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Original Research Article

Calcined Green Mussel Shell Waste as a Bioaggregate in Pervious Concrete Paver Blocks

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Abstract

Ineffective management of green mussel shell waste could worsen environmental issues. Green mussel shell waste can be used as a bioaggregate because it contains 90% $CaCO_3$, which is similar to limestone and is generally chemically inert. Seashells calcined at high temperatures and fine particle sizes exhibit limited reactivity. This study aimed to analyze the amount of green mussel shell waste produced, the performance of calcined green mussel shell bioaggregate, the optimal substitution of bioaggregate in pervious concrete paver blocks, the performance of pervious concrete paver blocks, and the influencing factors. The methods used were observational to calculate the amount of waste produced over eight consecutive days and experimental to determine the mechanical and physical performance of pervious concrete paver blocks with bioaggregate substitution levels of 0%, 6%, 12%, 18%, and 24% at a test age of 28 days. The production of green mussel shell waste in the 2025 planting season was 86.7 kg/day. The test results for pervious concrete paver blocks showed that the compressive strength, porosity, and permeability values were within the ranges recommended by ACI 522R-10, 2010 and SNI 03-0691-1996 for permeable concrete used as parking area pavement material.

Keywords: Green mussel shell waste; calcination; bioaggregate; pervious concrete paver blocks; sustainable construction

1. Introduction

Tambak Lorok is a fishing village located in North Semarang City, which borders the Java Sea (Triantoro et al., 2017). The lives of fishing village communities largely depend on their marine natural resources. Green mussels (*Perna viridis*) belong to the bivalve mollusks, and this biota is widely distributed along the edges of the Indo-Pacific region (Fauzi et al., 2022). Green mussels spawn throughout the year, with spawning in Indonesia occurring in April, May, August, and November (Cappenberg, 2008). Green mussels are a type of shellfish found every year in Tambak Lorok, Semarang. This green mussel has economic value because its production (capture and aquaculture) is stable with and increasing (Fitriah et al., 2018; Martínez-García et al., 2017; Trianto et al., 2017). Owing to the high demand from diverse markets, green mussels are often sold shelled (without shells). The peeling process produces mussel shell waste, as shown in **Figure 1**. Green mussel shell waste in Central Java in 2019 reached 8,750 tons, and ineffective management of shell waste has the potential to cause environmental problems that reduce the standard of living for nearby communities (Ismail *et al.*, 2022). Green mussel shells can be utilized as bioaggregates, serving as fillers, replacements, and a natural animal-derived concrete mixes (Artismo et al., 2024; de Freitas et al., 2024).

Figure 1. Accumulation of green mussel shell waste

Seashells are composed of 97% polycrystalline $CaCO_3$ in the form of calcite, aragonite, and a small percentage of biological polymers from chitin, proteins, and glycoproteins (de Freitas *et al.*, 2024). The $CaCO_3$ in seashells is similar to that in limestone used in the production of portland cement, so it can be concluded that the bioaggregate is inert and there are no problems with hydration reactions or bonding properties (Eo and Yi, 2015; Mo et al., 2018; Mohammad et al., 2017). Furthermore, Bekkeri et al. (2024); Hamada et al. (2025); Luo et al. (2024); Yang et al. (2024), found that high-temperature washing and calcination treatments with fine particle sizes can exhibit limited reactivity. According to Hong and Choudhury (2024); Wang et al. (2019), this reactivity and these effects are minimal compared to the increase in porosity and water absorption. Martínez-García et al. (2017), stated that seashells need to be washed before use to remove and reduce organic matter, sediment, chloride and sulfate ions. High chloride and sulfate contents can potentially damage concrete. According to Shao et al. (2024), chloride ions and organic matter can be removed by calcination at temperatures above 850°C. According to Nguyen et al. (2017), seashells used as bioaggregates must have a particle size distribution similar to that of natural aggregates. Using uncrushed seashells creates voids, thus reducing the compressive strength. Zhu et al. (2024) state that the size of the seashells used to replace fine aggregate should be < 5 mm, while the coarse aggregate should range from 16-25 mm. According to Zhu et al. (2024), the properties of seashell aggregates reported in the literature are presented in Table 1.

Table 1. Physical properties of seashell aggregates.

Seashell Type	Size (mm)	Fineness Modulus	Specific Gravity	Water Absorption (%)
Oyster	0.074–2	-	2.42	-
	<2	2.27	2.29	-
	<4.75	2	2.1	7.7
	<5	2.8	2.48	2.9
	<5	3.66	-	6.84
	<5	3.72	-	8.87
	<5	1.85	2.59	1.61
	25	7.68	2.67	0.4
Scallop	<5	4.4	2.64	3.65
Mussel	<0.075	-	2.82	-

Seashell Type	**Size (mm)**	**Fineness Modulus**	**Specific Gravity**	**Water Absorption (%)**
	0–1	1.9	2.73	4.12
	1–4	4.64	2.65	2.56
	4–16	5.38	2.62	2.17
Cockle	4.75–6.3	-	2.64	2.5
	6.3–9.5	-	2.09	1.8

