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Research Article

Balancing Mechanical Strength and Hydraulic Functionality of Fine Aggregate Free Pervious Concrete Using Expanded Vermiculite

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ABSTRACT

Pervious concrete is widely used for sustainable pavement applications due to its ability to reduce surface runoff and enhance groundwater recharge; however, its application is often limited by low mechanical strength caused by the absence of fine aggregates. This study focuses on identifying an optimal balance between mechanical strength and hydraulic functionality of fine aggregate free pervious concrete through the incorporation of expanded vermiculite (EV) as a lightweight aggregate substitute. EV was introduced at 0%, 5%, 10%, and 15% as a partial replacement of the fine aggregate fraction typically present in conventional concrete. Specimens were designed using a modified volumetric approach based on ACI 522R-10. Compressive strength was evaluated at 7 and 28 days, while porosity and permeability were assessed at 28 days. The results show that increasing EV content significantly enhances compressive strength, reaching 17.08 MPa at 15% EV due to internal curing and pore densification. However, excessive EV incorporation leads to a sharp reduction in porosity and permeability, indicating a loss of hydraulic functionality. A balanced performance was achieved at 5% EV, where meaningful strength improvement was obtained while maintaining effective infiltration capacity. These findings highlight the importance of dosage control when designing fine aggregate free pervious concrete systems for infiltration dependent applications.

1. Introduction

Urban development has intensified various environmental challenges, including increased surface runoff, localized flooding, and reduced groundwater infiltration capacity. In response, pervious concrete has emerged as a sustainable alternative to traditional impermeable paving materials, offering the ability to facilitate water infiltration through its interconnected pores [1 - 3]. By reducing runoff and recharging groundwater, pervious concrete supports the development of eco–friendly urban infrastructure.

However, a major limitation of pervious concrete lies in its comparatively low mechanical strength and durability [4 – 7], particularly when fine aggregates are omitted to preserve porosity. To address this challenge, researchers have explored the incorporation of supplementary materials aimed at improving strength while maintaining permeability. One such material is vermiculite, a naturally occurring phyllosilicate mineral known for its low density, high water absorption capacity, thermal insulation, and fire resistance [8 – 10]. When expanded at high temperatures (650–950 °C), vermiculite increases its volume up to 30 times, enhancing its performance in cementitious composites [11, 12 – 15]. In lightweight concrete applications, vermiculite has been shown to reduce thermal conductivity and improve durability at elevated temperatures [16], and even has environmental benefits such as reducing storm runoff pollution [17].

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Several studies have established that mineral admixtures can significantly enhance the mechanical properties of pervious concrete. Silica fume and fly ash, for example, improve both compressive strength and pore structure while maintaining permeability [17, 18]. Accelerated carbonation methods have also been shown to densify the microstructure of vibro-compacted porous concrete, offering strength gains without compromising water flow [19-20]. Furthermore, Lyu et al. [21] demonstrated strong correlations between compressive strength, porosity, and permeability depending on aggregate size and mix design, highlighting the importance of balancing mechanical and hydraulic properties. Cao et al. [21] also reported promising results for vegetative lightweight pervious concrete with mineral admixtures, achieving compressive strengths as high as 17.7 MPa.

In Indonesia, urbanization continues to reduce green space due to rapid infrastructure development and low public awareness of sustainable land use [21, 22]. Impermeable surfaces like asphalt and dense concrete limit rainwater infiltration, aggravating environmental issues. Pervious concrete, which typically consists of cement, coarse aggregate, water, and little or no fine aggregate [20, 23], presents a viable alternative. Yet, due to its intentionally porous structure, pervious concrete tends to exhibit reduced compressive strength and durability [22]. Incorporating vermiculite offers a potential solution to improve both strength and sustainability. As noted by Prakash et al. [22], vermiculite can serve as a partial replacement for fine aggregates in concrete, enhancing mechanical properties. Similarly, Azad et al. [19 – 23] found that vermiculite, when used with other mineral additives like dolomite or quartz, not only improves strength but also contributes to environmental benefits such as pollutant reduction.

