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Sustainable Construction Using Aragonite Sand from Mussel Shell Biowaste: Enhancing Building Material Development

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ABSTRACT

This study investigates the feasibility of using aragonite sand made from Perna viridis mussel shells as a sustainable substitute for natural sand in building materials. Growing demand for natural sand has resulted in serious environmental issues, such as habitat destruction, resource depletion, and elevated greenhouse gas emissions, driven by fast urbanization and infrastructural expansion. The goal of this project is to encourage sustainable building methods, lessen environmental deterioration, and alleviate sand scarcity by turning mussel shell biowaste into aragonite sand.

X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) were among the chemical and microstructural tests used to verify the shells' composition and crystalline structure. The material's mechanical fitness for use in building was demonstrated by these tests, which confirmed a high calcium carbonate ($CaCO_3$) content and the presence of an aragonite phase. Samples of mortar were made with different percentages of aragonite to natural sand replacement (25%, 50%, 75%, and 100%), and after 7, 14, and 28 days of water curing, their compressive strengths were measured.

A replacement ratio of 25% was found to have the greatest and most stable compressive strength during all curing times, satisfying load-bearing construction requirements. Even if their strength declined, higher replacement ratios might still be used in decorative or non-load-bearing applications.

This study provides a workable answer to waste management and raw material shortages by confirming that aragonite sand can be used as a partial substitute for natural sand. Additionally, by encouraging responsible consumption, environmental preservation, and resilient urban growth, this strategy supports the Sustainable Development Goals (SDGs). The results open the door for creative and sustainable building solutions by converting biowaste into useful building materials that benefit the circular economy.

Keywords: bio brick block, aragonite sand, construction and building material, sustainable development goals (SDGs), environmental impact

INTRODUCTION

In order to lessen the influence on the environment and increase the value of biological waste, the viability of producing aragonite sand from green mussel shells (Perna viridis) to replace natural sand in construction is evaluated. To assess the aragonite sand made from mussel shells, which has appropriate mechanical and chemical qualities and can be used in varied replacement ratios for different kinds of construction project.

The fishing sector, especially coastal fisheries and aquaculture, is crucial to Thailand's economic and social growth because it contributes significantly to the country's food supply and exports while also giving coastal people a steady stream of revenue and jobs (Figure 1). Thailand's mussel aquaculture industry generates thousands of tons of product per year, according to Juntarashote et al. (2020), greatly boosting local economies in areas like Ban Laem (Phetchaburi), where mussel farming is the main source of income. Ban Laem is a crucial sample location for this study, which examines the effects of aquaculture waste on the environment firsthand.

The accumulation of waste shells in mangrove ecosystems severely impacts local biodiversity. Singsawat (Singsawat et al., 2020) note that shell waste increases soil salinity in these environments, impedes native plant growth (such as mangroves), and disrupts the habitat for aquatic species that are dependent on this ecosystem. The effective management of waste mussel shells by fishing communities is crucial for reducing odor pollution and maintaining environmental health (Figure 2).

Figure 1

Mussel Farming in Thailand

Figure 2

Mussel Shell Waste Turning White (Following Prolonged Exposure to the Environment)

The buildup of abandoned mussel shells in public locations including roadsides, mangroves, and community spaces presents serious problems for the mussel farming sector. The decomposition of organic matter in discarded shells can lead to the release of harmful gases such as hydrogen sulphide (H_2S) and sulphur dioxide (SO_2), which negatively affect the health and well-being of nearby communities (Heaney et al., 2011; Kim et al., 2014). Moreover, shells' natural breakdown results in obvious environmental deterioration, changing their structure from green to white as a result of calcium carbonate erosion (Chan & Yeo, 2018).

Simultaneously, the environment is greatly impacted by the rising demand for natural sand worldwide, which is being driven by expanding urbanization and economic growth. Sand mining from riverbeds and coastal areas harms ecosystems lowers biodiversity, increases coastal erosion, and worsens flooding, endangering local populations and releasing greenhouse gases into the atmosphere (Torres et al., 2017; Zhang et al., 2018).

This study examines aragonite sand made from mussel shells as a sustainable substitute for natural sand in building to address the buildup of shell waste and environmental problems associated with sand extraction. The use of shell biowaste not only increases the strength and durability of concrete (Edalat-Behbahani et al., 2019), but it also lessens the reliance on natural sand by about 20% (Olivia & Oktaviani, 2017), minimising environmental damage. But if mussel shell biowaste is not managed properly, it can result in organic contamination, disagreeable smells, and a haven for insects that spread disease (Zhang et al., 2018). Effectively reducing waste-related environmental impacts and enhancing overall waste management are possible with the use of shell waste in construction (Zhang et al., 2018).

The objective of this study is to assess the viability and efficiency of using aragonite sand made from mussel shells as a sustainable building material, which will lessen environmental harm and increase the value of biowaste (Camba et al., 2021).

The accumulation of waste from mussel shells results in an unsanitary and disorderly environment. Thailand produces approximately 38,000 to 52,000 tons of mussels annually, based on data from national reports between 2020 and 2023. This production volume is driven by the continued expansion of mussel farming and processing activities in key coastal provinces (FAO, 2020; NSTDA, 2022; ResearchGate, 2021). Figure 3 (below) illustrates the volume of mussel shell waste generated over five years. The data shows a steady increase in mussel shell waste (from 50,000 tons in 2020 to 52,000 tons in 2023) which directly correlates with the increasing demand for seafood and the expansion of the mussel industry.

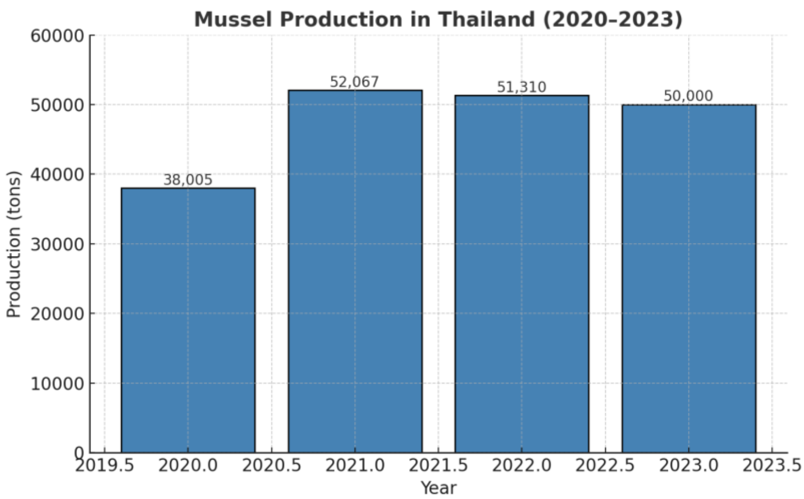
The steadily increasing volume of waste has resulted in multiple environmental challenges. Research has proven that excessive amounts of shell waste can disrupt local ecosystems, contribute to water pollution, destroy habitats, and diminish biodiversity (Kantachumpoo & Kirtikara, 2020). Furthermore, improper waste management exacerbates these issues by allowing biowaste to accumulate, leading to a proliferation of harmful bacteria and algae which pose additional risks to marine life and ecosystems (Pati, 2019).

Figure 3 illustrates the constant increase of mussel shell waste caused by the increase of mussel farming and processing over a 5-year period. This increase highlights the necessity for effective waste management strategies and guidelines to leverage the waste generated from shells. Effectively managing this waste can reduce detrimental environmental impacts and increase the value of waste materials. The negative environmental impacts also extend to the local community and tourism sector, particularly in coastal areas where tourism is a primary source of income (Smith et al., 2022). Improper disposal of shells causes unpleasant odors, impairs the visual aesthetics of tourist destinations, and diminishes the quality of life among the neighboring communities. The accumulation of mussel shell waste over time can spread fetid odors across a wide area and affect nearby residents. Without proper management, shell waste creates an ideal breeding environment for disease-carrying pests such as flies and mosquitoes which pose a risk to public health by spreading transmissible pathogens such as dengue fever and gastrointestinal infections (Maya et al., 2009). Additionally, the improper disposal of shell waste negatively affects the marine ecosystem; the alteration of water and soil conditions leads to habitat destruction and disrupts the food chain for aquatic organisms. As shell waste accumulates, it can reduce the population of aquatic organisms (such as shrimp and fish) which impacts local fishing industries (Sreebha & Padmalal, 2011).

However, effective waste management can create opportunities. Local industries can exploit the waste by producing lime from the shells

Figure 3

The Annual Increase in Shellfish Waste from 2020 to 2023



which contributes to the circular economy and supports SDG 12 (Responsible Consumption and Production) (Ghafoori & Bucholc, 1996).

Within the Ban Laem community, mussel shells are disposed of in open areas for extended periods, resulting in changes caused by their exposure to sunlight and environmental processes. Shells which are exposed to the environment will dry out as evaporation and sunlight decompose the organic matter. Additionally, microorganisms (such as bacteria and fungi) contribute to the decomposition process, leading to a cleaner shell (McLachlan & Brown, 2006). Given time, physical processes (involving sand, water, and wind) will polish the shells, remove foreign substances, and leave them smooth and white (Palmer, 2000). This process aligns with SDG 14 (Life Below Water) which concerns the promotion of sustainable practices in shell waste management and the minimization of ecosystem damage.

Sand Scarcity and Environmental Impacts

Sand is the second most important resource for construction after water, essential for producing concrete, glass, and asphalt. Rapid urbanization and economic growth have significantly increased sand demand, leading to a global shortage (Peduzzi, 2014; Torres et al., 2017). The World Economic Forum (Forum, 2023) predicts that by 2050, 68% of the global population will live in cities, further escalating the need for building materials. Unsustainable sand extraction has caused severe environmental degradation, including soil erosion, ecosystem disruption, and biodiversity loss (Beiser, 2018; Sreebha & Padmalal, 2011), as well as greenhouse gas emissions contributing to climate change (United Nation Environment Programme [UNEP, 2023]). Additionally, excessive sand mining disrupts aquatic life and water ecosystems, often resulting in water shortages (Koehnken et al., 2020; Stehlik, 2021; Raven, 2022; Springer, 2023). Sustainable solutions include investing in research and development, promoting recycled materials, and implementing regulations to control sand mining (Hack, 2016; Peduzzi, 2014). Recycled materials such as crushed glass and demolition debris serve as viable alternatives, reducing both sand demand and construction waste (Forum, 2023). Sustainable mining practices, aligned with Sustainable Development Goals (SDGs), are essential for protecting ecosystems and ensuring long-term resource availability (Responsible Mining Foundation & Columbia Center on Sustainable Investment, 2020; United Nation Environment Programme [UNEP], 2019).

Between 2018 and 2022, global sand consumption increased by an average of 1.75 billion tons annually, driven by urban expansion and infrastructure development (UNEP, 2019). Manufacturing and glass production also require vast amounts of sand, exacerbating shortages and environmental damage (Peduzzi, 2014; Beiser, 2018). To mitigate these challenges, investment in R&D is crucial for developing alternative materials, including recycled construction debris and sustainable sand substitutes (Bendixen et al., 2019). Prioritizing sustainable innovations aligns with SDG 12, which emphasizes responsible consumption and production (UNEP, 2023). By adopting alternative materials and advancing sustainable practices, industries can meet future demand while minimizing environmental impact.

Aragonite as a Potential Sand Substitute

Aragonite, a calcium carbonate ($CaCO_3$) mineral found in mollusk and coral shells, differs from calcite in its orthorhombic crystalline structure, enhancing its stability and durability (Lee, 2021). This structural advantage makes it a promising alternative to natural sand in concrete. Its mechanical strength, elasticity, and resistance to wear are further reinforced by organic compounds such as proteins and polysaccharides (Addadi & Weiner, 2014). The presence of magnesium in seawater promotes aragonite formation by inhibiting calcite growth, thereby making aragonite the more stable polymorph in marine environments (Berner, 1975). Nacre, primarily composed of aragonite, enhances shell strength and resilience through biomineralization, making it suitable for durable construction materials (Mann, 2018; Addadi & Weiner, 2017). Amid growing concerns over sand scarcity, aragonite derived from mussel and oyster shells aligns with global sustainability goals by promoting biowaste recycling (Subramanian et al., 2019). Studies have shown that incorporating 25–50% mussel shells into concrete mixtures enhances compressive strength, with 28-day tests reaching 30 MPa (Gupta & Patel, 2019). Similarly, plaster containing 50% mussel shells has been explored as a sustainable alternative, offering improved durability and corrosion resistance, with compressive strength reaching up to 28 MPa (Koehnken et al., 2020). Research by Edalat-Behbahani et al. (2019) demonstrated a 15% increase in concrete strength (to 45 MPa) when 20% of mussel shells were added, reducing mass and achieving a density of 2350 kg/m³.

Sand Test when Mixed with Arroganite Shells

To assess the impact of aragonite-shell mixtures, sand samples with varying concentrations (10–30%) were tested for fineness, cleanliness, and compressive strength (Siddique & Up, 2004). The high calcium carbonate content in shells contributed to increased concrete strength while reducing environmental waste and natural sand demand. In regions with significant shell waste, repurposing aragonite shells can mitigate disposal issues (Wang et al., 2018). Research indicates that aragonite-shell concrete reduces CO_2 emissions and aligns with sustainable development goals (Wang et al., 2018). Additionally, its high calcium carbonate content enhances resistance to sulphate corrosion, further improving durability (Manjunath, 2019).

