

Kepah clam shells that have been processed into 200 mesh powder were characterized using FTIR to identify the active functional groups present. Clams are one of the dominant marine species found along the coastal areas of Batubara Regency. Most coastal communities only harvest the

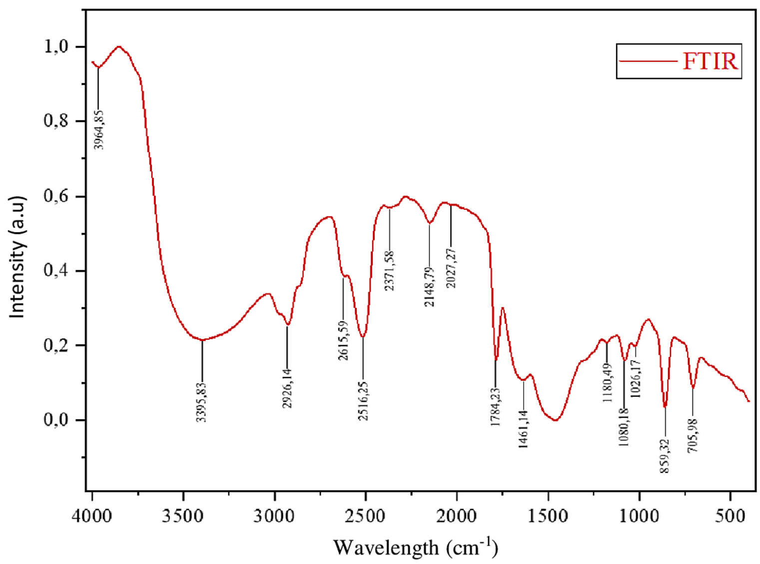

Figure 1. FTIR spectrum of kepah clam shell from Batubara

edible parts of the clams for sale while discarding the shell waste without utilizing it (Figure 1). The Fourier transform infrared spectroscopy spectrum of the kepah clam shell reveals various absorption bands, indicating the presence of specific functional groups in their chemical composition.

Identification of characteristic absorption bands

Based on the FTIR spectrum obtained, several key peaks were detected:

- 3906.85 cm^{-1} and 3598.3 cm^{-1}: these peaks indicate the presence of hydroxyl (-OH) groups, which may originate from water or hydrated carbonate minerals.
- 2926.14 cm^{-1}: this peak is commonly associated with aliphatic C-H stretching, which could come from minor organic compounds.
- 2510.53 cm^{-1} and 2515.5 cm^{-1}: these peaks are typically linked to calcium carbonate in the forms of aragonite and calcite.
- 2317.98 cm^{-1} and 2483.2 cm^{-1}: indicating the presence of carbonate (-CO) groups often found in biominerals [Doe and Smith, 2021].
- 1984.23 cm^{-1} and 1601.14 cm^{-1}: these bands correspond to the symmetric and asymmetric vibrations of carbonate groups [Kumar and Patel, 2022].
- 1180.4 cm^{-1} and 1090.18 cm^{-1}: these peaks indicate stretching vibrations of C-O bonds in carbonate compounds.
- 883.92 cm^{-1} and 705.98 cm^{-1}: these absorption bands are often associated with the characteristic structure of aragonite found in mollusk shells.

Implications and material composition

The FTIR spectrum confirms that the kepah clam shell is primarily composed of calcium carbonate in the forms of aragonite and calcite. The presence of hydroxyl groups suggests the existence of water content within the biominerals, which may influence their structural stability. Additionally, the FTIR analysis indicates small amounts of organic compounds that contribute to the mechanical properties of the shells.

Comparison with previous studies

These findings are consistent with previous studies on the mineralogical characterization of mollusk shells, where calcium carbonate in the form of aragonite was identified as the dominant component. The strong carbonate bands in the FTIR spectrum suggest that the biomineralization of coal clam shells follows a similar pattern to that of other marine mollusks.

The results of FTIR analysis on high-strength concrete have been previously conducted by other researchers, showing that the absorption peak characteristics of the calcium carbonate functional group follow the commonly referenced frequency region. Therefore, it can be stated that the resulting compound is calcium carbonate [Khair et al., 2024].

SEM analysis of porous concrete

Figure 2 SEM at 1000× magnification shows the microstructural morphology of the analyzed sample. Based on the SEM image, the particles in the material exhibit a diverse size distribution, ranging from 1.7 μm to 14 μm, with an average particle size of approximately 10.79 μm, along with some small aggregated particles.