In pervious concrete research, the quality and consistency of aggregate properties play a crucial role in determining both mechanical performance and hydraulic behavior. Therefore, the characterization of aggregates should follow standardized testing procedures to ensure reliable and comparable results. In this study, the grading and quality requirements of aggregates refer to ASTM C33/C33M [23], while the amount of materials finer than the 75 µm sieve is evaluated in accordance with ASTM C117 [24]. In addition, the specific gravity and water absorption of coarse aggregates are determined based on ASTM C127 [25], and the bulk density (unit weight) and void content of aggregates are measured following ASTM C29/C29M [26]. The use of these standardized methods ensures that the material properties used in pervious concrete mixtures are properly controlled and suitable for performance-based evaluation.

Although numerous studies have investigated the use of vermiculite in lightweight and porous concrete, most of them focus on conventional concrete systems containing fine aggregates or emphasize general performance enhancement. Limited attention has been given to fine-aggregate-free pervious concrete systems, where hydraulic functionality is as critical as mechanical strength. In such systems, excessive densification may improve compressive strength but simultaneously disrupt pore connectivity, leading to a loss of permeability. Therefore, the present study aims to investigate the influence of expanded vermiculite (EV) as a lightweight aggregate substitute on the balance between mechanical strength and hydraulic functionality of fine aggregate free pervious concrete. By evaluating compressive strength, porosity, and permeability at varying EV dosages, this study seeks to identify an optimal dosage threshold that enhances structural performance while preserving effective water infiltration. This approach provides practical insights for the design of pervious concrete intended for infiltration dependent urban infrastructure.

2. General Methods

This research investigates the performance of fine aggregate free pervious concrete incorporating expanded vermiculite (EV) as a lightweight aggregate substitute at dosage levels of 0%, 5%, 10%, and 15%. The study focuses on evaluating the influence of EV incorporation on key performance parameters, including compressive strength, porosity, and permeability, in order to identify an optimal balance between mechanical strength and hydraulic functionality. The scope of this study includes the design, production, and laboratory testing of cylindrical pervious concrete specimens with dimensions of 150 × 300 mm. The materials used in this research consist of Portland cement, coarse aggregate, expanded vermiculite, water, and a polycarboxylate based plasticizer. No fine aggregate was used in any mixture to preserve interconnected pore structures essential for pervious concrete behavior. All concrete mixtures were proportioned using a modified volumetric approach in accordance with ACI 522R-10, which defines pervious concrete as a near-zero slump material composed of cement, coarse aggregate, little or no fine aggregate, water, and chemical admixtures [19]. The experimental program was conducted at the Civil Engineering Laboratory, Burangkeng, West Java, Indonesia.

2.1. Research Scope and Objectives

The scope of this study encompasses a systematic evaluation of three principal performance parameters, namely compressive strength, porosity, and permeability, which collectively govern the mechanical reliability and hydraulic functionality of fine aggregate free pervious concrete in practical applications. In this context, the present research seeks to address the following research questions:

1. How does the incorporation of expanded vermiculite (EV) as a lightweight aggregate substitute influence the compressive strength of fine aggregate free pervious concrete?
2. What is the effect of increasing EV content on the porosity characteristics of pervious concrete?
3. How does EV incorporation affect the permeability and pore connectivity of pervious concrete systems?
4. Is there a discernible trade off relationship between mechanical strength enhancement and hydraulic functionality with increasing EV dosage?

Accordingly, the objectives of this study are as follows:

1. To evaluate the effect of varying expanded vermiculite content on the compressive strength development of fine aggregate free pervious concrete.
2. To analyze changes in porosity resulting from the incorporation of expanded vermiculite.
3. To assess the influence of expanded vermiculite on the permeability behavior of pervious concrete.
4. To identify an optimal expanded vermiculite dosage that achieves a balanced performance between mechanical strength and hydraulic functionality.

Through this investigation, the study aims to contribute to the development of sustainable pervious concrete technologies by providing experimental evidence on dosage controlled expanded vermiculite incorporation for infiltration-dependent concrete applications.

2.2. Testing Stages in the Laboratory

The The experimental program was conducted in a controlled laboratory environment to ensure accuracy, repeatability, and reliability of the test results. All testing procedures were performed in accordance with relevant ASTM standards and ACI guidelines, particularly ACI 522R-10, to maintain methodological consistency throughout the study. The experimental work was divided into two main stages: material characterization and performance evaluation of pervious concrete mixtures. In the first stage, laboratory tests were carried out to determine the physical properties of the constituent materials, including Portland cement, coarse aggregate, and expanded vermiculite (EV).