Diffractogram results of freshwater mussel shell powder from *Corbicula bensoni* and *Lamellidens marginalis* showed the presence of $CaCO_3$ in the form of aragonite and calcite crystals (Chakraborty *et al.*, 2020). The chemical composition of seashells changes upon calcination. Deng et al. (2025) stated that uncalcined seashells contain more $CaCO_3$, while calcined seashells contain more CaO. Research by Martínez-García et al. (2017) shows that the thermogram of the mussel shell at a temperature of 285.5°C indicates the release of water contained (hydration) and water trapped in the pores (interstitial) of the mussel shell. The peak endothermic point occurred at 720.9°C, indicating the decomposition of all $CaCO_3$ crystals (aragonite and calcite) within the mussel shell. This process is called calcination, and mussel shells lose weight owing to the release of large amounts of CO_2. According to Budihardjo et al. (2021), the calcination reaction in seashells is shown in the following equation:

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

It should be noted that the CaO content in the calcined seashells depends on the type of seashells, cleaning method, and calcination temperature. Felipe-Sesé et al. (2011), green mussel shells calcined at 1100°C can yield 87.21% CaO, while Lertwattanaruk et al. (2012), found that green mussel shells calcined at 550°C only yielded 53.38% CaO. Budihardjo et al. (2021), added that seashells processed by pyrolysis at 800°C yielded 97% CaO. According to Artismo et al. (2024), mussel shells have inherent characteristics that make them suitable as a fine aggregate substitute. According to Zhu et al. (2024), the chemical composition of seashell waste from several sources is presented in Table 2.

Table 2. Chemical composition of seashell aggregates (%).

Seashell Type	**$CaCO_3$/CaO**	**SiO_2**	**Al_2O_3**	**MgO**	**Fe_2O_3**	**Na_2O**	**K_2O**	**SO_3**	**P_2O_5**	**LOI**
Raw										
Seashell	89.56	4.04	0.42	0.65	-	0.98	-	0.72	0.2	-
Oyster	95.32	1.01	0.26	0.71	0.15	1.18	-	0.66	-	-
River shell	95.99	1.28	0.4	0.68	-	0.98	-	0.72	0.2	-
Mussel	96.9	1.3	-	-	0.5	-	0.4	0.3	-	-
Cockle	97.6	0.13	0.1	0.32	0.28	1.22	0.03	0.12	-	-
Calcined										
Snail	51.09	0.6	0.51	0.69	0.56	1.2	0.12	0.19	0.21	40.54
Cockle	51.56	1.6	0.92	1.43	-	0.08	0.06	-	-	41.84
	51.91	0.38	0.65	-	0.05	-	-	-	-	-
Oyster	51.06	2	0.5	0.51	0.2	0.58	0.06	0.6	0.18	44.16
	53.81	0.4	0.22	0.7	0.04	-	-	-	-	44.87
Cardiidae	52.34	3.65	1.15	0.42	0.2	0.35	0.13	0.47	-	41.25
Scallop	53.7	0.1	0.1	0.18	0.03	0.5	0.01	0.32	-	44.4
Periwinkle	52.1	27.2	6.42	0.82	4.64	0.26	0.25	0.26	-	-
	55.53	26.26	8.79	0.4	4.82	0.25	0.2	0.18	0.05	-
Clam	53.92	0.46	0.2	0.22	0.04	-	-	-	-	45.16
	67.7	0.39	0.28	-	0.02	-	-	-	-	-
Mussel	53.7	0.2	0.13	0.33	0.03	-	-	-	-	45.61

Seashell Type	$CaCO_3/CaO$	SiO_2	Al_2O_3	MgO	Fe_2O_3	Na_2O	K_2O	SO_3	P_2O_5	LOI
	87.21	0.55	0.03	0.49	0.05	0.5	0.04	-	0.09	-

The construction sector has increasingly recognized the need for a shift towards sustainability in recent years (Martínez-García *et al.*, 2017). The concept of sustainability in the construction sector refers to the development of materials using natural or recycled materials (Asdrubali et al., 2015). Sustainable building is a development approach whose design, construction, and orientation are intended to reduce or eliminate negative environmental impacts (Debrah et al., 2022; Fei et al., 2021). Porous or permeable pavements are promoted as effective sustainable drainage systems to reduce runoff and surface flooding (Kia *et al.*, 2021). Pervious concrete paver blocks (PCPB) are porous or permeable pavements designed with a fully porous internal structure that allows water to pass directly through the internal structure. Pervious concrete paver blocks are suitable for installation and placement, with absorption being a more crucial factor than compressive strength, durability, and stability of the concrete. Matthew et al. (2024) added that pervious concrete paver blocks are only suitable for road pavements with light vehicle traffic. A comprehensive study on the production of pervious concrete paver blocks from bioaggregates derived from seashell waste is integral to developing sustainable construction materials that functionally support the application of sustainable building concepts. Based on these descriptions, this study provides an overview of the amount of green mussel shell waste produced in Tambak Lorok, Semarang, and determines the mechanical and physical performance of pervious concrete paver blocks under varying levels of calcined bioaggregate substitution.