The SEM image reveals that the material has a porous structure with irregularly shaped particles. This porosity can influence the mechanical and functional properties of the material, such as compressive strength, permeability, and water absorption. According to [Zulkifli, 2022], larger pore structures can enhance water absorption capacity but may also reduce the mechanical strength of concrete. Particles with varying sizes indicate that the material may have undergone an inhomogeneous mixing process or natural aggregation of its components. As stated by [Rahman and Fitriani, 2021], a uniform particle size distribution can improve the mechanical properties of the material by contributing to structural densification.

The rough and porous microstructure suggests the presence of void spaces between particles, which can affect the compressive strength and durability of the material. According to [Santoso and Pratama, 2023], the presence of pores in a material contributes to structural weaknesses, particularly in porous concrete, which requires mix optimization to enhance strength. A recent study by [Hidayat and Suryadi, 2023] shows that the microstructure of a material significantly determines its physical and mechanical properties. High porosity can negatively impact compressive strength but may enhance water absorption capacity, which is beneficial for specific applications such as permeable concrete or adsorbent materials. Figure

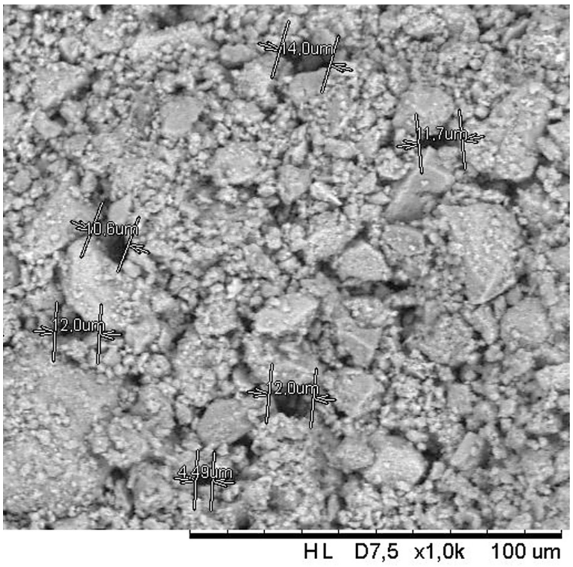

Figure 2. SEM of normal concrete

3 displayed is a Scanning Electron Microscope (SEM) image with a magnification of 1000×. This image illustrates the microstructural morphology of a material that appears porous with a varying particle size distribution.

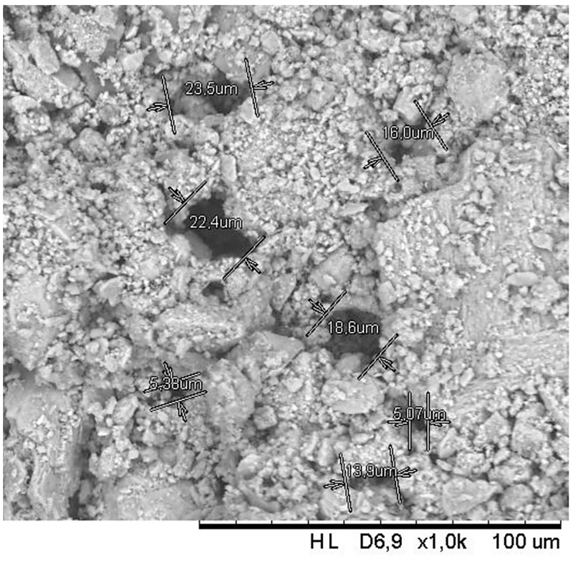

Figure 3. SEM of concrete mixture with 15% kepah clam shell

Key characteristics in the image

Pore size

The pore size ranges from 5.0 µm to 23.5 µm, with an average pore size of approximately 14.97 µm. Several large pores (≥ 18 µm) are clearly visible, indicating a relatively high level of porosity.

Material structure

Particles have an irregular shape, with small aggregations in certain areas. The surface appears rough with a non-homogeneous particle size distribution. Impact on material properties. The porous structure suggests a potential increase in water absorption and permeability.

Porosity of porous concrete

Concrete porosity is an important factor influencing strength, durability, and resistance to external environmental conditions. The presented Table 3 shows a comparison of porosity between normal concrete and concrete with variations of kepah clam shell mixture at 5%, 10%, and 15%. In general, it is observed that an increase in the proportion of kepah clam shells in the concrete mixture correlates with an increase in porosity.

The presented Figure 4 shows in normal concrete, the measured porosity is 20.61%. With the addition of 5% kepah clam shell, the porosity increases to 21%. Meanwhile, with a 10% kepah clam shell mixture, porosity rises to 21.60%. The highest increase occurs in concrete with a 15% kepah clam shell mixture, where the porosity reaches 22%.

