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Study on the possibility of using perlite in producing bio-coating mortar to protect concrete used for drainage structures in Vietnam

Nguyen Cong Thang[1*], Vu Van Linh[2], Nguyen Thi Hai[3], Nguyen Van Tuan[1], Keun-Hyeok Yang[4]

[1]Faculty of Building Materials, National University of Civil Engineering, 55 Giai Phong, Hai Ba Trung, Hanoi, Vietnam.

[2] Vietnam Institute for Building Materials, 235 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam.

[3] Laboratory of Applied Microbial Ecology, VNU Institute of Microbiology and Biotechnology, 144 Xuan Thuy, Hanoi, Vietnam.

[4] Department of Architectural Engineering, Kyonggi University, Suwon 16227, Kyonggi-do, South Korea.

KEYWORDS

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ABSTRACT

This study investigates the application of porous perlite in bio-coating mortar production, focusing on its bacterial immobilization capability and its effect on mortar properties. Mortar samples with different perlite contents of 0%, 10%, 15%, 20%, 25%, and 30% (by vol. of sand) were evaluated for unit weight, flexural strength, and compressive strength under two conditions: (1) standard environments and (2) wastewater exposure. Results indicate that the addition of perlite reduces flexural and compressive strength due to its lightweight and porous structure. However, no significant differences were observed between the two tested environments. This study highlights the potential of perlite in developing lightweight, durable, and efficient bio-coating mortar, making it a promising material for construction in specialized environmental conditions.

1. Introduction

Concrete corrosion is one of the major issues affecting the durability and lifespan of construction structures, especially in domestic wastewater environments. Wastewater contains various organic and inorganic compounds as well as microorganisms, among which the presence of hydrogen sulfide (H_2S) is the primary cause of corrosion. H_2S is formed under anaerobic conditions due to the decomposition of sulfur compounds in wastewater. In sewer systems, H_2S escapes from the wastewater, adheres to the concrete surface, and is oxidized by sulfur-oxidizing bacteria such as *Thiobacillus*, converting it into sulfuric acid (H_2SO_4) [1-3]. The chemical reaction between sulfuric acid and calcium hydroxide ($Ca(OH)_2$) in concrete produces expansive products such as gypsum ($CaSO_4 \cdot 2H_2O$) and ettringite, leading to cracking and structural degradation of the concrete [4, 5]. The impact of corrosion not only reduces the load-bearing capacity of concrete but also increases the cost of repairing and maintaining drainage systems. In severe cases, sewer systems can fail completely, leading to environmental pollution and disruptions in public services. To mitigate the effects of corrosion, one effective solution is to apply a protective mortar coating on the concrete surface. However, traditional coatings often have a short lifespan or insufficient resistance to the acidic wastewater environment. Therefore, recent studies have focused on incorporating bacteria with porous materials such as vermiculite and perlite to develop bio-mortar coatings for protecting concrete in aggressive environments.

Bacteria immobilized in porous materials such as vermiculite and perlite are then incorporated into the protective mortar coating for concrete. This not only creates a durable protective layer but also provides the ability to self-heal cracks [2, 6]. Perlite is a commonly used porous material in mortar coatings, providing an ideal environment for bacterial growth. With its exceptional water retention capacity, perlite has a lightweight, porous structure that creates microcavities for bacteria to thrive while enhancing water vapor release. This improves the long-term durability of the coating in harsh environmental conditions. When combined with bacteria in mortar coatings, perlite not only enhances mechanical properties but also optimizes conditions for bacterial biological processes, thereby improving concrete protection efficiency. Bacteria immobilized in porous materials, such as *Bacillus subtilis*, are often used due to their ability to induce biomineralization by producing calcium carbonate ($CaCO_3$). [7, 8]. This process works based on the mechanism where bacteria use urea or organic compounds present in the wastewater environment as a source of nutrition. During metabolism, they produce the enzyme urease, which breaks down urea into ammonia (NH_3) and carbon dioxide (CO_2). The CO_2 then combines with calcium ions (Ca^{2+}) in the environment to form $CaCO_3$. This $CaCO_3$ layer fills the pores and cracks on the concrete surface, reducing the permeability of H_2S gas and water, thereby preventing corrosion [9, 10]. At the same time, $CaCO_3$ helps enhance the durability and resistance to chemical agents in the wastewater environment.