The characterization of coarse aggregate involved tests for specific gravity and water absorption, sieve analysis, and bulk density, following the applicable ASTM standards. Expanded vermiculite (EV) was characterized in terms of its specific gravity and water absorption capacity, given its significant influence on water demand and internal curing behavior. The second stage involved the mixing, casting, curing, and testing of fine aggregate free pervious concrete specimens with varying expanded vermiculite contents. All mixtures were proportioned using a modified volumetric approach in accordance with ACI 522R-10. After casting, the specimens were cured under moist conditions until the designated testing ages.

Subsequently, the specimens were subjected to compressive strength testing, porosity determination, and permeability measurement to evaluate the influence of expanded vermiculite incorporation on both the mechanical performance and hydraulic functionality of the pervious concrete system. The results of the coarse aggregate characterization are presented in Table 1.

Table 1. Coarse Aggregate (CA) Test Results

Testing	Standard	Standart Value	Test Value
Sieve analysis	ASTM C-33	6 – 8 FM	6,00
Material finer than a 75-µm	ASTM C-117	< 1%	0,5
Specific Gravity	ASTM C-127	< 2,8 g/cm³	2,435
Water Absorption	ASTM C-127	2% - 5 %	3,811
Bulk Density	ASTM C-29	1200-1600 kg/m³	1,537

The coarse aggregate exhibited a fineness modulus of 6.00, which falls within the recommended range for pervious concrete applications in accordance with ASTM C33 and ACI 522R-10 [19-26]. The percentage of material finer than the 75-µm sieve was 0.5%, indicating minimal presence of dust or clay particles that could adversely affect paste aggregate bonding. The measured specific gravity (2.435 g/cm³) and bulk density (1537 kg/m³) are characteristic of normal weight coarse aggregates and confirm the suitability of the material for structural pervious concrete applications. The water absorption value of 3.811% indicates moderate aggregate porosity, which may influence the effective water content of the mixture and was therefore considered during the mix design process to ensure consistent hydration behavior. In addition to coarse aggregate testing, expanded vermiculite (EV) was characterized to assess its physical properties and suitability as a lightweight aggregate substitute in fine aggregate free pervious concrete mixtures. The characterization focused on specific gravity and water absorption capacity, as these parameters govern the internal curing potential and water demand of lightweight materials. The results of expanded vermiculite testing are presented in Table 2.

The The very low specific gravity of 0.50 g/cm³ confirms the lightweight and highly porous nature of expanded vermiculite (EV), distinguishing it clearly from normal weight aggregates. Rather than primarily reducing concrete density, this characteristic allows EV to function as a lightweight aggregate substitute capable of occupying inter aggregate voids in fine aggregate free pervious concrete systems. The high water absorption capacity of approximately 250% indicates a strong ability of EV to retain and gradually release moisture. In this study, EV was therefore used in a pre wetted surface dry (PWSD) condition to control the effective water content and avoid unintended reductions in workability or inconsistencies in hydration. The physical appearance of the expanded vermiculite used in this study can be seen in Figure 1.

Table 2. Vermiculite Test Results

Testing	Test Value
Specific gravity	0.50 g/cm³
Water Absorption	250%

Figure 1. Expanded vermiculite (EV)

This behavior supports the role of EV as an internal curing agent, promoting continued cement hydration and microstructural development. These physical characteristics are consistent with findings reported in previous studies [2, 15, 16]. However, in the context of fine-aggregate-free pervious concrete, the results suggest that while EV can enhance hydration and compressive strength, excessive incorporation may lead to pore blockage, thereby reducing porosity and permeability. This observation underscores the importance of dosage control when utilizing expanded vermiculite in pervious concrete systems where hydraulic functionality is a primary performance requirement.

2.3. Concrete Mix Design

The concrete mixtures in this study were proportioned following the recommendations of ACI 522R-10, which emphasize a gap graded aggregate structure to achieve interconnected pore networks in pervious concrete. Unlike conventional concrete, which typically consists of both coarse and fine aggregates, all mixtures in this study were designed as fine aggregate free systems to preserve hydraulic functionality. A modified volumetric approach was adopted to maintain an approximate total mixture volume of 1 m³ for all mix variations. Instead of replacing fine aggregate by weight, expanded vermiculite (EV) was introduced as a lightweight aggregate substitute representing the fine aggregate fraction typically present in conventional concrete.