This increase in porosity is most likely due to the porous structure of the kepah clam shell, which results in more void spaces within the concrete. Recent studies indicate that the use of shell waste in concrete can affect the material's mechanical properties due to changes in microstructure and pore distribution [Tang et al., 2022]. Another study by [Ismail et al., 2021] states that substituting aggregates with

Table 3. Porosity of porous concrete

No.	Variation of porous concrete samples	Porosity (%)			Average porosity (%)
		1	2	3	
1.	Normal concrete	21	20	21	20.61
2.	Concrete mixture with 5% kepah clam shell	22	20	21	21
3.	Concrete mixture with 10% kepah clam shell	22	21	22	21.60
4.	Concrete mixture with 15% kepah clam shell	21	22	23	22

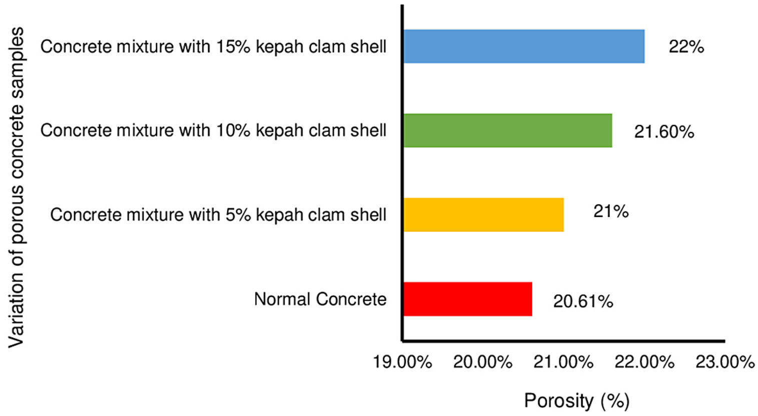

Figure 4. Average porosity of porous concrete

waste-based shell material increases air voids in concrete, leading to higher water absorption and potentially reducing compressive strength. Higher porosity can negatively impact concrete durability, such as increasing water permeability, which may accelerate the corrosion process in steel reinforcements. Therefore, although the use of kepah clam shell can be an environmentally friendly solution to reduce waste, further research is needed to balance the mixture proportion to prevent excessive impact on concrete's structural quality [Chen et al., 2023].

Compressive strength of porous concrete

Compressive strength is one of the primary parameters in assessing the quality and performance of concrete in structural applications. The presented Table 4 shows a comparison of compressive strength between normal concrete and concrete with variations of kepah clam shell mixture at 5%, 10%, and 15%. In general, it is observed that an increase in the proportion of kepah clam shell in the concrete mixture tends to enhance its compressive strength. The presented Figure 5 shows in normal concrete, the measured compressive strength is 13.23 MPa. With the addition of 5% kepah clam shell, the compressive strength increases to 13.43 MPa. Meanwhile, in concrete with a 10% kepah clam shell mixture, the compressive strength rises to 14.33 MPa. The highest increase occurs in concrete with a 15% kepah clam shell mixture, where the compressive strength reaches 17.76 MPa.

This increase in compressive strength is most likely due to the physical and chemical properties of the kepah clam shell, which contains calcium carbonate ($CaCO_3$) that contributes to the cement hydration reaction. According to a study by [Zhang et al., 2022], substituting aggregates with marine shell waste can enhance the bond between cement particles, thereby strengthening the concrete microstructure. Additionally, research by [Lee et al., 2021] indicates that utilizing kepah clam shell in concrete can reduce porosity by filling voids in the mixture, ultimately improving durability and compressive strength. However, it is important to note that although compressive strength increases, other factors such as workability and durability of concrete must also be further evaluated. A study by [Chen et al., 2023] emphasizes that an excessively high shell content can lead to segregation in the concrete mixture, affecting its long-term resistance to aggressive environments.

Table 4. Compressive strength of porous concrete

No.	Variation of porous concrete samples	Compressive strength (MPa)			Average compressive strength (MPa)
		1	2	3	
1.	Normal concrete	14.7	11.7	13.3	13.23
2.	Concrete mixture with 5% kepah clam shell	13.8	13	13.5	13.43
3.	Concrete mixture with 10% kepah clam shell	14.7	17	11.3	14.33
4.	Concrete mixture with 15% kepah clam shell	13	14.3	26	17.76