Concrete corrosion caused by wastewater is a major challenge in construction, especially for structures like pipes. Therefore, using bio-coating mortar improves the lifespan and performance of the structure, opening up new directions in the development of environmentally friendly construction materials. While research on bio-coating mortar

*Corresponding author: thangnc@huce.edu.vn

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has been conducted using vermiculite porous material, studies on other materials available and potential in Vietnam, such as perlite, are limited. Therefore, this study will evaluate the ability of perlite to immobilize bacteria and its potential application in the production of protective bio-coating mortar.

2. Materials and Methods

2.1. Materials

Materials used in this study included Portland cement, mechanical properties of cement meet the requirements of Vietnamese standard TCVN 2682:2020 [11].

The dispersible polymer powder from Wacker, commercially known as Vinnapas-5010N, is a product of the copolymerization of vinyl acetate and ethylene. The use of polymer improves adhesion between the coating mortar and the substrate while also improving flexural strength, deformation resistance, and abrasion resistance of the mortar [12]. The fine aggregate used has a mean size of 0.315 mm. The porous material used in this study is perlite, which is an inert material with its pH of 7–7.5 whose stability is not affected by acids or microorganisms. Perlite has a porous structure with high porosity and properties suitable for microbial cultivation. The image of perlite particles and their structure is shown in Figure 1.

The physical and mechanical properties of cement, sand, polymer, and perlite are presented in Table 1. The chemical composition is shown in Table 2.

Table 1. Physical properties of cement and aggregates.

Properties	Unit	Cement	Perlite	Sand
Density	g/cm^3	3.1		2.638
Bulk density	g/cm^3		0.203	2.600
The specific surface area	m^2/g	0.387	2.816	0.021
The volume stability	mm	0.2		
pH	-		7.45	
Water absorption	%		264	
Compressive strength at 3 days	MPa	33.5		
Compressive strength at 28 days	MPa	54.6		
Mean particle size	µm	17.3		
Particle size range	mm		0.14–2.5	0.14–0.315

Table 2. Chemical composition of cement and perlite.

Material	Chemical composition (by wt. %)								
	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	CaO	Fe_2O_3	K_2O	TiO_2
Cement	0.099	1.386	4.083	16.961	3.656	68.495	3.778	0.763	0.407
Polymer	0.450	0.338	10.917	11.307	0.372	74.618	0.735	0.141	0.855
Perlite	3.433	0.060	13.770	74.725	-	0.850	0.794	6.088	0.097

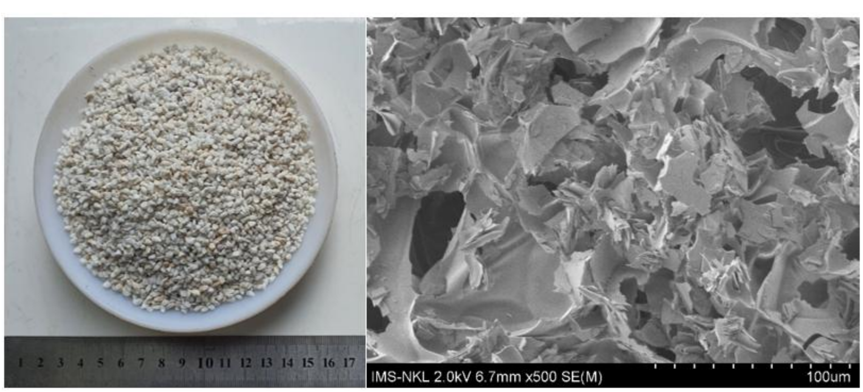

Figure 1. SEM images of perlite particles.

2.2. Biomimetic mortar mix composition

Based on the research results on the influence of material composition on the compressive strength of bio-coating mortar, the study has identified the appropriate material content when using porous materials. To achieve a target compressive strength above 20 MPa, flexural strength above 5 MPa, the mix design selected a sand-to-binder (S/B) ratio of 1.8 and a water-to-binder (W/B) ratio of 0.4 by wt., ensuring suitable flexural and compressive strength [13].