METHODOLOGY

Research Methodology

Step 1: Prepare aragonite sand samples by grinding mussel shells from Ban Laem, Phetchaburi Province, into the appropriate grain size. Then analyze their chemical composition using X-ray Fluorescence (XRF), examine the crystal structure with X-ray Diffraction (XRD), and investigate microscale surface characteristics with Scanning Electron Microscopy (SEM).

Step 2: Prepare 5 cm mortar samples following ASTM C109 guidelines, using a cement-to-sand ratio of 1:3, with varying ratios of natural sand to aragonite sand (25:75, 50:50, 75:25, 100:0). Cure the samples in water for 7, 14, and 28 days.

Step 3: Conduct compressive strength tests on the mortar samples according to ASTM C109, comparing results with Thailand's Industrial Standard TIS 58-2021, to determine the optimal mix ratio for producing Bio brick blocks suitable for practical applications.

An analysis was conducted on the surface structure and chemical composition of the sample containing aragonite sand (derived from mussel shells from the Ban Laem community in Phetchaburi Province). The shells were ground to the correct grain size of aragonite sand and a fluorescence x-ray technique wasemployed to analyse thechemical composition of the sample.

The shells were ground to the correct grain size of aragonite sand and a fluorescence x-ray technique was employed to analyze the chemical composition of the sample. To determine the quantity of each element in the concrete samples, the aragonite's crystal structure was analyzed via the X-ray diffraction method. An XRD test was employed to estimate the characteristics and structure of the crystal formation and high-power magnification imaging with scanning electron microscopy was used to analyze the texture of the aragonite sand. An SEM test was employed to observe the microscale surface and the details of the structure. A mortar (measuring 5cm along each edge) made with a 1:3 cement-to-sand ratio was subjected to a compressive strength test per ASTM C109. The 3 parts of sand within the ratio consisted of additional ratios between natural sand and aragonite sand, as shown in Figures 4, 5, 6 and 7 (25:75, 50:50, 75:25 and 100:0, respectively) which had been subjected to water curing for 7, 14, and 28 day. The test results and comparison process were conducted per TIS 58-2021 requirements (which is the standard adopted for concrete blocks in Thailand). The purpose is to determine the ratio required to achieve the optimum strength for testing alternative application design bio brick blocks. This involves analyzing various compositions and their properties to identify the most effective mix. Once the optimal ratio is established, further experimentation can be conducted to assess durability and sustainability in real-world conditions. This will ensure that the bio brick blocks not only meet structural requirements but also contribute positively to environmental goals. Additionally, the findings may pave the way for innovative construction methods that utilize eco-friendly materials.

The goal of choosing five mortar samples for each mix ratio is to improve the precision and dependability of the test findings. A sufficient number of samples minimizes the influence of variability and errors that may arise during sample preparation, mixing, and testing while also enabling more accurate statistical analysis and evaluation. This guarantees that the test findings accurately reflect the characteristics of the material. In order to limit variability, the materials' size and proportion must be carefully regulated, aragonite sand of uniform size must be used, all sample batches must be continuously mixed, and the samples must be cured under uniform, standardized conditions. Furthermore, elements that can generate variability will be further reduced by calibrated testing equipment run by highly skilled staff, producing test results that are more precise and dependable.

During the experiment, the required sizes (per ASTM C33 standard) of crushed shell were obtained by sieving (during which they were ground into smaller sizes as required).

Figure 4

Ratios

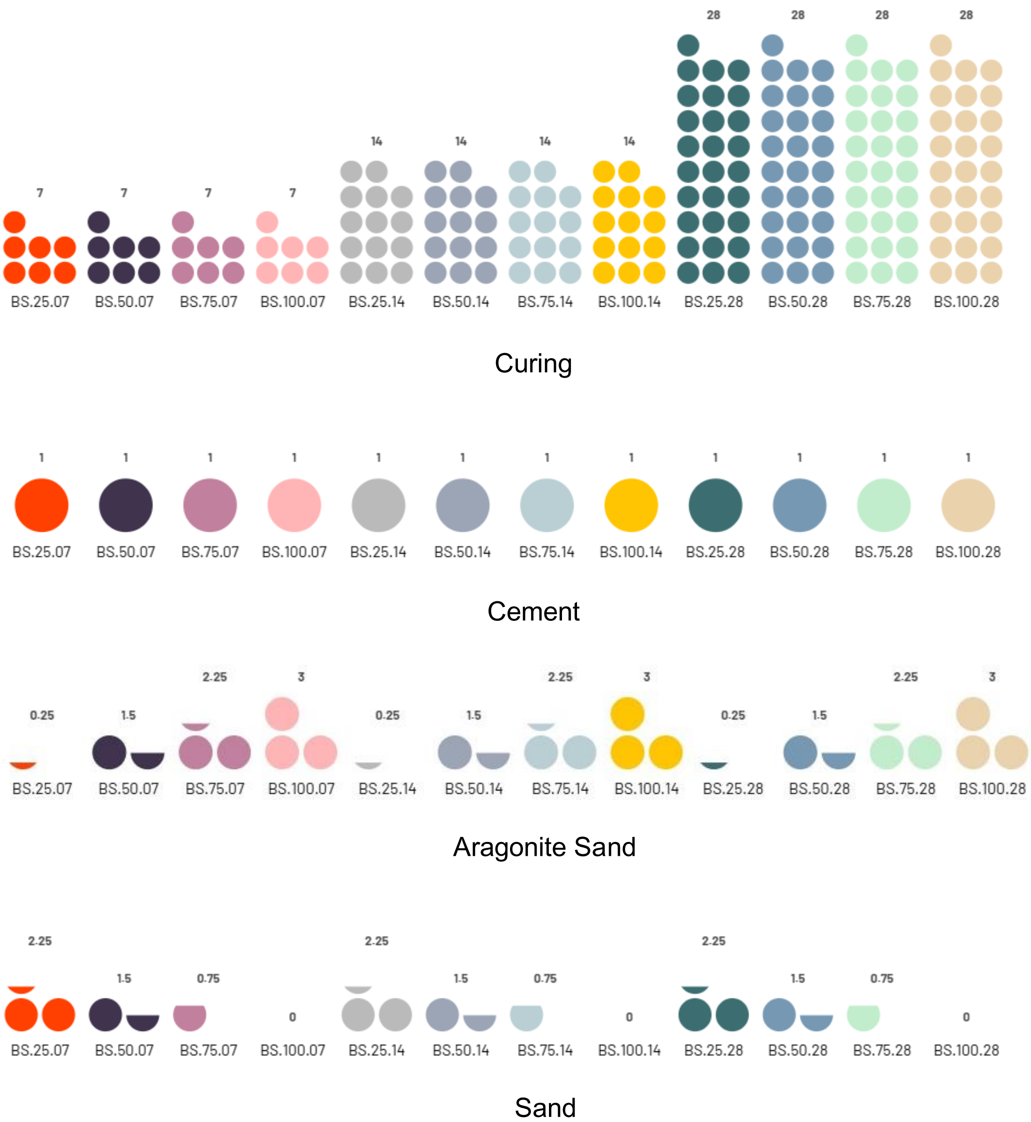


Figure 5

Ratio of Aragonite Sand to Natural Sand (by Weight)

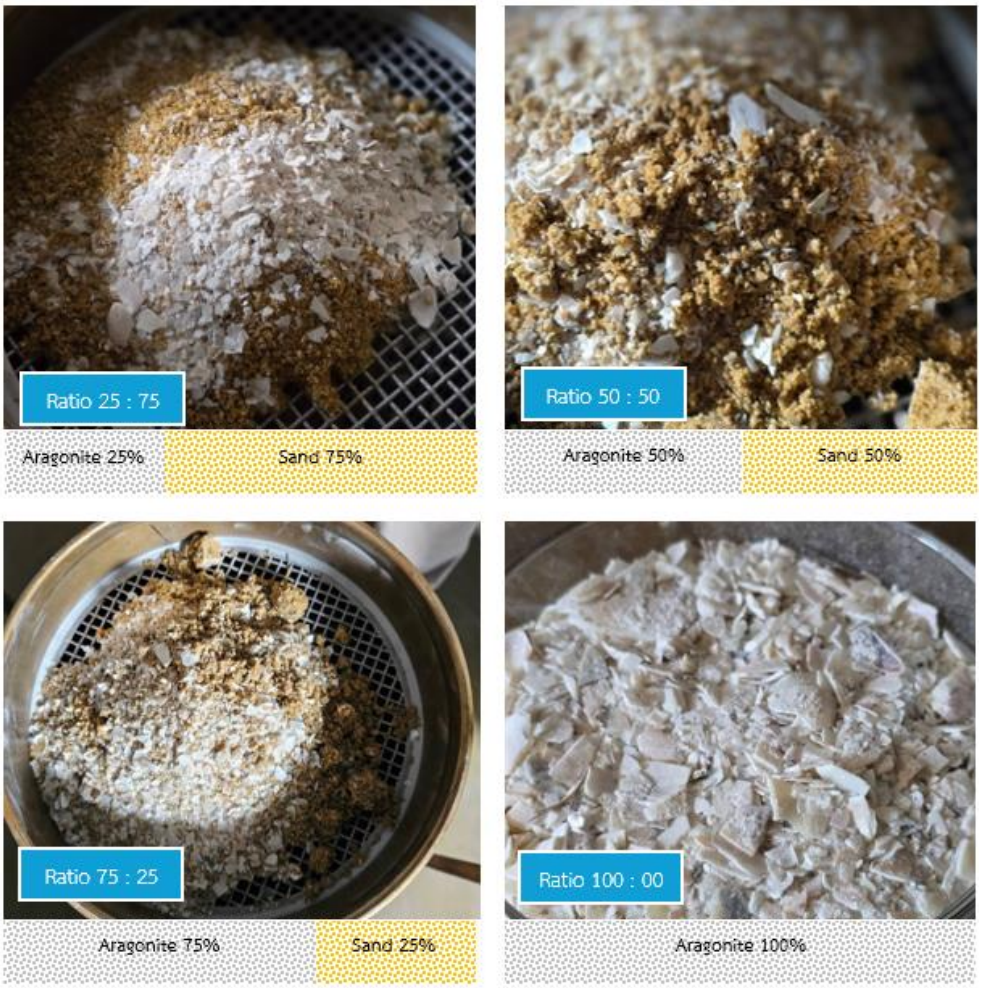


Figure 6

Crushed Mussel Shells

Figure 7

Ingredients in Mortar

Table 1

Sand Mixing in each Ration by Weight (500 grams)

Aragonite Ratio (%)	Natural Sand Ratio (%)	Aragonite Weight (g)	Natural Sand Weight (g)
25	75	125	375
50	50	250	250
75	25	375	125
100	0	500	0

Table 2

Average (Mid-point) of % Retained (per ASTM C33)

Mesh Size	Mid-point % Passing	Mid-point % Retained	Weight Retained (g)
4	100.000%	0.000%	0.000
8	92.500%	7.500%	37.500
16	67.500%	32.500%	162.500
30	42.500%	57.500%	287.500
50	20.000%	80.000%	400.000
100	6.000%	94.000%	470.000
Pan	1.000%	99.000%	495.000

Table 3

Ratio 25 : 75 125g Aragonite Sand : 375g natural sand in Figure 8

Mesh Size	Weight Retained (g)	Aragonite (25%) (g)	Natural Sand (75%) (g)
4	0.000	0.000	0.000
8	37.500	9.375	28.125
16	162.500	40.625	121.875
30	287.500	71.875	215.625
50	12.500	3.125	9.375
100	2.500	0.625	1.875
Pan	0.000	0.000	0.000

Figure 8

Ratio 25: 75 125g Aragonite sand: 375g natural sand

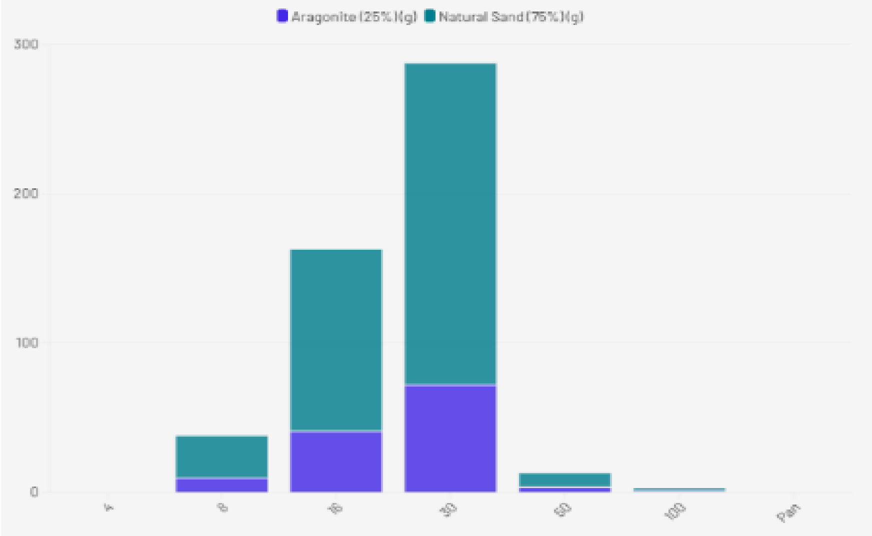


Table 4

Ratio 50: 50 250g Aragonite sand: 250g natural sand in Figure 9

Mesh Size	Weight Retained (g)	Aragonite (50%) (g)	Natural Sand (50%) (g)
4	0.000	0.000	0.000
8	37.500	18.750	18.750
16	162.500	81.250	81.250
30	287.500	143.750	143.750
50	12.500	6.250	6.250
100	2.500	1.250	1.250
Pan	0.000	0.000	0.000