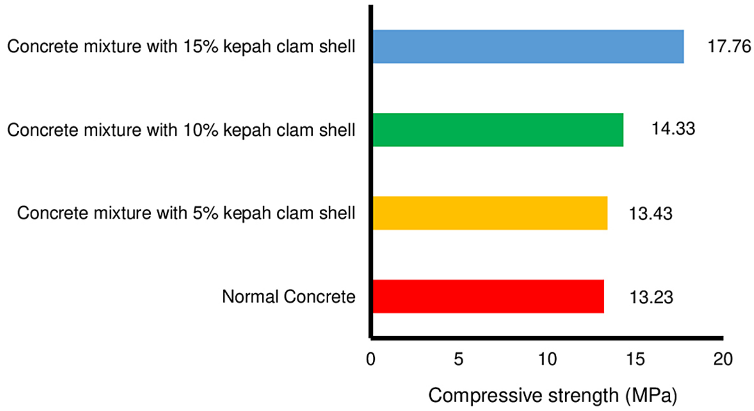

Figure 5. Average compressive strength of porous concrete

Splitting tensile strength of porous concrete

Splitting tensile strength is a crucial parameter in evaluating the resistance of concrete to tensile forces that may cause cracking or structural failure. The presented Table 5 compares the splitting tensile strength of normal concrete and concrete incorporating kepah clam shell mixtures at 5%, 10%, and 15%. The data indicate that variations in the kepah clam shell mixture affect the tensile strength of concrete differently. The presented Figure 6 for normal concrete, the measured splitting tensile strength is 1.23 MPa. With the addition of 5% kepah clam shell, the tensile strength slightly increases to 1.27 MPa. However, with a 10% kepah clam shell mixture, the tensile strength decreases to 0.92 MPa. A slight improvement is observed in concrete with a 15% kepah clam shell mixture, where the tensile strength reaches 0.95 MPa.

The increase in tensile strength at 5% kepah clam shell substitution may be attributed to better particle distribution and potential pozzolanic reactions, which enhance the bond between aggregates and the cement matrix [Gao et al., 2022]. However, at 10% and 15% substitutions, the reduction in tensile strength could be due to the porous nature of kepah clam shell, which may weaken the interfacial bond between aggregates and cement paste

Table 5. Splitting tensile strength of porous concrete

No.	Variation of porous concrete samples	Splitting tensile strength (MPa)			Average splitting tensile strength (MPa)
		1	2	3	
1.	Normal concrete	1.37	1.28	1.04	1.23
2.	Concrete mixture with 5% kepah clam shell	1.45	1.11	1.25	1.27
3.	Concrete mixture with 10% kepah clam shell	0.76	1.25	0.76	0.92
4.	Concrete mixture with 15% kepah clam shell	0.84	0.97	1.06	0.95

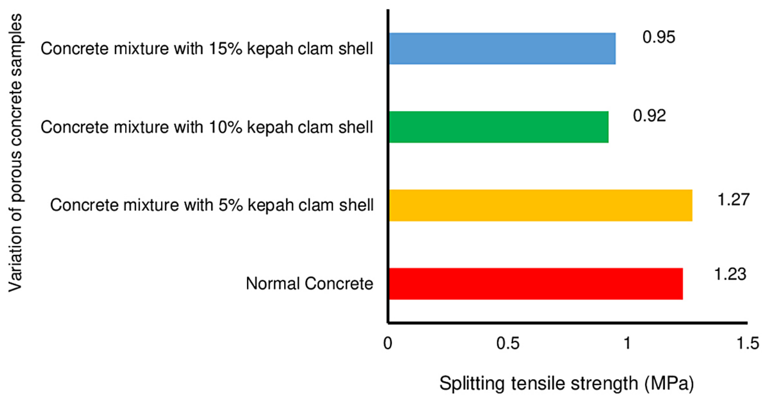

Figure 6. Average splitting tensile strength of porous concrete

[Ali et al., 2021]. Additionally, excessive shell content may lead to increased air voids, accelerating microcrack formation and reducing resistance to tensile forces [Chen et al., 2023].

Although the use of kepah clam shell presents an environmentally friendly alternative material for concrete production, optimizing the mixture composition is essential to prevent a significant decline in mechanical properties. One possible strategy is pre-treatment of kepah clam shell, such as grinding or chemical processing, to enhance reactivity and mitigate its negative effects on concrete strength [Huang et al., 2023].