Four mixture variations were prepared with EV contents of 0% (control), 5%, 10%, and 15%, while the coarse aggregate content was kept constant at 1053 kg/m³ across all mixtures. Expanded vermiculite was incorporated to progressively modify the pore structure of the concrete matrix, allowing an evaluation of its influence on both mechanical and hydraulic performance. To ensure consistency among mixtures, a constant water-to-cement ratio of 0.32 was maintained, and a polycarboxylate-based plasticizer was added at 1% by weight of cement to improve paste cohesion and reduce segregation rather than to enhance workability. No fine aggregate was used in any mixture, in accordance with pervious concrete design principles. The results of Concrete Mix Proportions volume of 1 m³ in Table 3.

Table 3. Concrete Mix Proportions 1 m³

Material	Percentage of vermiculite				Unit
	0%	5%	10%	15%	
Split Stone 10/20mm	1053	1053	1053	1053	kg/m³
Cement	330	330	330	330	kg/m³
Water	105.6	105.6	105.6	105.6	kg/m³
Plasticizer	3.3	3.3	3.3	3.3	kg/m³
Vermiculite	-	19.7	39.5	59.2	kg/m³

The control mixture containing 0% expanded vermiculite (EV) was used as the reference for performance comparison. In the modified mixtures, EV was incorporated as a lightweight aggregate substitute in increasing dosages of 5%, 10%, and 15%, while the coarse aggregate content was kept constant. This approach enabled a systematic evaluation of the influence of EV dosage on the pore structure without altering the primary coarse aggregate skeleton. By maintaining constant cement content, water to cement ratio, and curing conditions across all mixtures, a polycarboxylate based plasticizer was incorporated at a constant dosage of 1% by weight of cement in all mixtures.

The primary purpose of the plasticizer was not to increase workability, but to improve paste cohesion and reduce segregation in the fine aggregate free pervious concrete system. Given the absence of fine aggregates and the high water absorption capacity of expanded vermiculite, the plasticizer assisted in achieving more uniform paste distribution around coarse aggregates and enhanced paste aggregate bonding without compromising the interconnected pore structure. Maintaining a constant plasticizer dosage across all mixtures ensured that variations in mechanical and hydraulic performance could be attributed primarily to the effect of expanded vermiculite incorporation rather than changes in admixture content. the observed variations in compressive strength, porosity, and permeability can be directly attributed to the incorporation of expanded vermiculite. The subsequent sections present and discuss the experimental results to assess how EV dosage governs the trade-off between mechanical performance and hydraulic behavior of pervious concrete.

3. Results and Discussion

This section presents and discusses the experimental results obtained from fine aggregate free pervious concrete specimens incorporating expanded vermiculite (EV) at dosage levels of 0%, 5%, 10%, and 15%. All mixtures were proportioned following a modified volumetric approach in accordance with ACI 522R-10, with fine aggregate completely omitted to preserve interconnected pore structures. The primary objective of this section is to evaluate how EV incorporation governs the balance between mechanical strength and hydraulic functionality of pervious concrete.

The results are organized into three sub-sections corresponding to the key performance parameters investigated in this study:

1. Compressive strength, representing the load bearing capacity of the pervious concrete;
2. Porosity, reflecting the void structure required for water storage and infiltration;

3. Permeability, indicating the ability of the concrete to transmit water through interconnected pores.

The performance of each mixture is systematically compared with the control specimen containing 0% EV, enabling a clear assessment of the influence of EV dosage on each parameter. The observed trends are interpreted in relation to the physical characteristics of expanded vermiculite, including its low density, high porosity, and high water absorption capacity, which affect internal curing, paste aggregate bonding, and pore connectivity. Where appropriate, graphical representations, tabulated data, and statistical summaries are used to support the discussion. Particular attention is given to the trade-off between compressive strength enhancement and the reduction in hydraulic performance, which is a critical consideration in optimizing pervious concrete for infiltration dependent applications.