2. Methods

Green mussel shells (*Perna viridis*) originate from Tambak Lorok, Semarang. Green mussel shell waste was collected and weighed by local collectors for eight consecutive days. Pervious concrete paver blocks (PCPB) were produced using Portland Composite Cement (PCC) as the base material, along with coarse aggregate, fine aggregate, green mussel shell bioaggregate, and water. This study used calcined green mussel shell (GMS) bioaggregates as a substitute for fine aggregates at 0%, 6%, 12%, 18%, and 24%. The selection of 6% substitution multiples was based on previous research findings showing that substitution above 20% can limit workability and reduce mechanical performance (Zhu *et al.*, 2024). PCPB-GMSx, where x represents the percentage of substitution of the green mussel shell bioaggregate with fine aggregate. The pervious concrete paver blocks were molded using an automatic hydraulic press machine that was vibrated for 10 s, with a mold size of 21 × 10.5 × 6 cm. The molded pervious concrete paver blocks were cured and tested on day 28. This research method was observational to calculate the amount of green mussel shell waste produced in Tambak Lorok, Semarang, and experimental to determine the effect of different levels of bioaggregate substitution on the mechanical (compressive strength) and physical (porosity and permeability) performance of pervious concrete paver blocks. Testing standards refer to the ACI 522R-10, 2010 and the SNI 03-0691-1996. The results will be presented in a descriptive and quantitative manner.

2.1. Processing Raw Shells into Bioaggregate

Green mussel shells were soaked for 3 days and then rinsed with water to remove organic matter, salt, chloride ions, and impurities. The samples were then dried in sunlight. The dried shells were crushed using a crushing machine until they became flakes, then calcined using a furnace (Blue M Moldatherm Box Furnace Model BF5184C-31) at 900 °C for 2 h, and finally ground using a chopper into a powder of approximately ± 180 µm.

a) b) c) d)

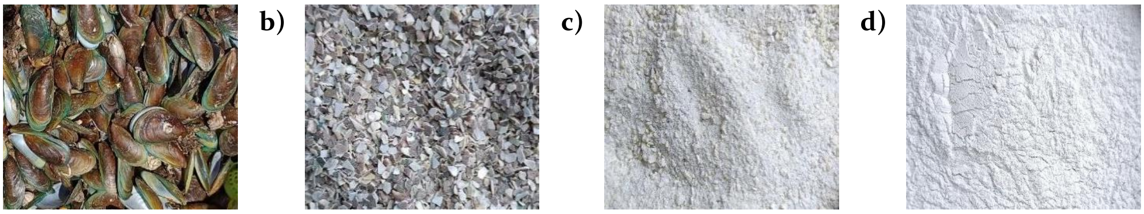

Figure 2. Appearance of green mussel shells at different stages of processing: a) whole shells, b) crushed shells, c) calcined shells, and d) powder.

2.2. Material Testing

The material components of pervious concrete paver blocks, including coarse aggregates, fine aggregates, and green mussel shell (GMS) bioaggregates, were tested to determine their specifications according to SNI. Each value represents the average of the two material tests. The test results are as follows.

Table 3. Testing materials

Properties	Standard Test Method	Result of the Materials		
		Coarse	Fine	GMS bioaggregate
Specific Gravity	SNI 1969:2016 and 1970:2016	2.642	2.711	2.263
Water Absorption		2.84%	2.57%	1.66%
Fineness Modulus	SNI 03-1968-1990	7.03	4.98	2.82
Water Content	SNI 1971:2011	0.53%	0.64%	-
Mud Content	SNI 03-4141-2015	0.89%	4.09%	-
LA Abrasion	SNI 03-2417-2008	25.59%	-	-
Organic matter	SNI 2816:2014	-	Plate Number 3	-

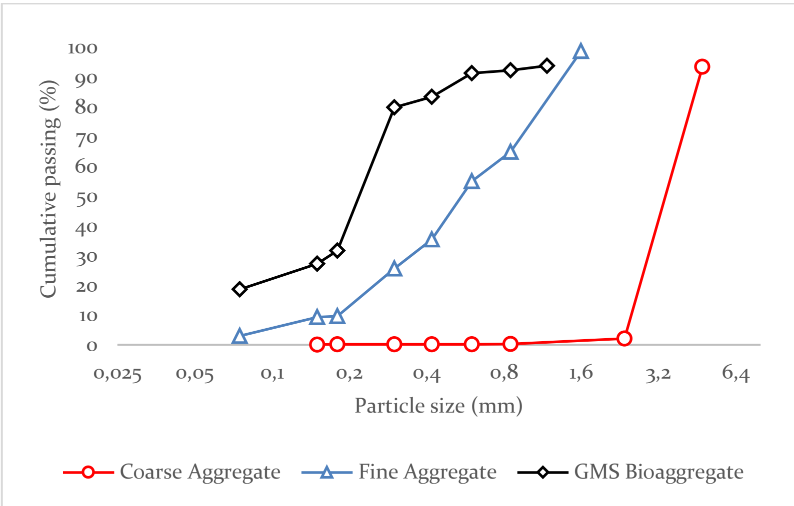

Figure 3. Particle size distributions of the materials.