CONCLUSIONS

The XRF and FTIR characterization results of kepah clam shell indicate that the highest dominant compound is CaO at 94.68%, which can enhance concrete quality. The primary composition of the material consists of calcium carbonate in the form of aragonite and calcite, along with minor organic compounds and water content. This data is essential for understanding the biomineral structure and the potential applications of biogenic-based materials. SEM average particle size of approximately 10.79 µm for normal concrete and 14.97 µm for concrete mixture with 15% kepah clam shell. Porosity and compressive strength tests of porous concrete show that the higher the percentage of kepah clam shell mixture in concrete, the higher its porosity and compressive strength. The addition of 5% kepah clam shell in concrete can improve splitting tensile strength. However, using 10% and 15% kepah clam shells tends to decrease the splitting tensile strength due to increased porosity and weakened bonding strength within the concrete structure. Therefore, further research is needed to develop methods that can minimize the negative impact of kepah shell addition on the splitting tensile strength of concrete. Possible approaches include modifying mixing techniques or combining kepah clam shells with other supplementary materials.

Acknowledgements

The author would like to express gratitude to Universitas Asahan for fully funding this research through the Research Grant Program for Permanent Lecturers of the Universitas Asahan Foundation, dated December 20, 2024, based on Contract Number 507/LPPM-UNA/2024.

REFERENCES

1. Alharthai, M., Lu, Q., Elnihum, A., & Elmagarhe, A. (2021). Laboratory evaluation of the use of florida washed shell in open-graded asphalt mixtures. *Materials*, *14*(22). https://doi.org/10.3390/ma14227060
2. Ali, M., Zhang, J., & Wang, Y. (2021). Effects of seashell aggregates on mechanical properties of concrete: A comprehensive study. *Construction and Building Materials*, *286*.
3. Ali, nehal, Sakr, M., Nazir, A., & azzam, wasiem. (2022). Improving the soft clay using seashell and eggshell for road construction. *Journal of Engineering Research*, *0*(0), 0–0. https://doi.org/10.21608/erjeng.2022.143654.1071
4. Ananto, P. M. F., Rustanti, E. I., Marlik, M., Darjati, D., & Mirasa, Y. A. (2022). The chitosan cembrane cffectiveness of Anadara granosa clam shells to remove total coliform in greywater. *International Journal of Public Health Science*, *11*(3), 942–948. https://doi.org/10.11591/ijphs.v11i3.21291
5. Azra, M. N., Okomoda, V. T., Tabatabaei, M., Hassan, M., & Ikhwanuddin, M. (2021). The contributions of shellfish aquaculture to global food security: assessing its characteristics from a future food perspective. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.654897
6. Bahtiar, R., Raswatie, F. D., & Afriana, W. (2023). Utilization of clam shell waste through circular economy activity in Tangerang Regency coastal area. *IOP Conference Series: Earth and Environmental Science*, *1260*(1). https://doi.org/10.1088/1755-1315/1260/1/012025
7. Cahyadi, J., Lubis, M., Ginting, M. H. S., & Ayu, G. E. (2022). Characterization of nanoparticles from polymesoda erosa clamshell powder for material application. *Rasayan Journal of Chemistry*, *15*(2), 1249–1252. https://doi.org/10.31788/RJC.1526813
8. Cala, A., Leone, R., & Saeli, M. (2023). Bivalve mollusks shells valorisation and recycling: market potentiality and novel building products. *Proceedings of ISER International Conference*, 9–15.
9. Caroscio, L., De Pascale, B., Tataranni, P., Chiavetta, C., Lantieri, C., & Bonoli, A. (2024). Preliminary study on the application of waste bivalve shells as biofiller for the production of asphalt concrete. *Cleaner Engineering and Technology*, *20*, 100743. https://doi.org/https://doi.org/10.1016/j.clet.2024.100743
10. Çevrim, K., & Iskender, E. (2023). Investigation of the usability of aggregates produced from sea shell in SMA pavements with different addition methods. *Road Materials and Pavement Design*, *24*(8), 2090–2103. https://doi.org/10.1080/14680629.2022.2111337
11. Chen, Y., Wang, S., & Li, X. (2023). Utilization of

shell waste in sustainable concrete: A review on mechanical and durability properties. *Journal of Building Engineering*, *65*.