Figure 9

Ratio 50: 50 250g Aragonite sand: 250g natural sand

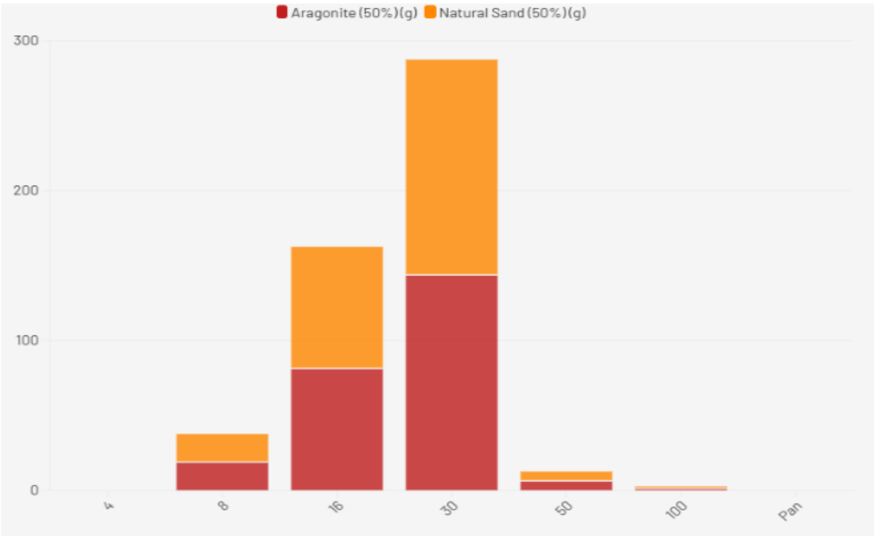


Table 5

Ratio 75: 25 375g Aragonite sand: 125g natural sand in Figure 10

Mesh Size	Weight Retained (g)	Aragonite (75%) (g)	Natural Sand (25%) (g)
4	0.000	0.000	0.000
8	37.500	28.125	9.375
16	162.500	121.875	40.625
30	287.500	215.625	71.875
50	12.500	9.375	3.125
100	2.500	1.875	0.625
Pan	0.000	0.000	0.000

Figure 10

Ratio 75: 25 Aragonite sand: 375g natural sand: 125g

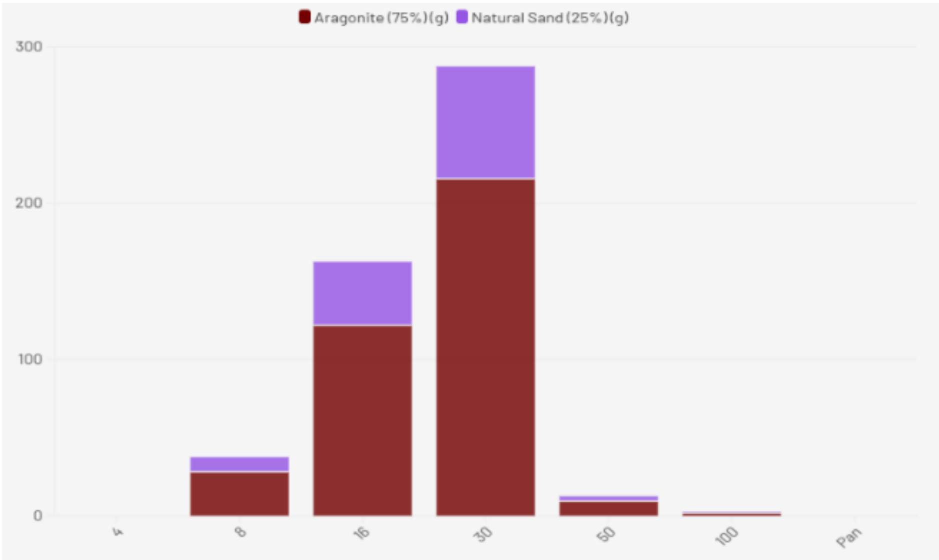


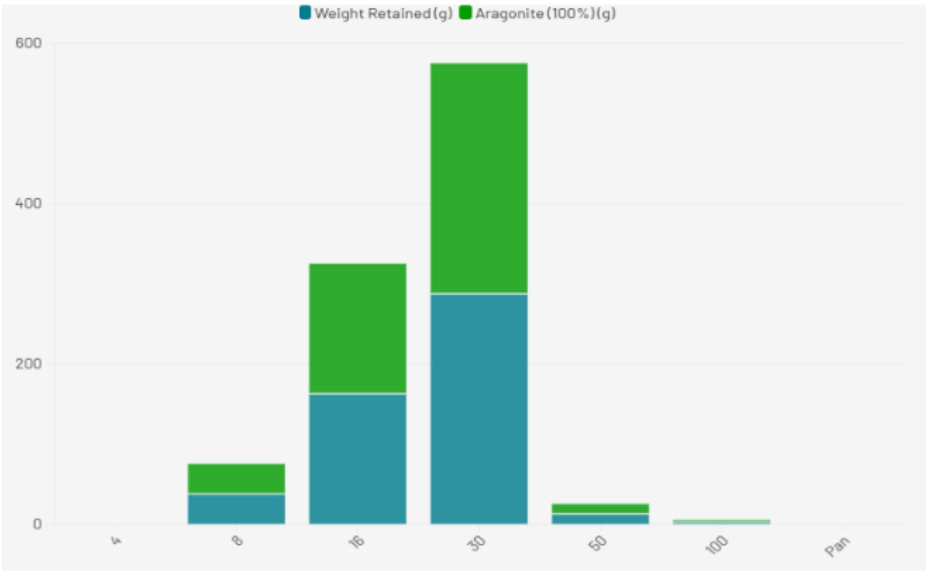
Table 6

100:0 Ratio 500g Aragonite sand: 0g natural sand in Figure 11

Mesh Size	Weight Retained (g)	Aragonite (100%) (g)	Natural Sand (0%) (g)
4	0.000	0.000	0.000
8	37.500	37.500	0.000
16	162.500	162.500	0.000
30	287.500	287.500	0.000
50	12.500	12.500	0.000
100	2.500	2.500	0.000
Pan	0.000	0.000	0.000

Figure 11

100:0 Ratio Aragonite Sand 500g: natural sand 0g



Manufacturing of Mortar s for Compressive Strength Tests

Only approved mortar is utilized to produce load-bearing concrete blocks that meet the required quality, strength and standards; therefore, any evaluation concerning the quality of the mortar requires compression testing which was performed per ASTM C109 standard. In Thailand, the standard employed to establish the standards for concrete blocks is TIS 58-2021.

This section details the ASTM C109 classification of mortar while adopting TIS 58-2021. ASTM C90 standard was adopted to determine the compressive strength of the mortar samples. This process was conducted per Clause 3.3 of ASTM C90 which establishes that the test must be performed at a ratio of 5 bales and isolated from water during the curing process (which occurred over three periods: one, two and four weeks). The following section contains the details of this process.

Each ingredient was weighed before being poured into the mixing container. Five balls were created in one entire mixing form while the desired time, ratio and incubation period were meticulously monitored. The desired ratio can only be achieved via accurate weighing (Doe, 2020).

Table 7

Cement to Sand Ratios for Testing

Cement (g)	Total Sand (g)	Aragonite Sand (g)	Natural Sand (g)
500	1500	375 (25%)	1125 (75%)
500	1500	750 (50%)	750 (50%)
500	1500	1125 (75%)	375 (25%)
500	1500	1500 (100%)	0 (0%)

Figure 12

Preparation of the Mortar before the Test by Drying and Weighing

Figures 12, 13, and 14 show the mortar was removed from the mold before being soaked in water and separated according to the three different curing times: Group 1 (7 days), Group 2 (14 days), and Group 3 (28 days). Once the required curing process was completed, the mortar was subjected to compression. The compression test is used to determine the strength of each mortar sample (Doe, 2020).

The pressure was recorded when the mortar reached the breaking point. Comparison was made for each curing period according to the TIS standard. Compression data is essential in determining the optimum strength of the mortar sample and can be used as a reference for future improvements (Johnson & White, 2019).

As previously noted, the Thai Industrial Product Standard TIS58-2021 establishes the requirements for concrete blocks utilized by the construction industry. TIS58-2021 states that conventional concrete blocks and load-bearing concrete blocks must possess at least 5 MPa and 10 MPa.

Figure 13

Compressive Strength Testing of Mortar in Different Mix Ratios

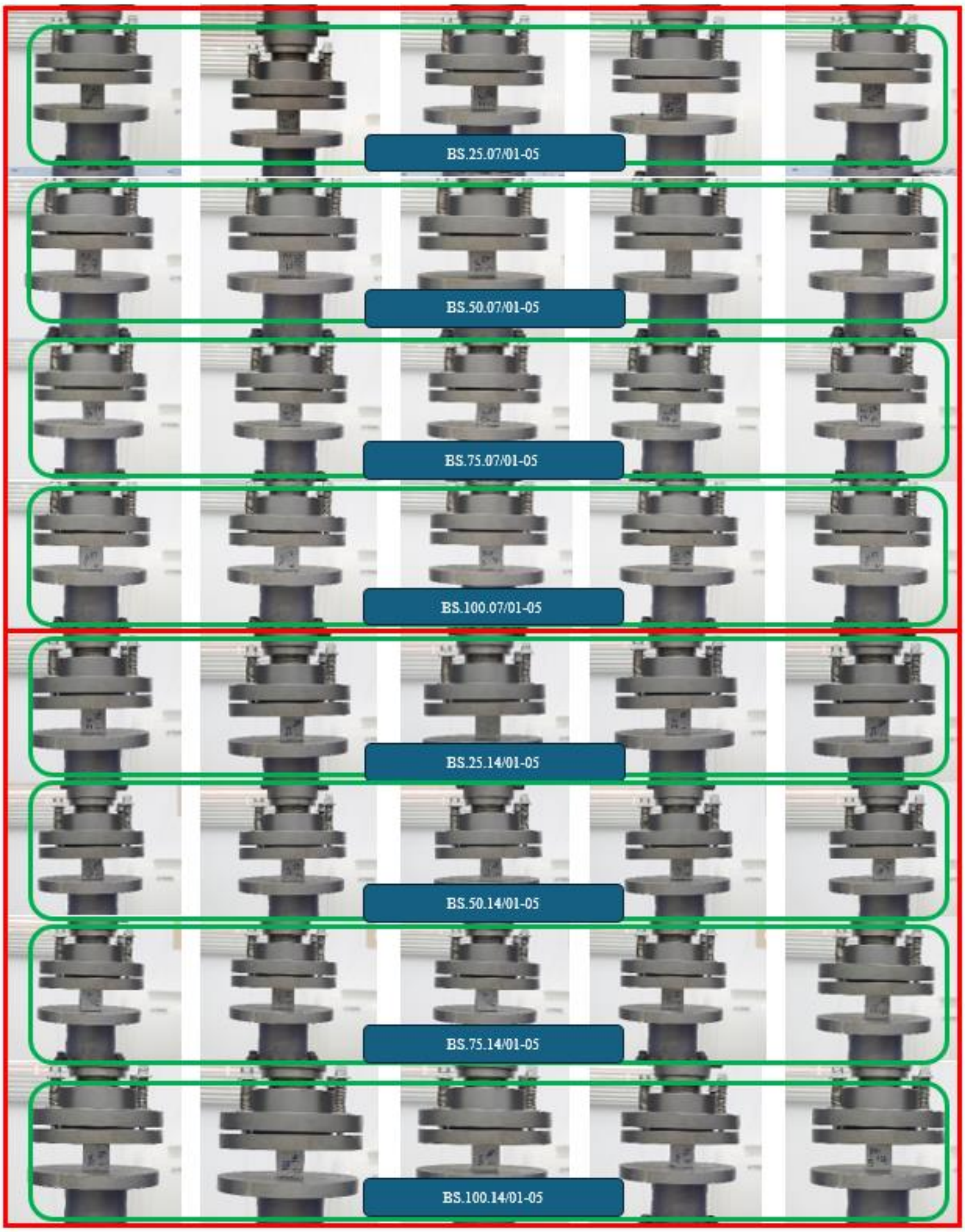
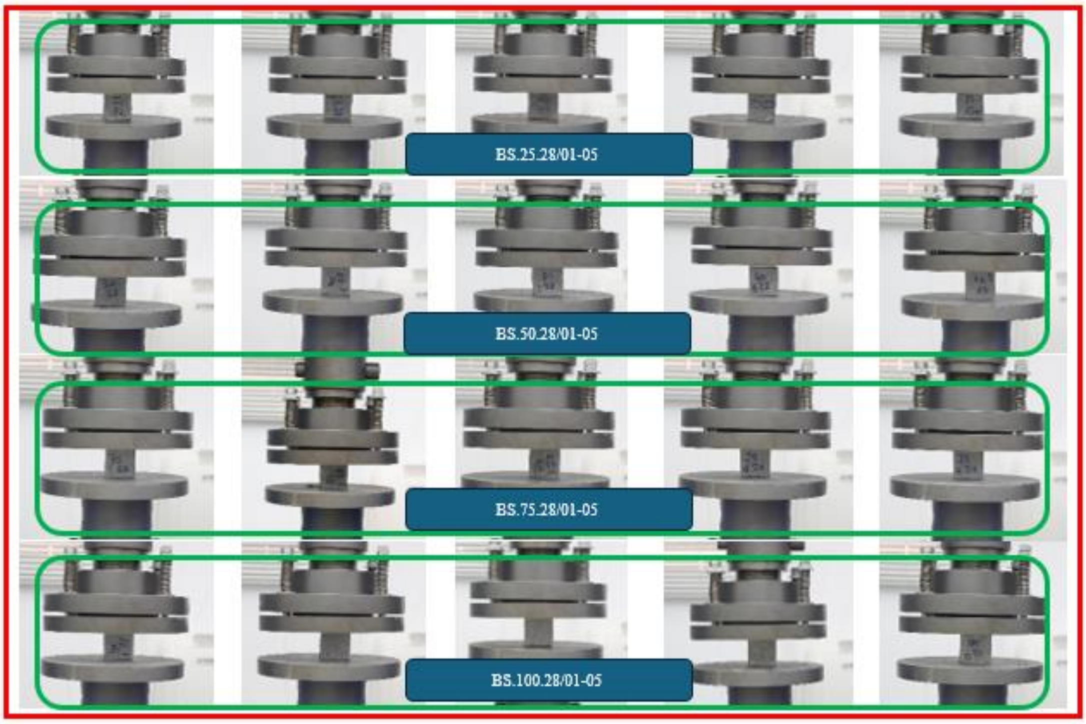