2.3. Production of Pervious Concrete Paver Blocks

Pervious concrete paver blocks were made by mixing coarse and fine aggregate materials, cement, and green mussel shell (GMS) bioaggregate until homogeneous, and then gradually adding water until all the materials were fully combined and had a shiny appearance. The W/C ratio was constant at 0.34. The pervious concrete paver blocks were molded in an automatic hydraulic press machine and vibrated for 10 s. The mix design for the pervious concrete paver blocks is presented in Table 4.

Table 4. Mix design (kg/m³)

Material	PCPB Variations				
	GMS0	GMS6	GMS12	GMS18	GMS24
Coarse aggregate	1321	1321	1321	1321	1321
Fine aggregate	101.7	96.6	91.5	86.4	81.3
Cement-PPC	393.8	393.8	393.8	393.8	393.8
Water	133.9	133.9	133.9	133.9	133.9
GMS bioaggregate	0	5.1	10.2	15.3	20.4

The precast pervious concrete paver blocks were covered with clear plastic and left to cure in a shaded area away from direct sunlight for one day. The curing process was continued using burlap sacks that were watered once a day until the blocks reached 28 d of age, as shown in Figure 4.

Figure 4. Curing process and pervious concrete paver block test objects.

2.4. Pervious Concrete Paver Blocks Testing

The pervious concrete paver blocks were tested at 28 d of age, with each parameter value representing the average of three tests. The following parameters were tested:

2.4.1. Compresive strength

The compressive strength is the ability of pervious concrete paver blocks to withstand loads up to the point of damage per unit area. The compressive strength value ranges from 2.8 to 28 MPa (ACI 522R-10, 2010). The following is the equation for the compressive strength value (SNI 03-0691-1996):

$$f'c = \frac{P}{A} \tag{1}$$

$f'c$ represents compressive strength (MPa), P is the maximum load (N), and A being cross-sectional area of specimens (mm²).

2.4.2. Porosity

Porosity is the ratio of the volume of voids to the total volume of a pervious concrete paver block. The porosity value ranges from 15% to 35% (ACI 522R-10, 2010). According to Zhang et al. (2023), the equation for the porosity value is as follows:

$$Pe = \left(1 - \frac{m2 - m1}{V.\rho}\right) x\ 100\% \tag{2}$$

where Pe is the effective porosity (%), m1 is the mass of the specimen in water (g), m2 is the dried mass of the specimen in air (g), V is the volume of the specimen (cm³), and ρ is the density of water (g/cm³).

2.4.3. Permeability

The permeability is the ability of a pervious concrete paver block to transmit water through its internal pores. The permeability coefficient ranges from 0.14 to 1.22 cm/s (ACI 522R-10, 2010). According to Akkaya and Çağatay (2021), the permeability coefficient equation is as follows:

$$K = \frac{L.a}{(t2 - t1).A} \ln \frac{h1}{h2} \quad (3)$$

where K is the coefficient of permeability (cm/s), L is the thickness of the specimen (cm), a is the area of the reservoir (cm^2), t2 - t1 is the time taken for the start and final head (s), A is the area of the specimen (cm^2), and h1 and h2 are the water levels of the start and finish points of the test (cm).

3. Result and Discussion

3.1. Green Mussel Shell Waste Generation

The collection and measurement of green mussel shell waste production at Tambak Lorok, Semarang, were conducted using collectors for eight consecutive days during the planting season (bamboo as the mussel cultivation medium) in February-March 2025. The average generation rate of green mussel shell waste in Tambak Lorok was 86.7 kg/day. Fishermen's catch and market demand influence the amount of green mussel shell waste generated.