Using these ratios as a basic, the study evaluated the quality of mortar incorporating perlite as a porous material for bio-coating applications, evaluating its effect on mortar properties. Perlite was replaced with different amounts of 0 %, 10 %, 15 %, 20 %, 25 %, and 30 % by vol. of sand. The selected mix maintained an S/B ratio of 1.8 and a W/B ratio of 0.4.

In this research, a polymer material was selected to improve adhesion, flexural strength, deformation resistance, and abrasion resistance of the mortar [12], with a content of 5 % by wt. of binder (B). The material composition ratios of the selected mortar mix are shown in Table 3.

2.3. Testing methods

2.3.1. Methods for immobilizing bacterial strains into porous materials

The Rhodobacter bacterial strain was isolated from wastewater drains in Vietnam. The culture medium for this bacterial strain is detailed in Table 4.

Sterilize the environment at 121°C for 20 minutes, remove it at 80°C, bubble N_2 gas for 5 minutes, allow it to cool, then add the heat-sensitive substances that were sterilized separately beforehand using a filtration membrane (Table 5).

Adjust the pH of the environment to 7, then transfer the medium to serum bottles or test tubes. Bubble N_2 gas for 30 seconds to expel oxygen, seal the bottles and test tubes with rubber stoppers with aluminum clamps or screw caps with ventilation holes. Use immediately or store in the dark.

Table 3. Mix composition of bio-coating mortar containing perlite.

No.	S/B ratio, wt.%	W/B ratio, wt.%	Polymer/B, wt.%	Perlite, % by vol. of sand
1	1.8	0.4	5	0
2	1.8	0.4	5	10
3	1.8	0.4	5	15
4	1.8	0.4	5	20
5	1.8	0.4	5	25
7	1.8	0.4	5	30

Table 4. Freshwater mineral medium for PNSB [14].

No.	Composition	Units	Value
1	Distilled water	L	1
2	NaCl	g	0.33
3	$CaCl_2$	g	0.037
4	$MgSO_4.7H_2O$	g	0.33
5	Yeast extract	g	1.0
6	Succinate	g	1.0

Table 5. Heat-sensitive substances added later to the environment.

Chemical	Unit	Value
KH_2PO_4/NH_4Cl (KH_2PO_4: 0.33 g/NH_4Cl: 0.5 g)	ml/l	50
Vitamin mixture	ml/l	1.0
Micronutrient mixture	ml/l	0.1
L-Cysteine 1M	ml/l	1.0
Na-acetate 1M	ml/l	1.0
$NaHCO_3$ 1M	ml/l	6.0
$FeSO_4.7H_2O$ 0.02%	ml/l	0.5
Vitamin B_{12}	ml/l	2.0

Table 6. Composition of the vitamin mixture [14].

Composition	Unit	Value
Nicotinic acid	mg/100ml	1.0
p – aminobanzoic acid	mg/100ml	1.0
Thiamine	mg/100ml	1.0
Biotin	mg/100ml	0.001
H_2O	mg/100ml	100
pH = 6.8		

Table 7. Composition of the micronutrient mixture [14].

Composition	**Unit**	**Value**
$ZnSO_4.7H_2O$	mg	10
$MnCl_2.4\ H_2O$	mg	3
H_3BO_3	mg	30
$CoCl_2.6\ H_2O$	mg	20
$CuCl_2.2\ H_2O$	mg	1
$NiCl_2.6\ H_2O$	mg	2
Na_2MoO_4	mg	3
H_2O	ml	1000
pH = 3 – 4		

The wastewater sample is inoculated into prepared medium bottles at a 10 % vol. ratio and cultured statically at 28–30 ˚C under light conditions. After 3–4 days, when the bacteria have grown well and clearly formed red pigments, the sample is transferred to a new medium bottle at the same ratio (10 % volume). The bacterial growth after each transfer is assessed based on the color change of the medium to purple or brown, and the bacterial density is roughly estimated by observing the culture under a microscope.