Figure 14

Compressive Strength Testing of Mortar in Different Mix Ratios



RESULTS

This study examined the feasibility of transforming mussel shells into aragonite sand for use in the construction industry and, as such, it plays a crucial role in developing the current understanding of this process Mussel shells are primarily composed of calcium carbonate and can be converted into aragonite sand which possesses the necessary mechanical and chemical properties to meet the requirements for building materials (Marastoni et al., 2017). X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analysis were conducted to determine the chemical composition and structure of the aragonite sand. The results indicated a high purity of aragonite, which is essential for ensuring the durability and strength of the resultant building materials. Furthermore, these analyses provided insight into the potential for utilizing mussel shells as a sustainable alternative to traditional aggregates, thus contributing to environmentally friendly construction practices.

XRD Test Results and Analysis

Figure 15 illustrates the mussel shell was subjected to XRD to analyze its crystal structure. The XRD graph presents the crucial peak characteristics inthe 2θ angle range of approximately 26°, 29°, 39°, 43°, 48°, and 50° (Figure 20) which signifies that the calcium carbonate is in aragonite form.

The high-intensity peak demonstrates the amount of minerals and the purity. The mussel shell sample containsshell sample contains a large quantity of aragonite; therefore, its suitability for use as an alternative to sand is evaluated as high quality and it is considered appropriate for application in the construction industry.

XRF (X-Ray Fluorescence Analysis)

XRF analysis tells us what chemicals are in the sample and records the results in signal intensity (KCps) and measured amount (PPM). It was found that 52.8% of the material Calcium oxide (CaO), a significant amount of calcium carbonate, was present in the sample sodium oxide (Na_2O) and strontium oxide (SrO). Moreover, the least present materials are silicon dioxide (SiO_2) and phosphorus pentoxide (P_2O_5).

SEM Image Analysis of Mussel Shells

Scanning electron microscopy (SEM) was employed to observe and analyze the surface structure and characteristics of the intact mussel shell and its powdered form. The images were magnified by x1000, x5000, andx10000 to provide a detailed view of the materials.

Table 8

Key Peaks from XRD Analysis

Angle 2θ (degrees)	Signal Intensity (Counts)
26°	High
29°	High
39°	Moderate
43°	High
48°	Moderate
50°	High

Figure 15

XRD Display Graph

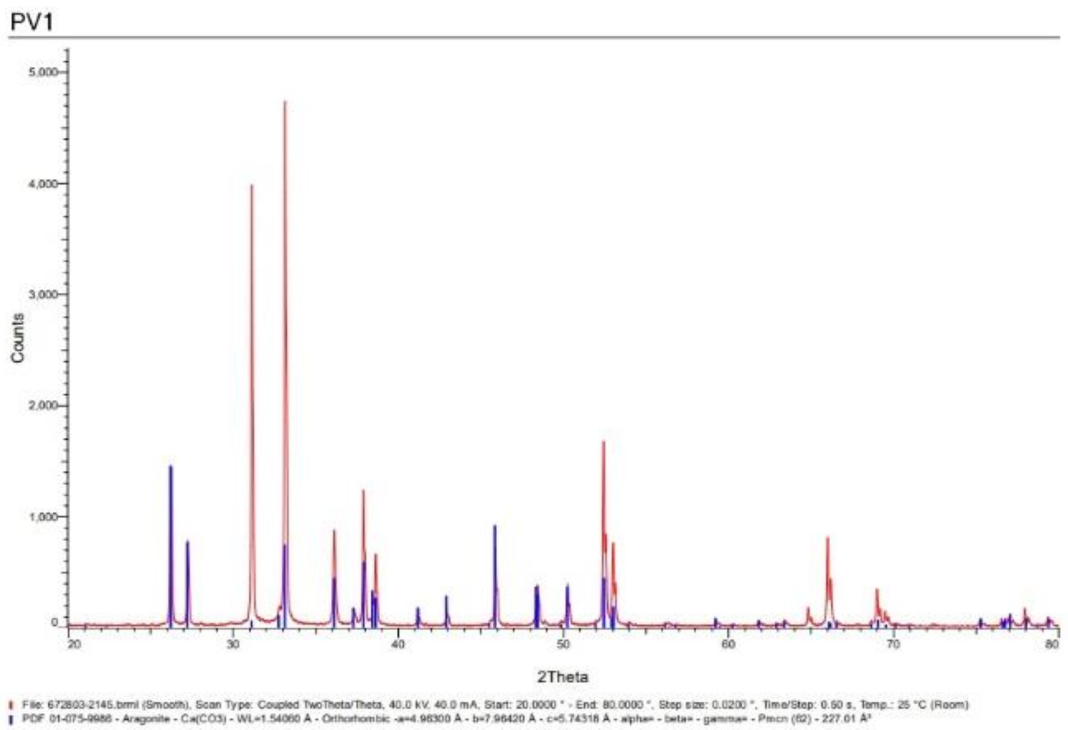
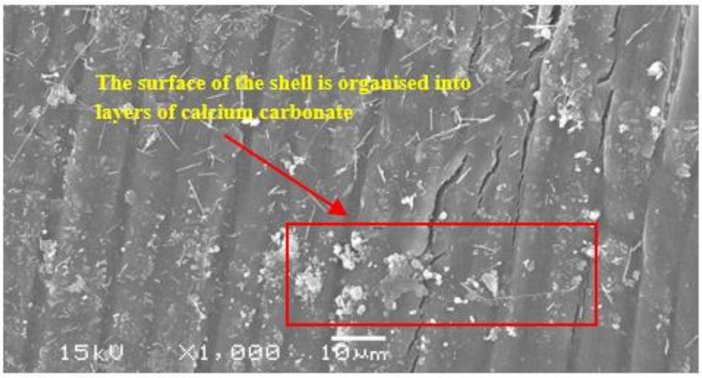


Figure 16

SEM x1000 Magnification Image of Mussel Shells



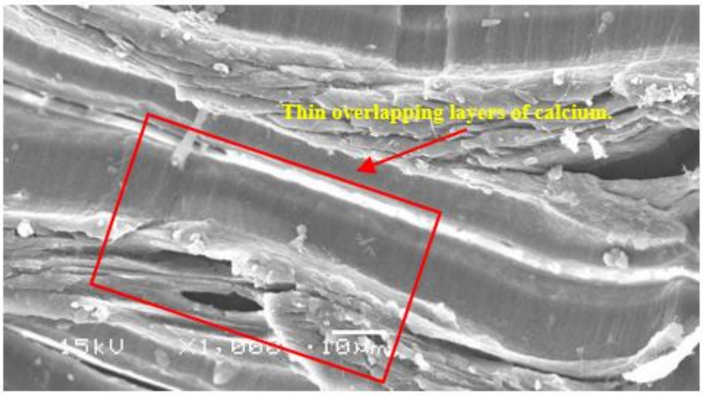


Figure 17

SEM x5000 Magnification Image of Mussel Shells

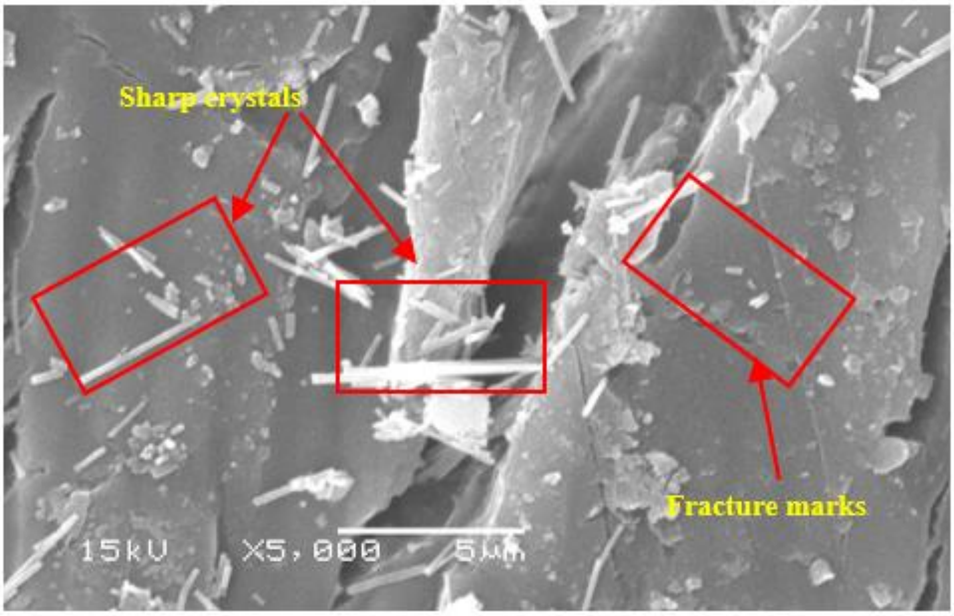


Figure 16 (x 1000 magnification) indicates that the surface structure of the mussel shell consists of thin layers of calcium carbonate arranged on top of each other. The gaps are the result of incomplete connections between layers.

Figure 17 (x5000 magnification) shows the core of the shell (the enlarged structure with observable thin plates) and reveals that each plate is madeup of sharp crystals. The presence of fractures indicates areas of fragility.

Figure 18

SEM x1000 Magnification Image of Crushed Mussel Shells

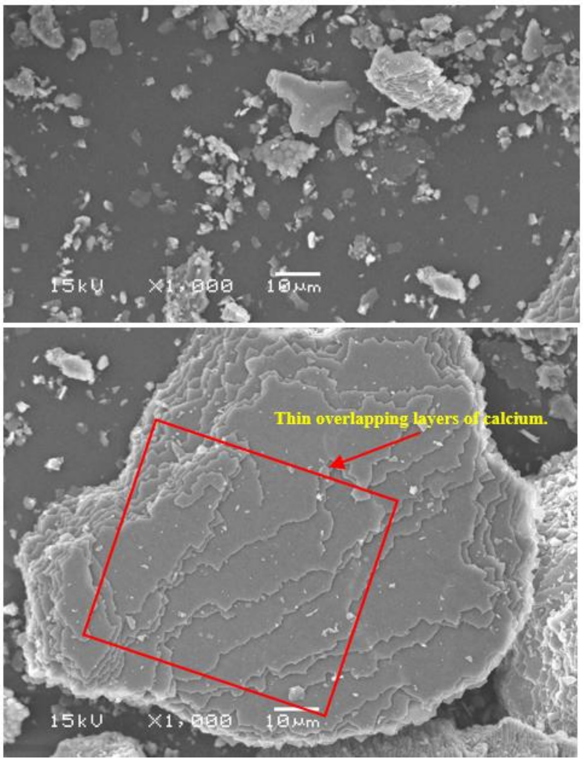


Figure 19

SEM x5000 Magnification Image of Crushed Mussel Shells

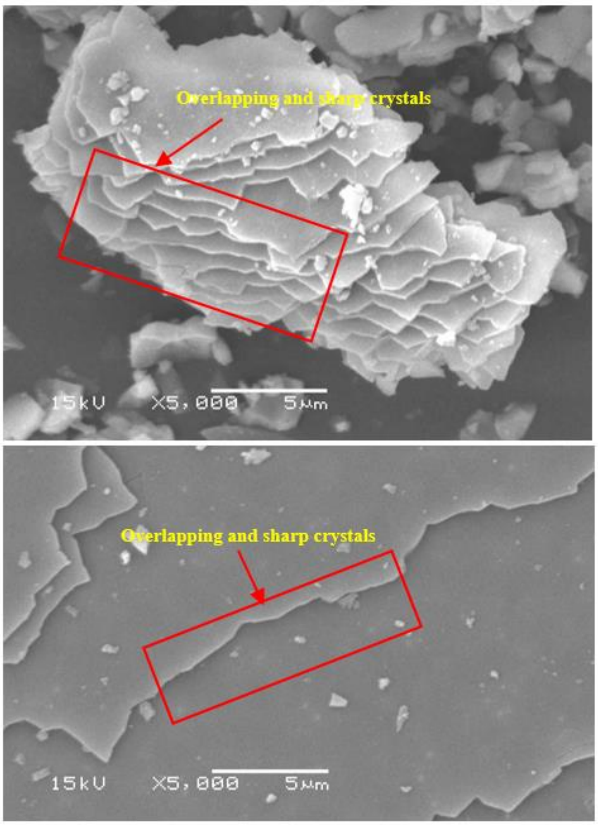


Figure 18 is a x1000 magnification of the powdered mussel shell. There are observable sharp crystalline structures and each particle contains different shapes which is indicative of unstable distribution.