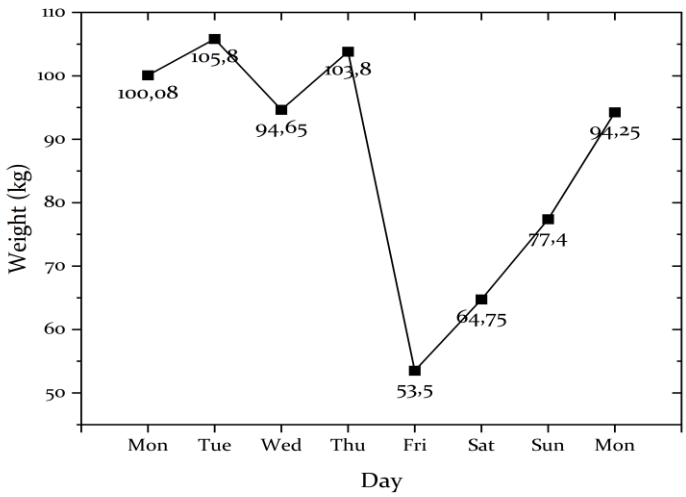

Figure 5. Green mussel shell waste production

Furthermore, the results presented in Figure 5 show that the production rate of green mussel shell waste on weekdays is quite constant, ranging from 94-105 kg/day, while on weekends, there is a decrease with a range of 53-74 kg/day. Based on interviews with fishermen and mussel shellers, it was found that most fishermen do not go out to sea on weekends because of religious activities and the tendency to repair their boats and sell their catch. This statement is supported by Rahmawati and Afriandi (2024), who state that the prohibition on fishing on Fridays and on major religious holidays is one form of applying religious values. Faisal (2013), added that there are four reasons behind the designation of Friday as a day of fishing prohibition, including fulfilling religious values, supporting ecological aspects (spawning and conservation of marine life), time for repairs, and time for family. The production value of green mussels fluctuates monthly and increases significantly during the harvest season. According to Dimas and Sutrisna (2018); and Hafid and Abu (2019), several factors can influence the catch of seashells, including the season, rainfall, fishermens age, experience, number of workers, fishing gear, boat engines, catch containers, and other factors.

3.2. Mechanical and Physical Properties of Pervious Concrete Paver Block

3.2.1. Compressive Strength

The compressive strength of pervious concrete paver blocks was determined using the Indonesian National Standard (SNI) method. The pervious concrete paver blocks were placed in a Compression Testing Machine (CTM), and the loading rate was gradually increased until the sample cracked. Based on SNI-03-0691-1996, the compressive strength values for all variations in fine aggregate substitution levels in pervious concrete paver blocks are classified as grade B, with values ranging from 27.21 to 18.75 MPa. The compressive strength results are presented in Figure 6. The compressive strength test results for pervious concrete paver blocks showed a slight decrease of 3.40% in PCPB-GMS6 compared with PCPB-GMS0. The smaller decrease in compressive strength at low substitution levels may be influenced by the conventional mixing and steering method, which affects the homogeneity. The different durations and energy consistency levels in this method led to a nonhomogeneous distribution of substituent particles, triggering segregation, adhesion, and suboptimal cement hydration. The results of research by Malau and Irwan (2024) show that the mixing method can affect the compressive strength of concrete. Mixing using the conventional method produced a compressive strength of 24.64 MPa, which was 17.87% lower than that of the semi- and ready-mix methods, which produced 30.58 MPa and 30.86 MPa, respectively. Research by Suarez-Riera et al. (2021) used rough cockle shells (*Acanthocardia tuberculata*) to replace sand in mortar. The results showed a decrease in compressive strength at low substitution (10%) and an increase at high substitution (15%). The compressive strength values for the control sample (36.5 MPa), SH 5% (36.5 MPa), SH 10% (32.5 MPa), and SH 15% (34.5 MPa) were also observed. This decrease was due to the presence of organic matter residues and the seashell structure, which is intrinsically more brittle, angular, and fissured than that of natural aggregates.

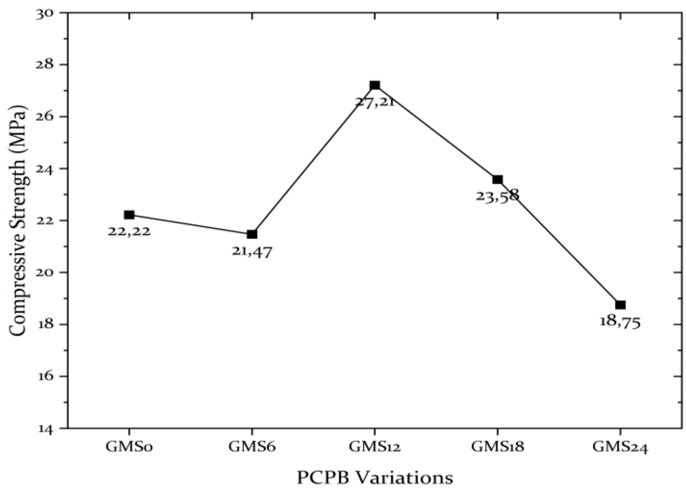

Figure 6. Compressive strength of pervious concrete paver blocks

The compressive strength increased significantly by 22.45% in PCPB-GMS12 compared with that in PCPB-GMS0. This increase was triggered by a balanced combination of natural aggregates and the percentage of seashell bio-aggregate replacement. The calcined shells with fine particle sizes (± 180 μm) exhibited an enhanced pore-filling effect owing to $Ca(OH)_2$ formation and residual CaO deposition, and mechanical compaction further increased the matrix density. Mo et al. (2018); and Zhu et al. (2024) stated that shell powder, which has a higher fineness level than cement, can act as a filler to improve particle packing and reduce pore voids, thereby increasing compressive strength. Liu et al. (2024) observed that CaO contributes to the interfacial bonding between aggregates and cement paste. Rashad (2023) confirmed that CaO can be used as a single activator in various precursors, with a range of 2.5-10% and an optimum of 5%. The addition of CaO can accelerate the formation of hydration products, thereby reducing micropores and increasing density and strength; however, it can also act as a diffusion barrier. Liao et al. (2023) supported that compressive strength increases with the addition of calcined shell bioaggregate in mortar, especially in the early stages, due to the dissolution of CaO, which produces $Ca(OH)_2$ to accelerate the pozzolanic reaction with metakaolin. The formation of C-S-H gel and calcium aluminate carbonate fills the voids and increases the density of the structures, whereas cement hydration products also strengthen the structure. Higher calcination temperatures are known to increase the formation of hydraulic phases (C_2S, C_3S, C_3A, and C_4AF) and reduce non-reactive impurities, thereby increasing the amount of hydration product. Hong and Choudhury (2024) reported that although seashells contain $CaCO_3$, which may have some pozzolanic effects, these effects are negligible compared to the reduction in strength caused by increased porosity and water absorption.