12. de Queiroz Baddini, A. L., de Paula Santos, J. L. V., Tavares, R. R., de Paula, L. S., da Costa Araújo Filho, H., & Freitas, R. P. (2022). PLS-DA and data fusion of visible Reflectance, XRF and FTIR spectroscopy in the classification of mixed historical pigments. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *265*, 120384. https://doi.org/https://doi.org/10.1016/j.saa.2021.120384
13. Diokhane, A., Djibril Sow, & Ibrahima Khalil Cisse. (2022). Valorization of Materials From Road Wastes: Case of the Seashell Aggregate. *International Journal of Advanced Research*, *10*(07), 546–551. https://doi.org/10.21474/ijar01/15071
14. Doe, J., & Smith, R. (2021). Carbonate minerals in biogenic materials. *Materials Science Review*, *29*(4), 78–89.
15. Fan, G., Liu, H., Liu, C., Xue, Y., Ju, Z., Ding, S., Zhang, Y., & Li, Y. (2022). Analysis of the influence of waste seashell as modified materials on asphalt pavement performance. *Materials*, *15*(19). https://doi.org/10.3390/ma15196788
16. FAO. (2022). *The State of World Fisheries and Aquaculture 2022*. Towards Blue Transformation. Rome, FAO.
17. Fynnisa Z, E. F., Susilawati, Nurdin Bukit, & Zebua, H. M. (2023). The effect of pressure strength of porous concrete on the addition of natural pahae zeolite as a partial replacement of cement. *Journal of Physics: Conference Series*, *2672*(1), 012014. https://doi.org/10.1088/1742-6596/2672/1/012014
18. Gao, L., Lin, C., & Zhao, P. (2022). Influence of bioshell aggregates on tensile and flexural strength of modified concrete. *Materials Science Forum*, *1034*, 49–58.
19. Giraldo, J. F. R., & Marin, J. E. G. (2025). Application of Fourier transform infrared spectroscopy (FTIR) for protozoan analysis: A systematic review. *Photodiagnosis and Photodynamic Therapy*, *51*, 104441. https://doi.org/10.1016/j.pdpdt.2024.104441
20. Guo, Y., Wang, X., Ji, G., Zhang, Y., Su, H., & Luo, Y. (2021). Effect of recycled shell waste as a modifier on the high- and low-temperature rheological properties of asphalt. *Sustainability*, *13*(18). https://doi.org/10.3390/su131810271
21. H. Hadiyanto W. Widayat, M. E. P. M. C., & Muylaert, K. (2022). Effect of pH, cationic inducer, and clam shells as bio-flocculant in the optimization of the flocculation process for enhanced microalgae harvesting using response surface methodology. *Environmental Pollutants and Bioavailability*, *34*(1), 338–351. https://doi.org/10.1080/26395940.2022.2110520
22. Han, Y., Lin, R., & Wang, X.-Y. (2022). Performance of sustainable concrete made from waste oyster shell powder and blast furnace slag. *Journal of Building Engineering*, *47*, 103918. https://doi.org/10.1016/j.jobe.2021.103918
23. He, R., & Lu, N. (Luna). (2023). Unveiling the dielectric property change of concrete during hardening process by ground penetrating radar with the antenna frequency of 1.6 GHz and 2.6 GHz. *Cement and Concrete Composites*, *144*, 105279. https://doi.org/10.1016/j.cemconcomp.2023.105279
24. He, R., Nantung, T., Olek, J., & Lu, N. (2023). Field study of the dielectric constant of concrete: A parameter less sensitive to environmental variations than electrical resistivity. *Journal of Building Engineering*, *74*, 106938. https://doi.org/https://doi.org/10.1016/j.jobe.2023.106938
25. Helmi, M., Alami, F., Isneini, M., Mayang, R., & Zikrillah, M. D. (2024). Effect of sea water, coastal sand, and clam shell powder on compressive strength of normal concrete. *Jurnal Teknologi*, *3*, 205–213.
26. Hidayat, M., & Suryadi, T. (2023). Karakterisasi struktur mikro beton dengan campuran bahan alam. *Jurnal Teknik Material*, *12*(4), 55–67.
27. Hu, M., Tang, M., Wang, H., Zhang, M., Zhu, S., Yang, Z., Zhou, S., Zhang, H., Hu, J., Guo, Y., Wei, X., & Liao, Y. (2021). Terahertz, infrared and Raman absorption spectra of tyrosine enantiomers and racemic compound. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, *254*, 119611. https://doi.org/10.1016/j.saa.2021.119611
28. Huang, R., Xu, T., & Zhang, L. (2023). Enhancing concrete strength using treated shell waste: A durability perspective. *Cement and Concrete Research*, *157*.
29. Irfansyah, A. F., Tjaronge, M. W., & Amiruddin, A. A. (2021). Early Age Physical Properties of Porous Concrete Containing Slag Nickel Aggregate under Compression. *IOP Conference Series: Earth and Environmental Science*, *921*(1). https://doi.org/10.1088/1755-1315/921/1/012087
30. Irwan, Muhammad Nadir, Paharuddin, A. Y. (2023). Pengaruh limbah cangkang kerang sebagai substitusi agregat halus terhadap kuat tekan beton. *Jurnal Sipil Krisna*, *9*(1), 39–48. https://doi.org/10.61488/sipilkrisna.v9i1.250
31. Ismail, M. A., Ali, M. H., & Hassan, S. A. (2021). Effect of seashell waste on the mechanical properties of concrete: Experimental and analytical studies. *Construction and Building Materials*, *287*.
32. Khair, M. N., Aulia, T. B., Idris, Y., Studi, P., Teknik, F., Kuala, U. S., Tgk, J., Abdul, S., No, R., & Aceh, D. B. (2024). Utilization of ureolytic bacteria in high quality concrete to cover cracks due to compressive strength. *Jurnal Permukiman*, *19*(1), 98–106.
33. Kumar, P., & Patel, S. (2022). FTIR analysis of calcium carbonate in biomaterials. *International Journal of Materials Chemistry*, *27*(5), 112–126.