In Figure19 (x5000 magnification), the observed particles contain sharper crystals consisting of thin plateswithsharp edges and an uneven distribution.

The SEM images illustrate the structure and characteristics of the mussel shell's structure in its original and crushed states. The structure consists of crystal and calcium carbonate arranged in layers which indicates that the mussel shell possesses the required physical properties for use in the construction industry. Moreover, the shells can be used as aragonite sand and form part of the materials required for the production of mortar and concrete blocks. The sharp crystals and sharp edges observed in the powder increase the strength and durability when used as a building material. Using crushed mussel shells as an alternative to natural sand in the construction industry decreases cost and minimizes the impact of construction on the environment. The results of the SEM analysis indicate that mussel shells demonstrate enormous potential as they possess the required strength and durability to act as an alternative to natural sand in the construction industry.

Sand sifting plays a prominent role in verifying a material's physical properties before they can be applied in the construction industry (which requires high strength and durability for materials such as mortar and concrete). The sand sifting test can determine the size of the sand particles and ascertain the product's mechanical properties.

Sand Sifting Analysis – Preliminary Results

At the ratio of 25:75, 50:50, 75:25 and 100. On this occasion, the weight of the remaining sand on the sieve was accurately measured. The results indicate that the dispersion of the sand particles was consistent (see Figures 20 to 23).

Figure 20

Sand Sifting Chart (25:75)

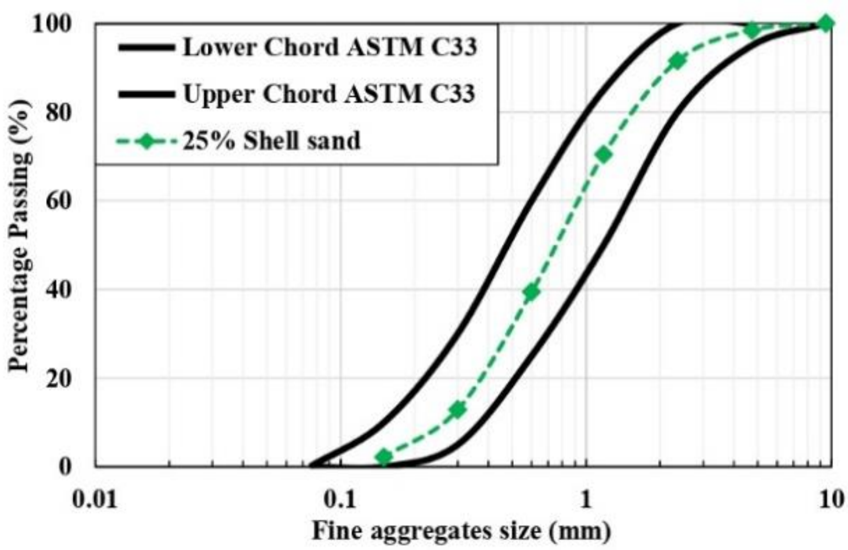


Figure 21

Sand Sifting Chart (50:50)

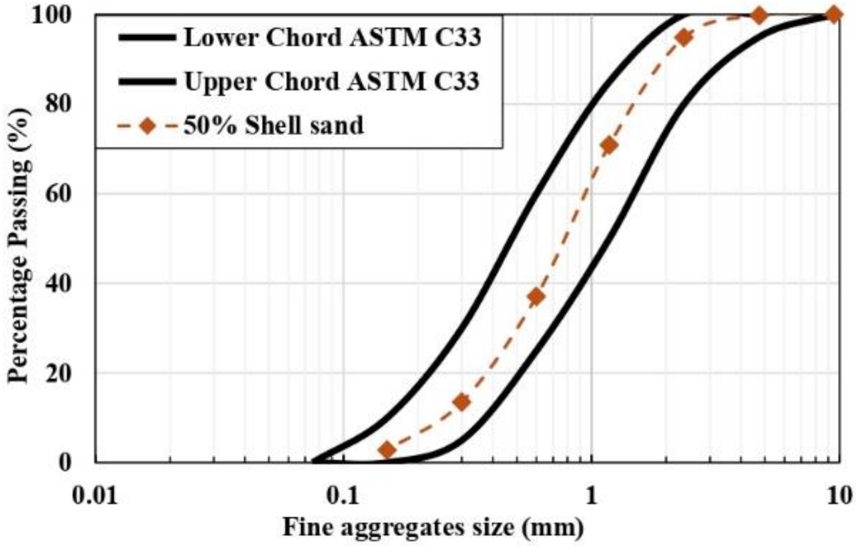


Figure 22

Sand Sifting Chart (75:25)

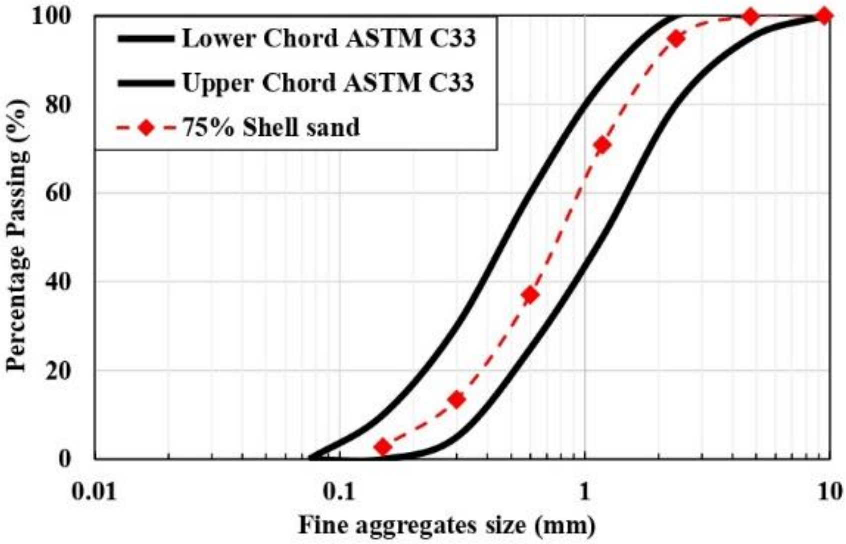
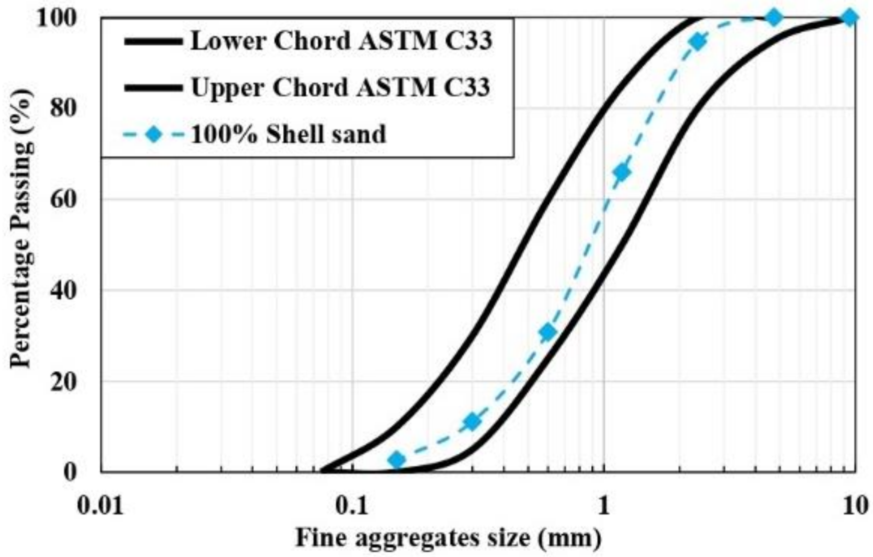


Figure 23

Sand Sifting Chart (100:0)



Mortar Compressive Strength Test

The compressive strength test for 5x5 cm mortar specimens, using aragonite sand from mussel shells as a replacement for natural sand at 25%, 50%, 75%, and 100%, yielded the following results: A total of 60 mortar specimens were tested, divided into groups, and cured for 7, 14, or 28 days. Increasing the replacement ratio resulted in a reduction in compressive strength. This decline was particularly noticeable in the specimens with 75% and 100% aragonite sand replacement. However, water curing enhanced the strength over time: the 28-day cured specimens exhibited the highest compressive strength (compared to those cured for 7 and 14 days). The 25% and 50% replacement ratios demonstrated optimal strength development, indicating that these proportions are appropriate for lightweight construction applications, even when using waste materials such as mussel shells as substitutes (Martínez-García et al., 2024). In this study, the mixing ratios of natural sand and aragonite mineral sand from seashells are defined as 25, 50, 75, and 100, corresponding to BS.25, BS.50, BS.75, and BS.100, respectively.

Compressive Strength Test Results after 7 Days of Water Curing

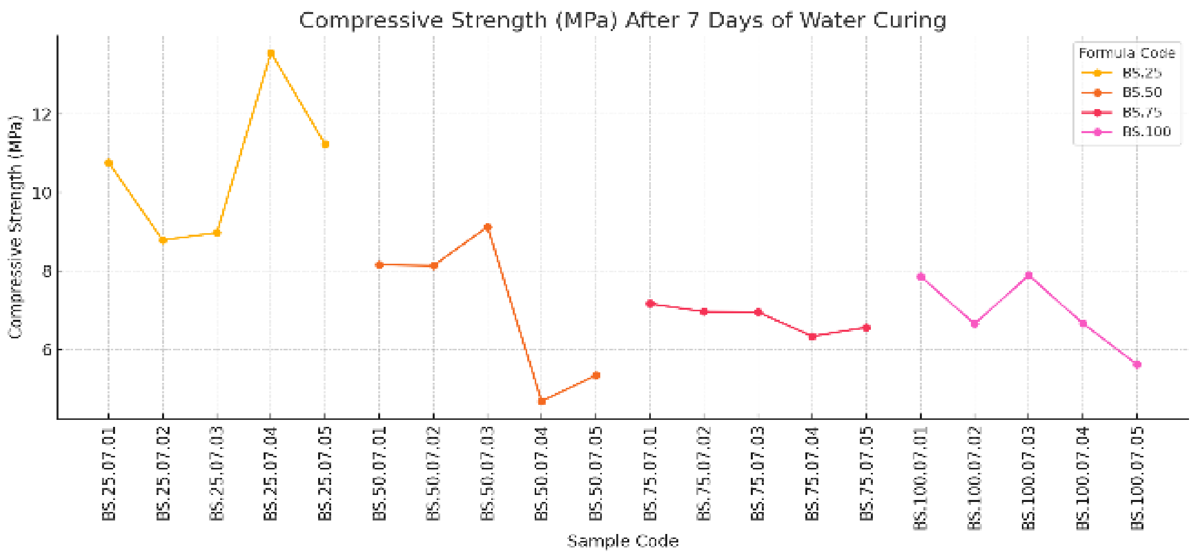
Figure 24 represents the compressive strength (MPa) of different concrete formulas (BS.25, BS.50, BS.75, and BS.100) following a 7-day water curing period. Among the tested formulas, BS.25 exhibited the highest compressive strength (13.55 MPa) which is indicative of superior mechanical performance. However, this formula exhibited a degree of variability with values ranging from 8.78 MPa to 13.55 MPa.

The BS.50 formula demonstrated a higher degree of variability: some samples exhibited a minimum strength of 4.69 MPa which reflects inconsistency in material behavior or curing efficiency. Contrastingly, the BS.75 formula displayed more consistent results, with compressive strength values ranging between 6.34 MPa and 7.17 MPa, indicating stability under uniform conditions.

The BS.100 formula recorded moderate compressive strength, with a maximum value of 7.89 MPa and a minimum of 5.62 MPa. The relatively wide range of results suggests that further optimisation of the material composition or curing conditions may be required to enhance consistency and strength.

Figure 24

Compressive Strength After 7 Days of Water Curing.