The compressive strength decreased sharply when the seashell substitution was increased to more than 12%. Sharp decreases in compressive strength of 13.33% and 31.11% were observed in PCPB-GMS18 and PCPB-GMS24, respectively, compared that with of PCPB-GMS12. Excessive substitution of calcined mussel shell bioaggregates with fine aggregates leads to an imbalance in component proportions. Seashells have an irregular, porous surface and, at fine or micron-scale sizes, possess a high specific surface area, which tends to reduce the availability of free water in the mixture. These conditions weaken cohesion, disrupt interparticle bonding, and reduce the availability of effective water, negatively impacting the hydration and hardening processes of pervious concrete paver blocks. This statement is supported by Shakrani et al. (2017), who stated that seashell bioaggregate exhibits a higher affinity for water than natural aggregate, likely due to the CaO content formed during calcination. Bekkeri et al. (2024) stated that 15% is the optimal dose for replacing part of the aggregate with seashell bioaggregate. de Freitas et al. (2024) explained that the flat, irregular, porous, and flat morphology of the shell aggregate can worsen the interfacial transition zone (ITZ) between the cement paste and aggregate, allowing air to enter and increasing porosity, thereby reducing compressive strength. This statement is supported by Hong and Choudhury (2024), who found that when the substitution of seashell bioaggregate in concrete exceeds 30%, it indirectly increases internal voids and water absorption, thereby disrupting the cement hydration process and weakening the concrete. Furthermore, Bamigboye et al. (2021); and Hamada et al. (2025) state that excessive CaO content in concrete mixes negatively impacts concrete strength development by inhibiting the initial hydration process. It also causes volume instability and weakens ITZ. These negative effects were more evident at higher levels of calcined seashell replacement.

3.2.2. Porosity

Porosity testing was conducted by immersing pervious concrete paver block samples in water until no bubbles were observed, weighing them in water using an Ohaus balance, removing the pervious concrete paver blocks from the water, drying them in an oven at 105 °C for 24 h, and weighing them again after they reached room temperature. The results of the porosity test are shown in Figure 7. The porosity increased by 1.35% in PCPB-GMS6 compared to that in PCPB-GMS0. This increase was due to the conventional mixing method, which led to material inhomogeneity because the applied force and energy were inconsistent during mixing. Another increase occurred in PCPB-GMS18 and PCPB-GMS24 compared to PCPB-GMS12, with increases of 1.68% and 5.04%, respectively. This increase was caused by an imbalance in the components due to excess CaO and the morphology of seashell aggregates, which differed from that of natural aggregates. According to Rashad (2023), excess CaO causes the hardening process to be too fast, the presence of heat expansion during CaO hydration increases porosity and instability of the Na_2O-CaO-SiO_2-Al_2O_3-H_2O gel in geopolymer-based mixtures with aluminosilicate precursors such as pozzolan (metakaolin or kaolin). Nguyen et al. (2013b) stated that the morphology of seashells influences the high porosity of pervious concrete paver blocks. The shells have a flat, thin shape, similar to a disk, whereas the natural aggregates are round and interlocking. Seashell aggregates were not compact and left empty spaces. The results of studies by Yang and Jang (2020); and Okoro and Oyebisi (2023) show that the addition of seashell powder increases the number of voids in the microstructure of concrete.

The 3.38% decrease in porosity in PCPB-GMS12 compared with in that PCPB-GMS0 may be due to the compaction method exceeding the predetermined time limit of 10 s per variation. The decrease in the porosity of PCPB-GMS12 remained within the tolerance limit. Liu et al. (2018) supported that the planar and volumetric porosity values have a relatively small difference, which is around ±3% from the design porosity of 21%. Although the compaction methods or tools used in this study may vary, a relatively small difference in porosity values is a normal phenomenon in pervious concrete. The study by Khankhaje et al. (2017) used cockleshells in 6.3 - 9.5 and 4.75 - 6.3 mm sizes as a substitute for coarse aggregate in pervious concrete at 28 days. The test results for both variations showed that porosity decreased at low substitution levels (25%) compared to the reference, and then increased at higher substitution levels (50% and 75%). Several factors that influence these results include the techniques used for mixing, spreading, and compaction energy in the mixture, which greatly affect the characteristics and final quality of the pervious concrete.