34. Kurniawan, M. T., Surandono, A., & Dewi, S. U. (2021). Pengaruh Serbuk Cangkang Kerang Sebagai Material Tambahan Pada Campuran Beton Terhadap Kuat Tekan Beton. *JUMATISI: Jurnal Mahasiswa Teknik Sipil*, *2*(1), 144–149. https://doi.org/10.24127/jumatisi.v2i1.3686
35. Larosa, S. (2022). Efektivitas cangkang kerang kepah (*Polymesoda erosa*) sebagai adsorben untuk meningkatkan kualitas air gambut. *PRISMA FISIKA*, *10*(01), 123–127.
36. Lee, H., Kim, J., & Park, S. (2021). Influence of seashell aggregate on the mechanical and durability properties of concrete. *Construction and Building Materials*, *294*.
37. Lin, C. W., Mattei, G., Cheibas, I., Du, C., Aejmelaeus-Lindström, P., & Gramazio, F. (2023). PneuPrint: 3D printing on inflatables. *Architecture, Structures and Construction*, *3*(2), 217–234. https://doi.org/10.1007/s44150-023-00092-x
38. Lv, S., Hu, L., Xia, C., Cabrera, M. B., Guo, Y., Liu, C., & You, L. (2021). Recycling fish scale powder in improving the performance of asphalt: A sustainable utilization of fish scale waste in asphalt. *Journal of Cleaner Production*, *288*, 125682. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.125682
39. Marinelli, A., & Rasheed, L. P. H. (2024). Considering environmental effects on porous concrete applications: an experimental investigation. *Procedia Structural Integrity*, *54*, 332–339. https://doi.org/https://doi.org/10.1016/j.prostr.2024.01.091
40. Megasari, S. W., Yanti, G., & Zainuri, Z. (2021). Research studies on composition of porous concrete on the sidewalk. *IOP Conference Series: Earth and Environmental Science*, *737*(1). https://doi.org/10.1088/1755-1315/737/1/012042
41. Mitaphonna, R., Ramli, M., Ismail, N., & Idris, N. (2023). Evaluation of geochemical signature in soil sampled from a 2004 indian ocean tsunami-stricken region in aceh province located in the western part of indonesia using scanning electron microscopy–energy dispersive X-ray (SEM-EDX) spectroscopy and its compat. *Philippine Journal of Science*, *152*(1), 485–499. https://doi.org/10.56899/152.01.38
42. Nafiyanto, I., Bayan, A. H., Sultan, M. A., Gaus, A., & Yuda, M. T. (2025). Efek penambahan serat polypropylene terhadap kuat tarik belah beton ringan. *Jurnal Komposit: Jurnal Ilmu-ilmu Teknik Sipil*, *9*(1), 79–86.
43. Pamungkas, C. D., Yuliyanti, A., & Ali, R. K. (2024). Preliminary study of potential hazardous trace elements and mineral deposits based on petrography and X-Ray fluorescence (XRF) of altered volcanic rocks in the papandayan geothermal prospect area and surrounding. *Conference Paper in AIP Conference Proceedings*, *January 2023*. https://doi.org/10.1063/5.0141021
44. Popescu, M., Rippmann, M., Liew, A., Reiter, L., Flatt, R. J., Van Mele, T., & Block, P. (2021). Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell. *Structures*, *31*, 1287–1299. https://doi.org/https://doi.org/10.1016/j.istruc.2020.02.013
45. Rahman, M. A., & Fitriani, R. (2021). Studi SEM dan XRD pada material geopolimer untuk aplikasi beton ramah lingkungan. *Jurnal Material dan Struktur*, *10*(3), 189–200.
46. Ramadhan, G., Muslim, F., & Sagita, L. (2021). Mechanical properties of porous concrete and design recommendation for low traffic road pavement in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *794*(1). https://doi.org/10.1088/1755-1315/794/1/012003
47. Rangan, P. R. (2023). Pengaruh pemanfaatan cornice adhesive sebagai bahan tambah terhadap kuat tarik belah beton berpori. *Jurnal Pendidikan Tambusai*, *7*(1), 2981–2991.
48. Ruslan, H. N., Muthusamy, K., Syed Mohsin, S. M., Jose, R., & Omar, R. (2022). Oyster shell waste as a concrete ingredient: A review. *Materials Today: Proceedings*, *48*, 713–719. https://doi.org/https://doi.org/10.1016/j.matpr.2021.02.208
49. Sánchez-Mendieta, C., Galán-Díaz, J. J., & Martinez-Lage, I. (2024). Relationships between density, porosity, compressive strength and permeability in porous concretes: Optimization of properties through control of the water-cement ratio and aggregate type. *Journal of Building Engineering*, *97*, 110858. https://doi.org/https://doi.org/10.1016/j.jobe.2024.110858
50. Santoso, D., & Pratama, R. (2023). Pengaruh porositas terhadap kuat tekan dan daya serap air pada beton berpori. *Jurnal Teknologi Konstruksi*, *18*(1), 78–89.
51. Seesanong, S., Wongchompoo, Y., Boonchom, B., Sronsri, C., Laohavisuti, N., Chaiseeda, K., & Boonmee, W. (2022). Economical and environmentally friendly track of biowaste recycling of scallop shells to calcium lactate. *ACS Omega*, *7*(17), 14756–14764. https://doi.org/10.1021/acsomega.2c00112
52. Setyawan, A., Suryoto, Wibowo, Rifai, M., Sumarsono, A., S, F., Handayani, & Qosam, O. I. (2021). Development of single sized aggregate porous concrete for sustainable road in low traffic area. *Journal of Physics: Conference Series*, *1912*(1). https://doi.org/10.1088/1742-6596/1912/1/012054
53. Sibagariang, D. I. S., & Priani, N. K. (2021). Pendidikan lingkungan melalui pengolahan limbah cangkang kerang di desa Kuala Indah, kabupaten Batu Bara Environmental education through processing shellfish waste in Kuala Indah village, Batu Bara district. *Pros. SemNas. Peningkatan Mutu Pendidikan*, *2*(1), 6–9.