Compressive Strength Test Results after 14 Days of Water Curing

Figure 25 illustrates the compressive strength (MPa) of different formulas (BS.25, BS.50, BS.75, and BS.100) after 14 days of water curing, highlighting variations in mechanical performance. BS.25 exhibits the highest strength (7.56–13.16 MPa) with some variability, while BS.50 shows more stable performance (7.71–11.27 MPa). BS.75 demonstrates moderate strength (6.10–8.76 MPa), whereas BS.100 records the lowest values (1.92–6.70 MPa), indicating the need for material or curing optimisation. These differences provide insights into the structural behavior of each formulation.

Compressive Strength Test Results after 28 Days of Water Curing

Figure 26 shows the compressive strength (MPa) of various formulas (BS.25, BS.50, BS.75, and BS.100) following 28 days of water curing. Each formula demonstrates distinct performance and variability across the samples. The BS.25 formula consistently achieves the highest compressive strength among the tested formulas, with values ranging from 12.13 MPa to 17.33 MPa, indicating robust mechanical properties. The BS.50formula shows moderate strength, with values between 7.58 MPa and 12.88 MPa. Some variability is observed; however, the results are relatively stable in comparison with curing durations. For BS.75, compressive strength ranges from 7.69 MPa to 10.63 MPa, with lower strength values compared to the BS.25 and BS.50 formulas. This formula's performance is consistent; however, they indicate reduced mechanical capacity. The BS. 100formula exhibits the lowest compressive strength, with values ranging from 6.98MPa to 9.64MPa.

Figure 25

Compressive Strength After 14 Days of Water Curing.

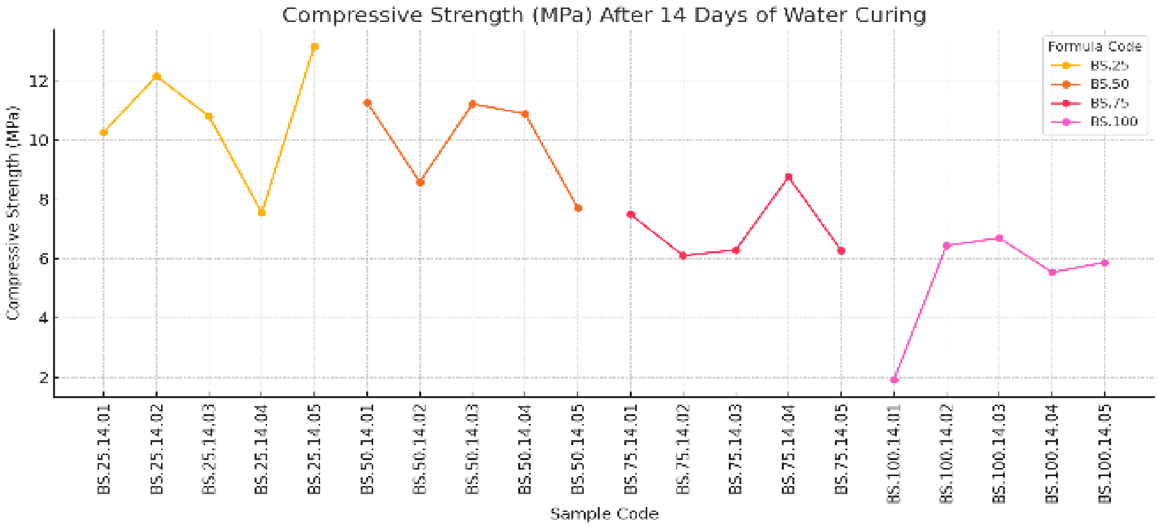


Figure 26

Compressive Strength After 28 Days of Water Curing.

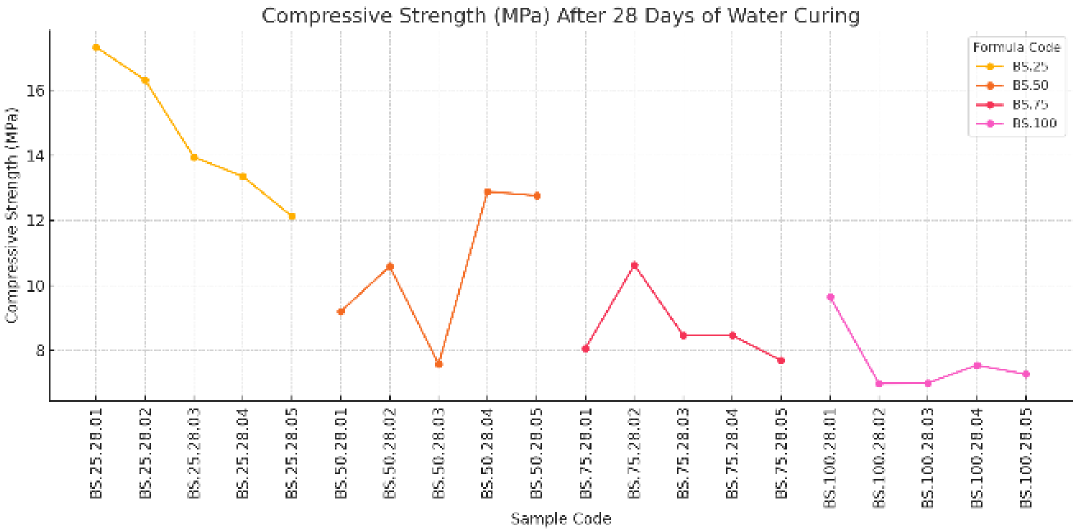


Table 9

Summary of Compressive Strength (MPa) by Curing Duration and Replacement Ratio

Replacement Ratio	**7 Days**	**14 Days**	**28 Days**
25%	13.55 ± 2.38	10.36 ± 2.80	14.73 ± 2.60
50%	6.91 ± 2.22	9.49 ± 1.78	10.23 ± 2.65
75%	6.76 ± 0.41	7.43 ± 1.33	9.16 ± 1.47
100%	6.76 ± 1.14	4.31 ± 2.12	8.31 ± 1.33

Note. Values are presented as mean ± standard deviation.

DISCUSSION

The inherent characteristics of construction materials affect the load-bearing capacity of the constructed surface (Mishra, 2022). Several studies highlight the potential of mussel shell-derived aragonite sand as a sustainable alternative to natural sand in construction. These studies confirm its chemical and mechanical suitability for mortar and concrete, reducing environmental impact and dependence on natural resources (Liao, 2024).

Microstructural Analysis and Physical Properties

Scanning Electron Microscope (SEM) analysis shows thin layers of calcium carbonate on the surface of mussel shells, which helps us understand how they are put together. After grinding, the particles exhibit sharp edges and irregular shapes, which enhance bonding strength in construction materials (Leone et al., 2023). The rough surface of the particles improves interlocking, enhancing the mechanical performance of mortar and concrete. Sand sifting ensures uniform particle distribution, consistency, and optimal performance in the final mix. This meticulous process not only maximizes the use of mussel shell waste but also contributes to sustainable building practices by reducing reliance on traditional aggregates. performance in construction applications.

Compressive Strength Test

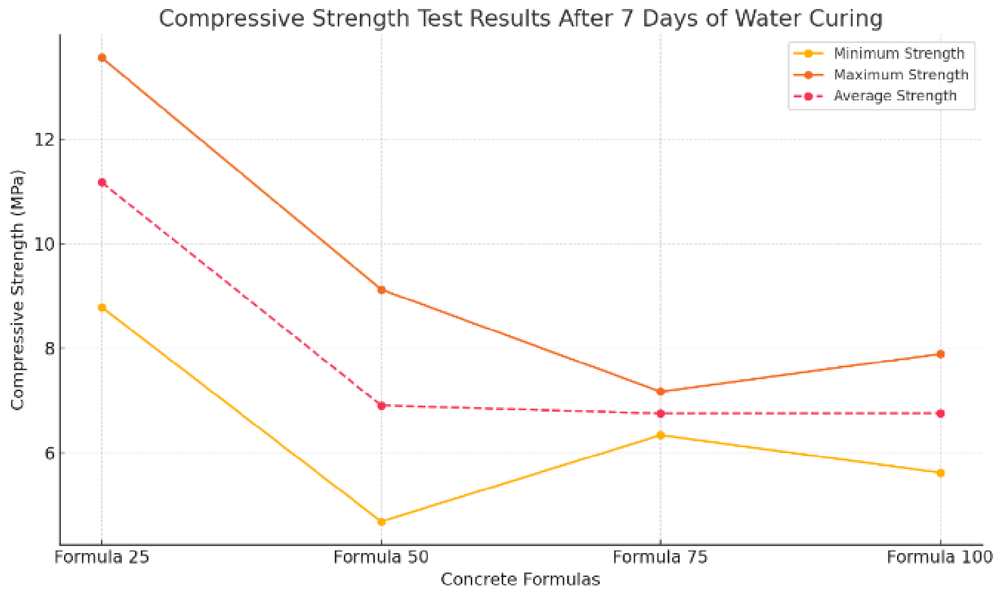
Compressive Strength Test Results following 7 Days of Water Curing

Figure 27 presents the compressive strength (MPa) of different concrete formulas (25, 50, 75, and 100) following a 7-day water curing period. The results show variations in compressive strength which signifies variable levels of performance across each formula. The detailed discussion and comparison of each formula's performance are as follows.

BS.25 exhibited the highest compressive strength (13.55 MPa), making it suitable for load-bearing structures despite some variability. BS.50 showed significant variations (4.69–9.12 MPa), indicating a need for material optimisation. BS.75 demonstrated moderate and stable compressive strength (6.34–7.17 MPa), suitable for non-load-bearing structures such as walls and partitions. BS.100 had the lowest compressive strength (5.62–7.89 MPa) and requires further improvement before use in construction.

Figure 27

Maximum Compressive Strength after 7 Days of Water Curing



Compressive Strength Test Results following 14 Days of Water Curing

Figure 28 shows the compressive strength (MPa) for various concrete formulas (25, 50, 75, and 100) following 14 days of water curing. Each formula displays different levels of compressive strength which provides insights regarding their performance over the curing period. The details and comparison of each formula's performance are as follows.

After 14 days, all formulas showed increased compressive strength. BS.25 remained the strongest (7.56–13.16 MPa), while BS.50 exhibited greater consistency (7.71–11.27 MPa), making it suitable for secondary structures. BS.75 had lower compressive strength (6.10–8.76 MPa), appropriate for non-load-bearing applications. BS.100 had the lowest strength (1.92–6.70 MPa), indicating a need for further material refinement.

Compressive Strength Test Results after 28 Days of Water Curing

Figure 29 shows the compressive strength (MPa) of various concrete formulas (25, 50, 75, and 100) following 28 days of water curing. Each formula demonstrates distinct performance and variability across samples, providing insights regarding the compressive strength stability and potential applications of each formula in construction. Detailed comparisons and observations for each formula are as follows.

After 28 days, BS.25 exhibited the highest and most stable compressive strength (12.13–17.33 MPa), making it ideal for high-load-bearing structures. BS.50 had moderate strength (7.58–12.89 MPa) and showed consistency, making it suitable for secondary structural applications. BS.75 had lower but stable strength (7.69–10.63 MPa), appropriate for non-load-bearing walls. BS.100 had the lowest strength (6.98–9.64 MPa) and requires further improvement for structural use. Compressive strength tests showed a strong correlation between curing duration and performance.