The sample enriched in the third transfer is used to isolate purple non-sulfur phototrophic bacteria (PNSB). The isolation process is carried out using the dilution method on a solid agar series (1%) with a medium similar to the enrichment phase. After adding the culture medium from the third enrichment sample (10 % volume), the solid agar tubes are bubbled with N_2 (or not bubbled for microaerophilic conditions) and incubated in an inverted position at 30 ˚C under continuous light. After 4–5 days, individual colonies formed in the solid agar tubes are picked using a Pasteur pipette and transferred to suitable anaerobic or microaerophilic media.

2.3.2. Method for determining the mechanical properties of mortar

The workability of the mortar mixture was determined by TCVN 3121-3:2022 [15].

The bulk density of the mortar mixture was determined according to TCVN 3121-6:2022 [16].

The flexural and compressive strength of the mortar sample were determined according to TCVN 3121-11:2022 [17]. The mortar mixture was poured into a mold with the size of 40 × 40 × 160 mm.

The compressive strength of mortar mixes using natural vermiculite was determined at 7 days and 28 days. After the mortar samples were prepared, they were cured under standard conditions (t = 27 ± 2 °C, RH ≥ 98 %) for 24 hours. Afterward, the samples were removed from the molds and cured in different environments, specifically:

(MT1): The sample was cured under standard conditions.

(MT2): The sample was cured in a wastewater environment, with the sample stored above the wastewater level (Figure 2).

Figure 2. Curing mortar samples in wastewater environment.

3. Results and discussions

3.1. Evaluation of bacterial immobilization capability on perlite material

To enhance the immobilization of microorganisms within the porous structure of the material, a suspension mixture of PNSH1 strain and perlite was continuously stirred for 72 hours at 150 rpm (Figure 3). After bacterial attachment to the porous material surface, the material was washed 2–3 times to remove free-floating cells and then suspended in a 0.9 % NaCl solution under anaerobic conditions. The solution containing the porous material was then ultrasonically treated to release immobilized bacterial cells into the liquid phase for further analysis.

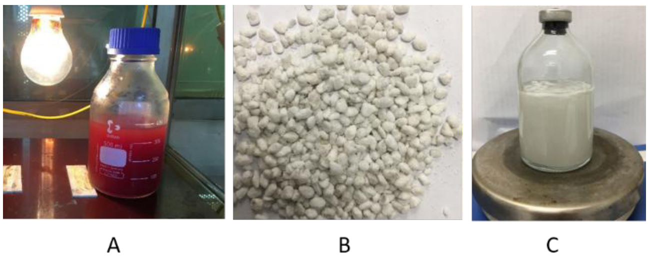

Figure 3. Immobilization of PNSH1 strain on perlite material, A– PNSH1 strain culture suspension, B – Perlite material, C – Microorganism immobilization process on perlite.

The viability of bacteria after immobilization on vermiculite was evaluated by counting the number of live cells in the suspension after ultrasonic treatment (Table 8).

Table 8. PNSH1 strain cell count during immobilization on perlite.

Sample	Bacterial cell count
Initial PNSH1 culture suspension	7.5×10^{9} MPN/mL
Material after bacterial immobilization on perlite	4.6×10^{7} MPN/g

The results (Table 8) indicate that the number of viable bacterial cells after immobilization on perlite reached 4.6×10^{7} MPN/g. Compared to vermiculite, the bacterial cell count on perlite was approximately 100 times lower (with vermiculite reaching 4.6×10^{9} MPN/g).

The evaluation of the immobilization and survival of non-sulfur photosynthetic bacteria on perlite in Vietnam demonstrates compatibility between the bacteria and this material. Although the bacterial survival rate on perlite was lower than on vermiculite, it still reached 4.6×10^{7} MPN/g, indicating its potential for application.

Future research will focus on evaluating the properties of mortar in both standard conditions and wastewater environments. Detailed results will be presented in the following sections.