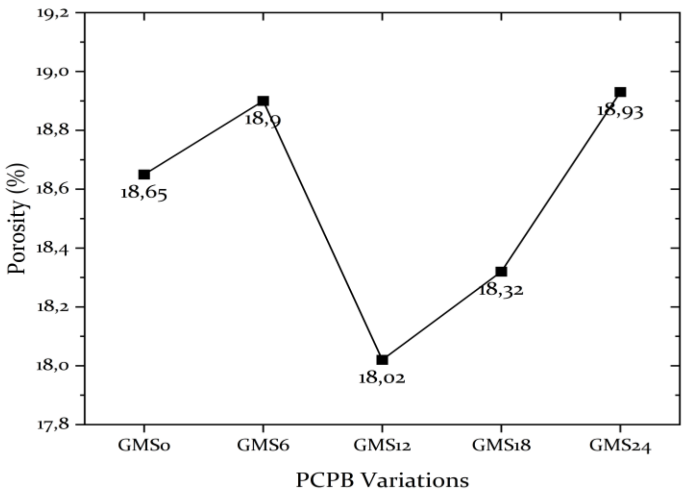

Figure 7. Porosity of pervious concrete paver blocks

This study consistently showed a porosity value of 18% across all variations. Several important factors that influence the formation of pore structure and hydraulic performance in pervious concrete paver blocks are determined by the aggregate size (large or small), aggregate composition (mixed or single), and the presence or absence of sand in the mixture. Nguyen et al. (2017) found that porous concrete with an interconnected pore system can be created with a single aggregate composition. Liu et al. (2018) expressed a different view, stating that a mixed aggregate composition would actually create a loosening effect, because large-sized aggregates are pushed by small-sized aggregates, creating inter-particle gaps that increase the internal void volume of pervious concrete, resulting in higher porosity. According to Adresi et al. (2023), the larger the aggregate size, the less the pore distribution, but the larger the pore size. Conversely, when the aggregate size was reduced, the number of pores increased, whereas the pore size decreased. This phenomenon occurs because, as the aggregate size increases, fewer locks and clamps form between the aggregate particles, resulting in a decrease in the pore distribution. Consequently, large aggregates produced concrete with higher porosity and wider pores than those produced using small aggregates. Nguyen et al. (2013a) highlighted when the seashells bioaggregate used as a substitute for porous concrete was smaller, the resulting porosity was lower. Fine aggregates or sand can be added to pervious concrete at a low ratio, but they are generally not added. Excessive addition of sand can close the interconnected pores in pervious concrete. According to ACI 522R-10, the ratio of fine aggregate or sand to coarse aggregate in pervious concrete ranges from 0-1:1. The results of research by Ibrahim et al. (2020) show that adding 10% fine aggregate to pervious concrete increases density and compactness, resulting in a 50% increase in strength.

3.2.3. Permeability

The permeability was determined using the falling-head permeability method with Darcy's law. Testing was conducted using a glass permeameter, with the top and bottom sides of the glass left open, with an area of 309.9 cm^2 and a height of 20 cm. During the permeability testing, all sides of the pervious concrete paver block sample were sealed with tape, then placed into the permeameter, and finally, precise EVA (Ethylene-Vinyl Acetate) rubber was added between the sample and the permeameter to prevent leakage when water was added. Figure 8 shows the permeameter test equipment used to measure the permeability values. The time was counted for 20 s from when the water reached its highest point in the permeameter, or 4.35 L. Results of the permeability test are shown in Figure 9. The permeability test results for the pervious concrete paver blocks in PCPB-GMS6 increased slightly by 2.04% compared to those of PCPB-GMS0. This increase was due to the conventional mixing method, which caused inhomogeneity in the material. This mechanism is thought to explain the initial increase in the permeability of PCPB-GMS6. An increase in the permeability was again observed in PCPB-GMS18 and PCPB-GMS24, by 36.98% and 129.55%, respectively, compared that with of PCPB-GMS12. This increase was caused by an imbalance in the components owing to excess CaO and the morphology of the shell, which was different from that of natural aggregates. Nguyen et al. (2013a); Khankhaje et al. (2017); Mo et al. (2018) argued that the increase in water permeability when seashells are used as a substitute for aggregates is due to the porous and angular shape of the seashell aggregates, which reduces the density of the concrete due to the disruption of the aggregate-cement structure during the compaction process. Elango and Revathi (2020) suggested that using coarse aggregates of the same size can obtain the maximum permeability. In this study, coarse aggregates with a uniform size of 5 mm were used. Castañeda et al. (2025) added that scallop shell microparticles can reduce cement paste drainage, which is the tendency of the paste to flow down and fill the voids between aggregate components before hardening.