Figure 28

Maximum Compressive Strength after 14 Days of Water Curing

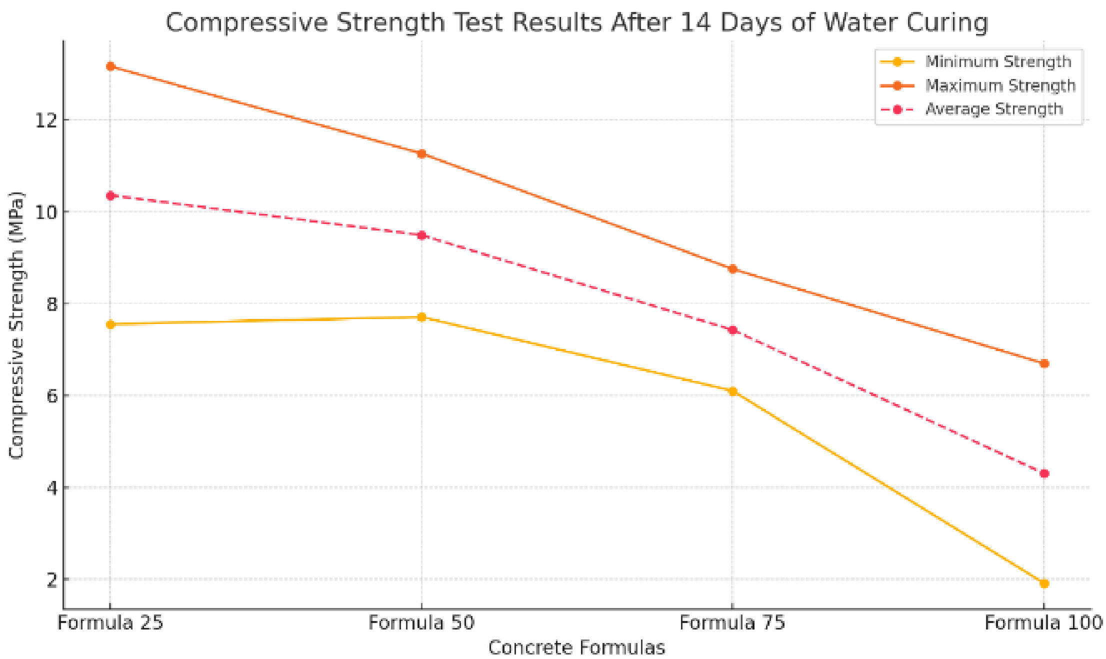
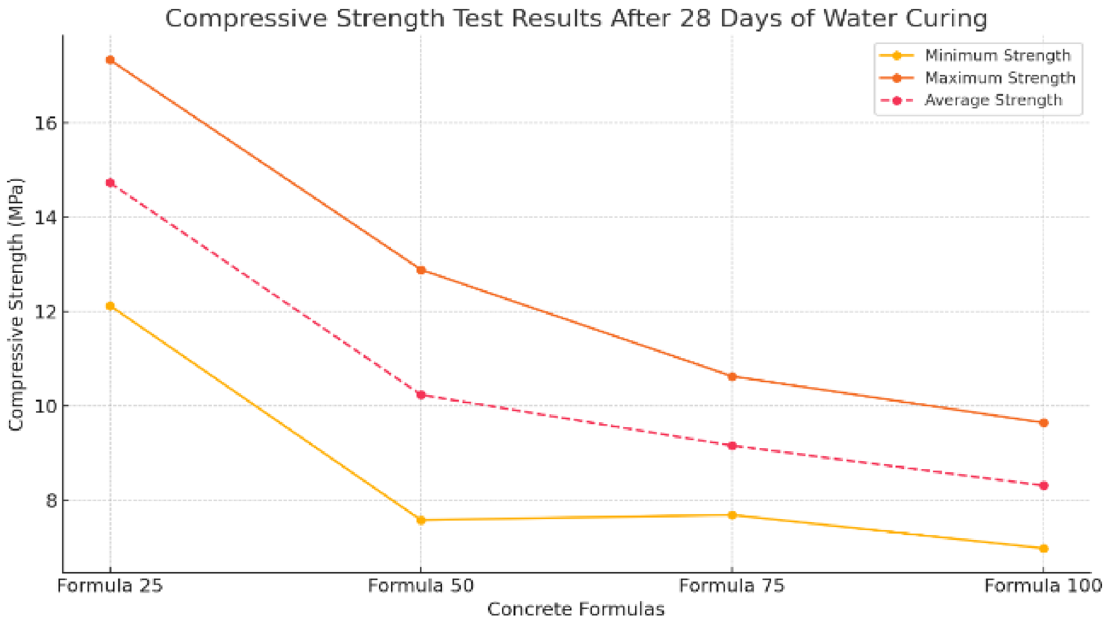


Figure 29

Maximum Compressive Strength after 28 Days of Water Curing



After **7 days**, BS.25 had the highest strength (13.55 MPa), suitable for load-bearing structures, while BS.50 exhibited variability (4.69–9.12 MPa), requiring optimisation. BS.75 showed stable but moderate strength (6.34–7.17 MPa), making it ideal for non-load-bearing applications, while BS.100 had the lowest values (5.62–7.89 MPa).

After **14 days**, all formulas improved, with BS.25 remaining the strongest (7.56–13.16 MPa). BS.50 became more stable (7.71–11.27 MPa), BS.75 remained moderate (6.10–8.76 MPa), and BS.100 had the lowest strength (1.92–6.70 MPa), limiting its structural use.

After **28 days**, BS.25 demonstrated the highest and most stable strength (12.13–17.33 MPa), ideal for load-bearing structures. BS.50 (7.58–12.89 MPa) performed reliably for secondary structures, while BS.75 (7.69–10.63 MPa) remained suitable for non-load-bearing applications. BS.100 had the lowest strength (6.98–9.64 MPa), requiring further improvement.

The results demonstrate that mussel-shell-derived aragonite sand is suitable as a sustainable aggregate alternative in construction. The observed compressive strength at a 25% replacement (17.33 MPa after 28 days) closely aligns with previous research on conventional sand and shell-based materials, such as Leone et al. (2023). Compared to conventional aggregates, mussel-derived aragonite's sharp-edged crystals significantly enhance mechanical bonding, positively impacting strength. However, strength reductions at higher replacements (75-100%) were consistent with Mishra's (2022) findings, indicating limitations for load-bearing uses.

These comparative insights underscore the optimal usage of aragonite sand as partial replacement to balance structural performance and environmental sustainability.

Influence of Aragonite Sand on Concrete Performance

The findings confirm that aragonite sand from mussel shells has the necessary chemical and mechanical properties for construction. XRD analysis verified the presence of aragonite, while XRF confirmed high calcium carbonate content, supporting its suitability as a natural sand substitute. SEM analysis showed that aragonite's irregular and sharp-edged structure enhances interlocking and improves concrete strength (Leone et al., 2023).

Microstructural Properties

Scanning Electron Microscopy (SEM) imaging revealed a layered and crystalline calcium carbonate structure in the mussel shells. After grinding, the aragonite particles exhibited sharp edges and irregular shapes, which enhance interlocking within concrete and contribute to higher compressive strength (Leone et al., 2023). These properties improve bond strength and mechanical performance, making aragonite sand a viable alternative to natural sand in concrete production.

Compressive Strength Results by Formula

Formula 25 (25% aragonite, 75% natural sand) had the highest compressive strength (15.62 MPa after 28 days) of all the curing periods. This means it is perfect for use in load-bearing structures that need to last a long time. In Formula 50, which is made up of 50% aragonite and 50% natural sand, the compressive strength was moderate (10.9 MPa after 28 days), and the performance was stable. Furthermore, this means that it can be used for secondary structural parts like walls or non-primary support structures. Formula 25, which is made up of 25% aragonite and 75% natural sand, had the lowest compressive strength (8.2 MPa after 28 days). This means it can be used for things like decorations or short-term installations where strength is not very important.

Overall, the varying performance of these mixes highlights the importance of selecting the right formulation based on the specific structural needs and longevity expectations of the project. Formula 75 (75% aragonite, 25% natural sand) had a moderate compressive strength and consistency. It is a good choice for non-load-bearing uses like walls or partitions that are not heavy. Formula 100 (100% aragonite, 0% natural sand) displayed the lowest compressive strength, which suggests that it is most suitable (given further, such as decorative elements or lightweight infill).

The unique properties of aragonite could also open avenues for creative designs, allowing architects and builders to explore innovative solutions while maintaining environmental sustainability, such as insulation or filler. In contrast, Formula 50 (50% aragonite, 50% natural sand) offered a balanced combination of strength and flexibility, making it a versatile choice for various lightweight applications. This formula has the potential to minimize material usage while still providing adequate performance in scenarios where structural integrity is not severely compromised.

Recommendations for Improvement

The notion of sustainable development (SD) was introduced in the prominent Brundtland Commission report 'Our Common Future' in 1987 (Das & Barman, 2024). While this study confirms the potential of aragonite sand as a sustainable alternative to natural sand, further research and refinements are required to optimise its performance and consistency.

- **Improving BS.100 compressive strength** Investigate longer curing durations beyond 28 days to assess whether strength continues to improve. Modify particle size gradation to enhance packing density and bonding. Consider blending aragonite with pozzolanic materials such as fly ash or silica fume to enhance mechanical strength and durability.
- **Long-term durability studies** Investigate how aragonite-based concrete withstands exposure to moisture, sulfate attacks, and freeze-thaw cycles. Conduct real-world structural tests to validate load-bearing potential under different climatic conditions.
- **Hybrid mixing strategies** Combining aragonite with other alternative aggregates (e.g., recycled glass, polymer-based sand) could enhance structural performance while maximizing sustainability.

Figure 30

Alternative Design Application from Biowaste (Aragonite Bio Brick Block)

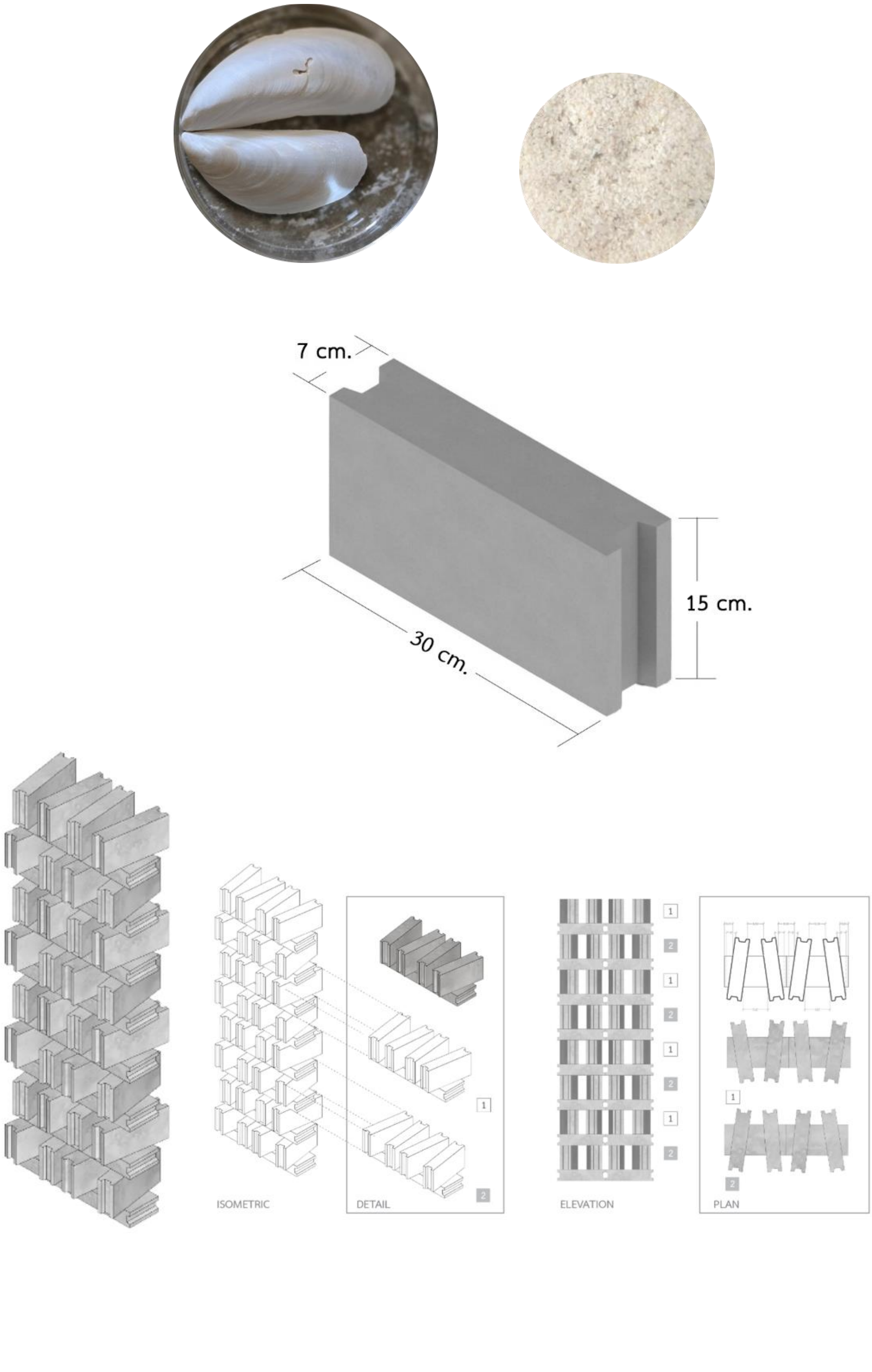
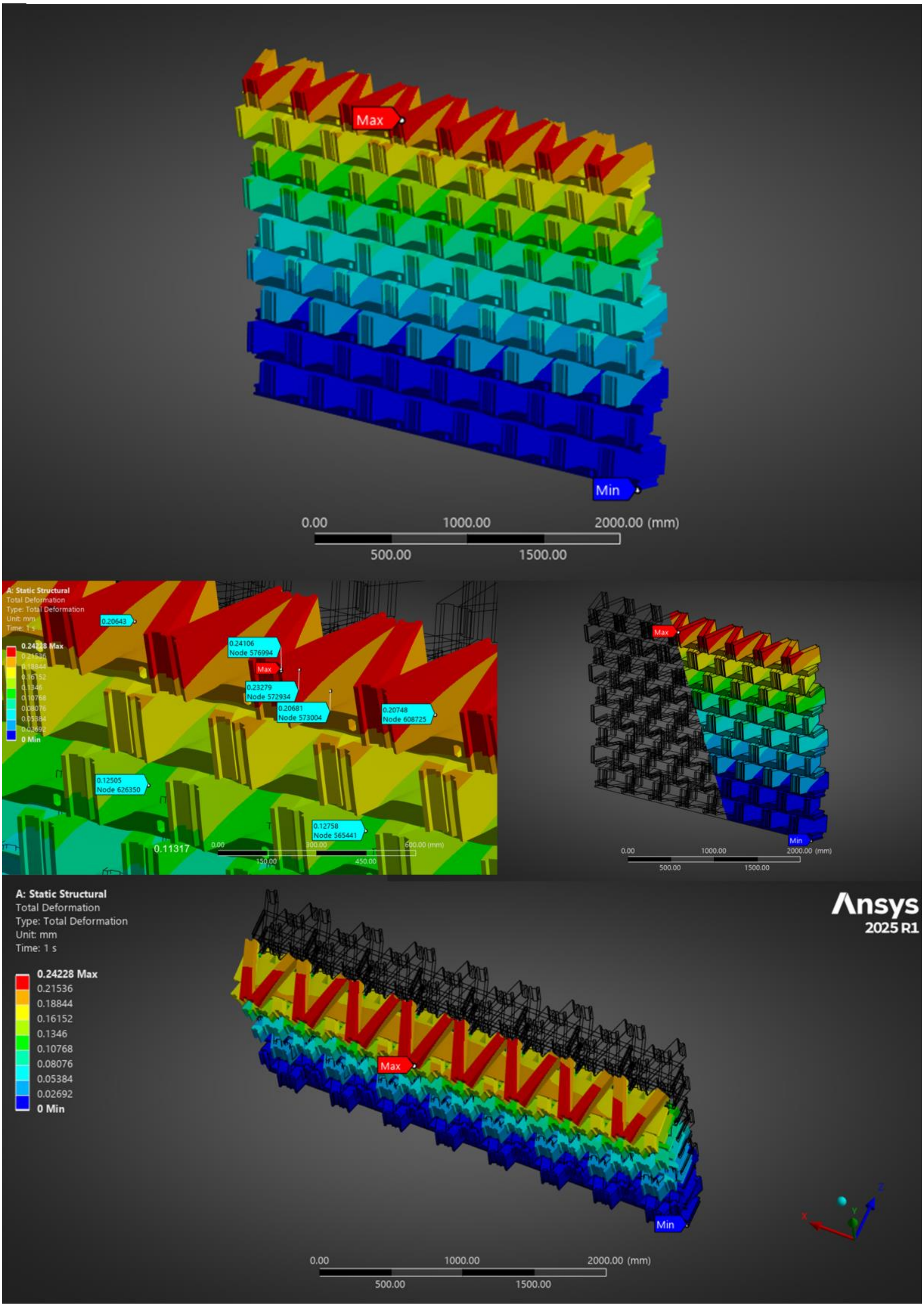