54. Soto, M. S. O., Pauletti, R. M. de O., & Meneghetti, L. C. (2024). On the use of flexible formworks for concrete structures. *Revista IBRACON de Estruturas e Materiais*, *17*(5), 1–15. https://doi.org/10.1590/s1983-41952024000500006
55. Syahrani, D. (2017). Pemanfaatan limbah cangkang kerang (Kepah) dan limbah kaca sebagai bahan alternatif substitusi parsial semen untuk campuran beton. *Jurnal Teknik Sipil Universitas Tanjungpura*, *17*(2).
56. Tang, J., Zhou, P., & Zhang, L. (2022). Microstructural and durability performance of concrete incorporating marine shell powder. *Cement and Concrete Composites*, *132*.
57. Trisakti, Y., Miratsi, L., & Budi Kurniawan, W. (2022). Sintesis dan Karakteristik $CaCO_3$ dari cangkang kerang kepah (*Polymesoda erosa*) sebagai doping anoda baterai lithium-ion. *Jurnal Riset Fisika Indonesia*, *3*, 19–24. https://doi.org/10.33019/jrfi.v3i1.3548
58. Widianingsih, W., Hartati, R., Azizah Tri Nuraeni, R., Riniatsih Hadi Endrawati, I., & Redjeki, S. (2020). The morphological variance Polymesoda erosa and *Polymesoda expansa* (Mollusc; Corbiculidae) in the Laguna Segara Anakan, Cilacap, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *530*(1). https://doi.org/10.1088/1755-1315/530/1/012021
59. Wu, J., Liu, Q., & Wu, S. (2022). Bionic synthesis of mussel-like adhesive L-DMA and its effects on asphalt properties. *Materials*, *15*(15). https://doi.org/10.3390/ma15155351
60. Yahyaee, T., & Mofidi, S. R. (2024). The impact of multi-walled carbon nanotubes on the mechanical and environmental properties of porous concrete in removing pollutants for use in surface runoffs. *Case Studies in Construction Materials*, *20*, e02697. https://doi.org/https://doi.org/10.1016/j.cscm.2023.e02697
61. Zhang, L., Huang, P., & Liu, X. (2022). Effect of marine shell waste on the compressive strength and microstructure of concrete. *Cement and Concrete Composites*, *133*.
62. Zulkifli, R., & Ramadhan, A. (2022). Analisis mikrostruktur beton berpori dengan penggunaan material alternatif. *Jurnal Teknik Sipil Indonesia*, *15*(2), 105–115.