Figure 8. Falling head permeameter test equipment

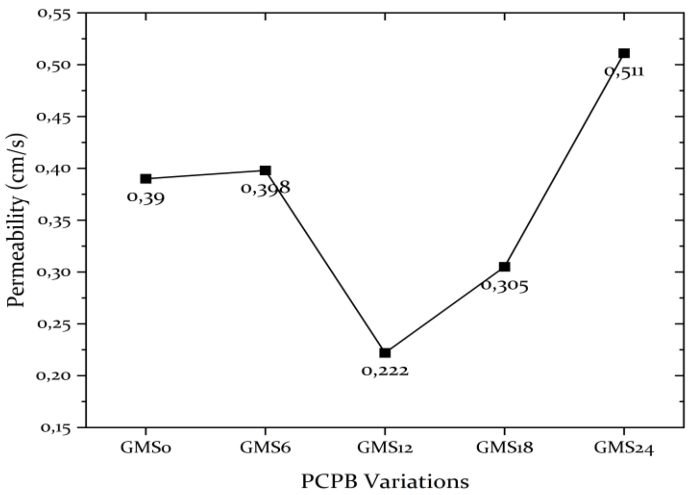

Figure 9. Permeability of pervious concrete paver blocks

A decrease in permeability of 42.90% was observed for PCPB-GMS12 compared that with of PCPB-GMS0. This decrease in the permeability is proportional to the decrease in porosity in the same variation, namely, PCPB-GMS12, indirectly connecting the two. In line with the porosity change, this decrease was due to the compaction method exceeding the specified time. Elizondo-Martinez et al. (2021) stated that the use of different compaction methods resulted in significant differences in influencing the internal structure of pervious concrete. An increased compaction force tends to increase the density and mechanical strength but decrease the porosity and permeability. This condition is caused by the increasingly dense arrangement of aggregates and the increased contact area between the cement paste and aggregates as the compaction pressure increases, resulting in narrower interparticle voids, which, in turn, reduce the water flow path within the concrete internal structure. Liao et al. (2023) state that mortar containing calcined oyster shell powder (10–60 μm) at various temperatures (800, 900, 950, 1000, and 1100°C), substituted for cement and with the addition of metakaolin, and tested at different ages, showed a decrease in permeability with increasing calcination temperature and initial mortar curing age. The decrease in the mortar permeability at 90 d was smaller than that at 28 d, indicating that in the early stages of curing, oyster shell powder played an active role in accelerating the pore-filling process through hydration and pozzolanic reactions. The reaction products, in the form of additional C-S-H and other bonded compounds, filled and closed the diffusion pathways within the mortar microstructure. As age increases, the pore structure becomes finer and denser owing to the accumulation of continuously developing hydration products, so that the rate of decrease in the permeability is not as great as at early ages.

The permeability appears to show a similar trend with changes in the porosity of the pervious concrete paver blocks, as shown in Figures 7 and 9. The porosity values for all pervious concrete paver block variations in this study were consistently 18%; however, the permeability values were inconsistent, ranging from 0.22 to 0.51 cm/s. This condition occurred because of the differences in the degree of pore connectivity. In simple terms, porosity describes the number of pores in relation to the total volume, whereas the permeability describes the interconnection of pores within that volume. Adresi et al. (2023), state that porosity and permeability are interdependent, meaning that different mixtures with the same porosity can exhibit different permeability values. According to Ćosić et al. (2015); and Akkaya and Çağatay (2021), the permeability is influenced by the number of pores, pore distribution, and inter-pore connectivity. Adresi et al. (2023), noted that pervious concrete has three types of pores, namely connected, semi-connected, and closed pores.

4. Conclusions

The production of green mussel shell waste in Semarang during the 2025 planting season reaches 86.7 kg/day. The amount of green mussel shell waste production is influenced by catch and market demand. The performance of green mussel shell bioaggregate calcined at 900°C for 2 hours without metakaolin intervention is limited to pore-filling, whereas the cement hydration reaction, forming C-S-H gel, increases structural density and enhances strength, albeit only to a limited extent. The optimal bioaggregate substitution range is 6-18%, considering ecological aspects and performance within the acceptable limits. The results of this study, compared with the control (PCPB-GMS0), show that low substitution (PCPB-GMS6) slightly decreased mechanical performance by 3.40%, while slightly increasing physical performance, as measured by porosity by 1.35% and permeability by 2.04%. Meanwhile, high substitution (PCPB-GMS24) significantly decreased mechanical performance by 15.65% and significantly increased physical performance, including porosity by 1.49% and permeability by 31.07%. Based on ACI 522R-10, 2010 and SNI 03-0691-1996 standards for permeable concrete, the results indicate that all tested parameters, such as compressive strength (2.8-28 MPa), porosity (15-35%), and permeability (0.14-1.22 cm/s), meet the required range for parking area paving materials. Factors influencing the performance of pervious concrete paver blocks include mixing and steering methods, compaction parameters (energy and duration), aggregate selection (size and composition), aggregate cleanliness, GMS bioaggregate ratio, fine-coarse aggregate ratio, water-cement ratio, pore number, pore distribution, and pore connectivity.

CRediT Author Statement

Muhammad Sholeh Arifin: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing, and Final approval of the version submitted. **Ika Bagus Priyambada:** Supervision and Review. **Budi Prasetyo Samadikun:** Supervision and Review. **Sheikh Kamran Abid**: Supervision and Review.

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