3.2. Effect of perlite content on the unit weight of mortar

Experimental results on the unit weight of mortar samples and the impact of perlite content on mortar density are shown in Figure 4. The experimental results indicated a gradual decrease in the unit weight of the mortar as the sand replacement ratio with perlite increased. At 0 % perlite, the unit weight was 2.058 g/cm³. When 10 % of the sand was replaced with perlite, this value dropped to 2.034 g/cm³, reflecting a 1.17 % reduction compared to the original sample. With a 20 % replacement, the unit weight further declined to 1.993 g/cm³, marking a 3.16 % decrease. At a 30 % replacement rate, the unit weight reached 1.932 g/cm³, representing a 6.12 % reduction compared to the control sample without perlite.

This decrease is primarily due to the significantly lower unit weight of perlite (0.203 g/cm³) compared to sand (2.6 g/cm³). As the perlite content increases, the lightweight aggregate gradually replaces the sand, reducing the unit weight of the mortar.

Although this reduction in bulk density may be beneficial for producing lightweight mortar, which helps reduce structural load and improve thermal insulation, additional mechanical strength evaluations are necessary to ensure practical application.

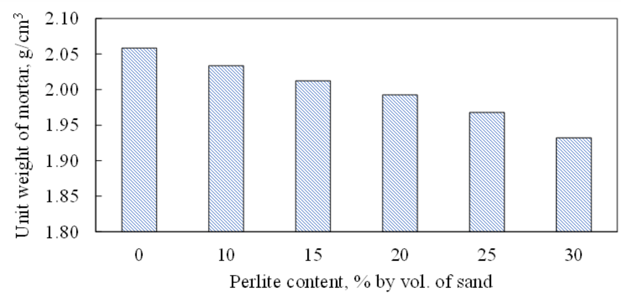

Figure 4. Effect of perlite content on the unit weight of mortar mixture.

3.3. Effect of perlite content on the flexural strength of mortar

The study on the effect of perlite content and curing conditions, i.e. MT1, MT2, on the flexural strength of bacteria-infused mortar is presented in Figure 5. The difference in curing environments may influence microbial activity and the formation of mortar structure, subsequently affecting the mechanical properties of the material.

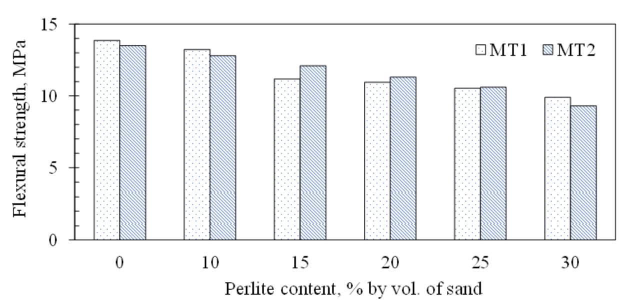

Figure 5. Effect of perlite content on flexural strength of mortar cured in different environments.

The experimental results demonstrated a gradual decline in the flexural strength of the mortar as the sand replacement ratio with perlite increased in both testing environments (Figure 5). Regardless of the curing environment (MT1 or MT2), the flexural strength of mortar decreased with the addition of perlite. In MT1, the control sample (0 % perlite, 13.9 MPa) experienced a 5.0 % to 28.8 % reduction with 10-30 % perlite substitution (by vol.). In MT2, the control sample (13.5 MPa) showed a comparable reduction range of 5.2 % to 31.1 %.

These findings suggest that the reduction in flexural strength resulted from the porous structure of perlite, which weakened the bond between aggregate particles. However, the difference in strength between the two curing environments was not significant. Despite the reduction in strength, all samples maintained values above 5 MPa, meeting desired technical requirements. This trade-off may be acceptable if the use of perlite provides additional benefits such as reduced weight, enhanced adhesion, or improved insulation properties.

3.4. Effect of perlite content on the compressive strength of mortar

The 28-day compressive strength of the mortar is presented in Figure 6 considering different perlite contents and environmental curing conditions.