Figure 31

Wall Simulation Using ANSYS (Illustrates Deformation)



Wall Simulation Using ANSYS

Figure 31 illustrates the simulation revealed the wall's ability to manage compressive forces in its curved segments which significantly enhances the overall stability of the structure. The modular arrangement effectively minimizes stress concentration in specific points which contributes to the long-term durability of the structure under load. Moreover, the wall analysed in this study is a modular configuration with interlocking layers. The modular units are arranged in a complex three-dimensional pattern designed to efficiently distribute compressive and tensile forces throughout the structure. The curved form of the wall integrates both structural integrity and aesthetic appeal and aligns with architectural principles that prioritise strength and design synergy. Additionally, the modular design facilitates easy assembly and disassembly which enhances its adaptability for various applications and minimises construction complexity.

Optimal Mixing Ratios for Sustainable Construction

The varying performance of different formulas suggests that aragonite sand can partially replace natural sand in construction materials. The 25% aragonite replacement (BS.25) achieved the best balance between strength and sustainability, demonstrating high compressive strength and stability across all curing durations. The 50% replacement (BS.50) provided moderate performance, making it a viable choice for secondary structural components. The 75% and 100% replacements (BS.75 and BS.100) exhibited lower strengths, making them more suitable for non-structural applications such as insulation, fillers, or lightweight walls.

Environmental and Practical Implications

The capacity for adaptation is associated with individuals' utilization of resources, particularly cultural and ecological resources, at multiple levels (Tienthavorn, 2025). Using aragonite sand derived from mussel shells aligns with sustainability goals by reducing dependency on natural sand and promoting waste utilisation. The process minimises environmental degradation caused by excessive sand mining while addressing waste disposal issues in coastal communities (Marastoni et al., 2017). Additionally, incorporating aragonite sand into construction materials can lower the carbon footprint of concrete production by reducing the demand for traditional aggregates (Wang et al., 2018). Aragonite's high calcium carbonate content also makes it more resistant to strength degradation over time, ensuring that structures maintain their integrity for longer periods. This durability not only enhances the lifespan of buildings but also contributes to long-term cost savings in maintenance and repair sulphate corrosion, which makes the material last longer (Manjunath, 2019).

Future Research and Recommendations

Sustainable Development has been advocated for several decades as an optimal framework for reconciling management with socio-economic and environmental objectives (Tachakitkachorn et al., 2021). Further studies should focus on refining the processing techniques for aragonite sand to enhance its consistency and mechanical performance, cost feasibility for construction. Long-term durability testing, including exposure to different environmental conditions, would provide additional insights into its real-world applications. Additionally, exploring hybrid mixing strategies that combine aragonite with supplementary cementitious materials (such as fly ash or silica fume) may further optimise its mechanical properties and sustainability benefits.

CONCLUSIONS

Global cities are progressively prioritizing green building programs, emphasizing energy efficiency, resource conservation, and minimal carbon emissions (Aduldejcharas, 2024). This study investigated the feasibility of using aragonite sand derived from mussel shells as a sustainable alternative to natural sand in construction (specifically in concrete). As natural sand resources face depletion due to increasing demand, alternative materials that leverage waste products, such as mussel shells, are essential for sustainable development. This study evaluated the chemical composition (see figures 30, 31, 32 and 33), structural properties, and compressive strength of concrete formulas with varying aragonite-to-natural sand ratios (25%, 50%, 75%, and 100%, respectively) over curing periods of 7, 14, and 28 days.

Chemical and Structural Properties

The XRD and XRF analyses confirmed high concentrations of calcium carbonate ($CaCO_3$) in the aragonite structure of mussel shells and established that calcium oxide (CaO) is the primary component (52.8%). This chemical composition suggests that aragonite sand has suitable properties for integration into concrete and provides a strong foundation for durability and stability (Marastoni et al., 2017).

Figure 32

Decorative Structure for Landscape

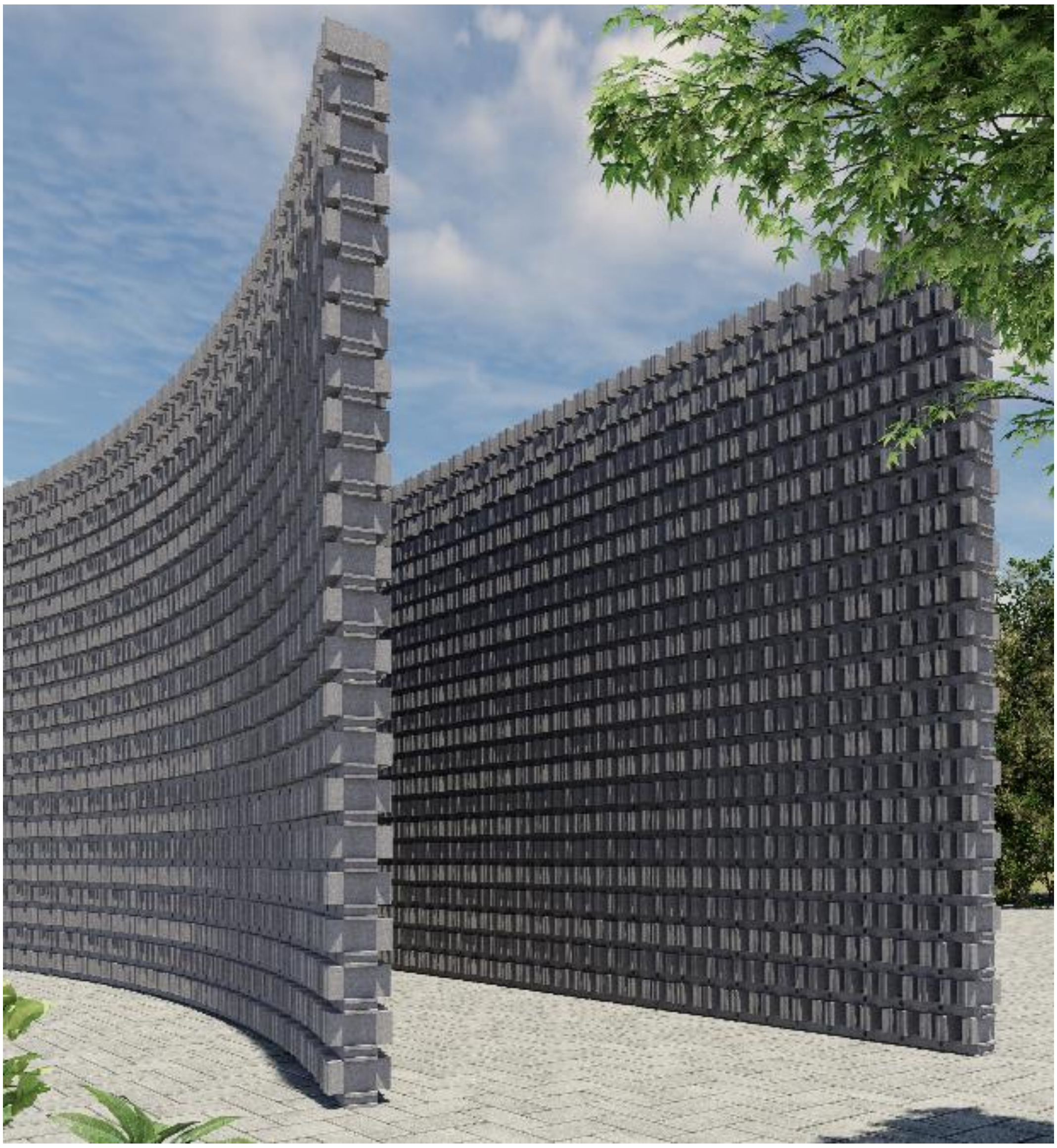
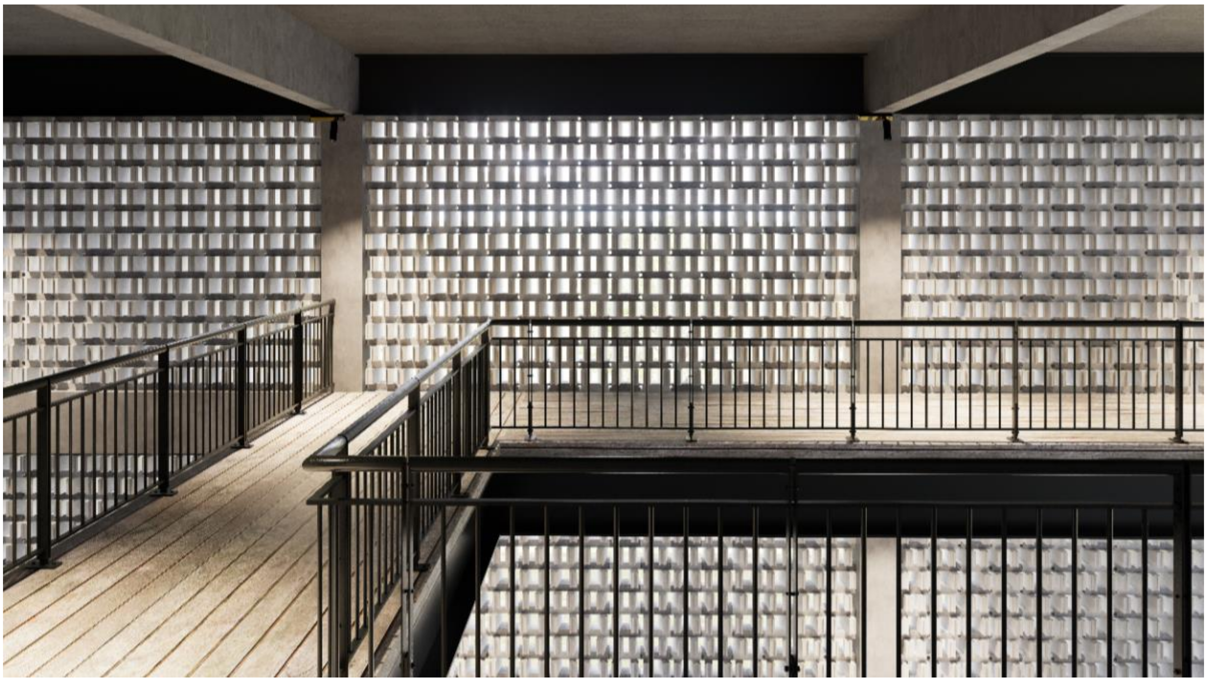


Figure 33

Structure for Exterior Facade Design (Shading Brick Block)

Figure 34

Structure for Interior Wall Design



This study confirms mussel-shell-derived aragonite sand as a promising sustainable alternative to natural sand, particularly at 25%-50% replacement levels. The practical implications suggest that 25% aragonite mixtures are suitable for structural applications, such as residential and small-scale infrastructure projects. Higher ratios (75%-100%) are recommended for non-load-bearing applications, including decorative or insulating materials. Identified limitations include variability in strength at higher replacement ratios, necessitating further optimisation of particle size and curing methods. Future research should explore material consistency, long-term durability under environmental stress, and hybrid mixtures with supplementary cementitious materials like fly ash or silica fume.

Adopting aragonite sand reduces environmental impacts associated with traditional sand extraction and addresses coastal waste management challenges, supporting the industry's transition towards sustainable construction practices.

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