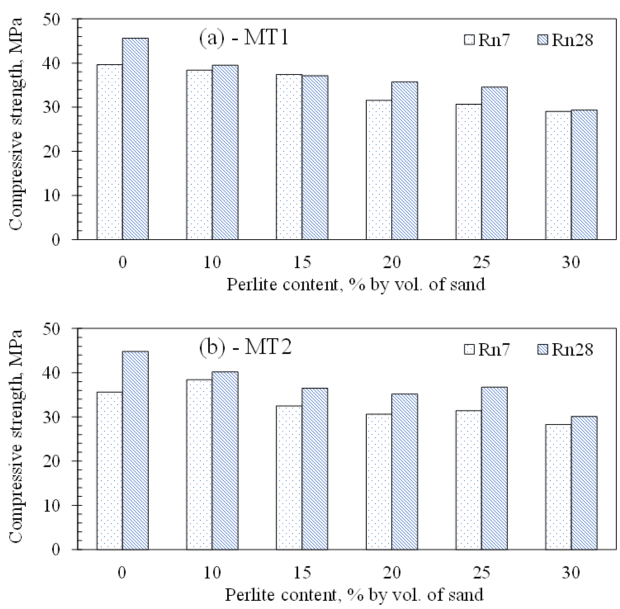

Figure 6. Effect of perlite on 28-day compressive strength of mortar cured in the different environments (a) MT1; (b) MT2.

The experimental results for the 28-day compressive strength of mortar with different perlite contents in two curing environments are presented in Figure 6.

The data consistently showed an inverse relationship between perlite content and compressive strength in both MT1 and MT2 environments. At 7 days, the control samples (0 % perlite) yielded the highest strengths, with 39.6 MPa (MT1) and 35.6 MPa (MT2). Introducing perlite (10-30 % sand replacement by vol.) significantly reduced compressive strength, up to 26.8 % (MT1) and 20.5 % (MT2) drop at 30 % perlite. This trend continued at 28 days, where the control samples reached 45.6 MPa (MT1) and 44.8 MPa (MT2). Replacing sand with perlite (10-30 % by vol.) at 28 days led to strength reductions ranging from 13.4 % to 35.8 % in MT1, and 10.1 % to 32.8 % in MT2.

The decrease in compressive strength is primarily attributed to the low unit weight and porous structure of perlite, which reduces the overall compactness of the mortar. Comparing the two curing environments, the compressive strength in MT2 was generally lower than in MT1 at 7 days. However, by 28 days, this difference was no longer significant, possibly because environmental factors had not yet strongly influenced the strength development in the early stages.

In terms of strength development from 7 to 28 days, the sample without perlite (0 %) increased from 39.6 MPa to 45.6 MPa in MT1, reflecting a 15.2 % increase. In contrast, with 30 % perlite replacement, the increase was only 1.0 % – 6.3 %, indicating a limited capacity for strength development over time. This may be due to perlite's non-reactive nature in the cement hydration process, as it primarily functions as a lightweight aggregate and a bacterial immobilization medium.

Despite the reduction in strength when using perlite, all samples maintained compressive strengths above 20 MPa, ensuring their practical applicability. However, when the perlite content exceeds 20%, the decline in compressive strength becomes more significant, which must be carefully considered in mix design.

4. Conclusions

Based on the research results, some following conclusions can be drawn:

- The evaluation of cell fixation ability on perlite hollow material shows that the number of cells fixed on perlite material, with the ability to survive, is 4.6×10^7 MPN/g. This confirms that perlite material from Vietnam is compatible with purple non-sulfur bacteria.
- As the perlite content increases, the unit weight of the mortar decreases. Replacing sand with up to 30 % perlite results in a gradual decrease in unit weight from 2.058 g/cm^3 (0 % perlite) to 1.932 g/cm^3 (30 % perlite).
- The flexural strength decreases gradually with increasing perlite content but still meets technical requirements. At 28 days, there is no significant difference in flexural strength between the samples cured in MT1 and MT2. The flexural strength of the mortar decreases from 13.9 MPa (MT1, 0 % perlite) to 9.9 MPa (MT1, 30 % perlite), with all samples maintaining a flexural strength above 5 MPa.
- With increased perlite content, the compressive strength of the samples decreases, but the mortar still meets the minimum requirement of 20 MPa. The compressive strength decreases from 45.6 MPa (MT1, 0 % perlite) to 29.3 MPa (MT1, 30 % perlite) at 28 days. The curing environment (MT1 and MT2) does not significantly affect the flexural and compressive strength of the mortar at 28 days.

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