3.1. Compressive Strength Testing

Compressive strength testing was conducted at 7 and 28 days to evaluate the mechanical performance of fine aggregate free pervious concrete incorporating expanded vermiculite (EV) at dosage levels of 0%, 5%, 10%, and 15%. The results demonstrate a systematic increase in compressive strength with increasing EV content at both testing ages. At 7 days, the average compressive strength increased from 9.27 MPa for the control mixture (0% EV) to 16.04 MPa for the mixture containing 15% EV, representing an increase of approximately 73%. A similar trend was observed at 28 days, where compressive strength increased from 10.55 MPa to 17.08 MPa, corresponding to an improvement of approximately 62%. All measured strength values fall within the typical range reported for pervious concrete according to ACI 522R-10 (2.8 – 28 MPa).

The observed strength enhancement can be attributed primarily to the internal curing effect of expanded vermiculite, which gradually releases absorbed water and supports continued cement hydration. Additionally, the presence of EV contributes to microstructural densification by partially occupying inter aggregate voids, thereby improving paste aggregate bonding. However, the incremental strength gain between 10% and 15% EV was relatively limited, indicating diminishing returns at higher EV dosages.

Figure 2 illustrates the compressive strength development at both curing ages. The results show that the most significant strength improvement occurred between 0% and 10% EV, while further increases in EV content resulted in a reduced rate of strength gain. This trend confirms that although higher EV contents enhance compressive strength, excessive incorporation does not yield proportional improvements. From a mechanical perspective, mixtures containing 10–15% EV exhibit the highest compressive strength. However, as discussed in subsequent sections, these strength gains must be evaluated in conjunction with porosity and permeability results to assess the overall balance between mechanical strength and hydraulic functionality, which is critical for pervious concrete applications.

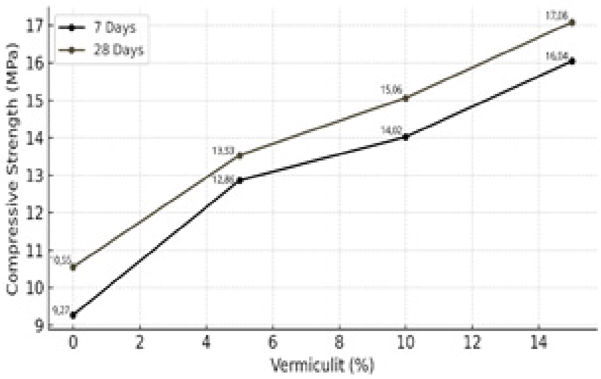

Figure 2. Compressive Strength Test Results

3.2. Porosity Testing

Porosity testing was performed at 28 days in accordance with ASTM C1754 [22], which is specifically developed to determine the interconnected void content of hardened pervious concrete. This method provides a direct representation of the pore network responsible for water infiltration and hydraulic functionality, making it more suitable for pervious concrete evaluation than conventional porosity tests. The control mixture containing 0% expanded vermiculite (EV) exhibited a void content of 19.13%, which lies within the recommended range for pervious concrete specified in ACI 522R-10 (15–35%). The incorporation of 5% EV resulted in a moderate reduction in void content to 16.95%, while still maintaining sufficient interconnected porosity to support effective water infiltration. In contrast, further increases in EV content led to a substantial decrease in interconnected void content.

Figure 3 illustrates the non linear decrease in interconnected void content with increasing EV dosage. The most pronounced reduction occurred between 10% and 15% EV, indicating a clear transition from hydraulically functional pervious concrete to a dense concrete structure. These findings demonstrate that moderate EV incorporation (up to 5%) preserves adequate porosity, whereas higher dosages compromise the primary hydraulic function of pervious concrete.

Mixtures containing 10% and 15% EV exhibited porosity values of 13.33% and 3.14%, respectively, both of which fall below the minimum threshold required for functional pervious concrete. These results indicate that excessive EV incorporation significantly disrupts pore connectivity, leading to a loss of effective hydraulic pathways. The observed reduction in porosity can be attributed to the void filling behavior of expanded vermiculite. Due to its fine particle size and highly absorptive structure, EV progressively occupies inter aggregate voids, causing macro pore blockage and increased matrix densification. While such densification contributes positively to compressive strength development, it adversely affects the interconnected pore system essential for infiltration.

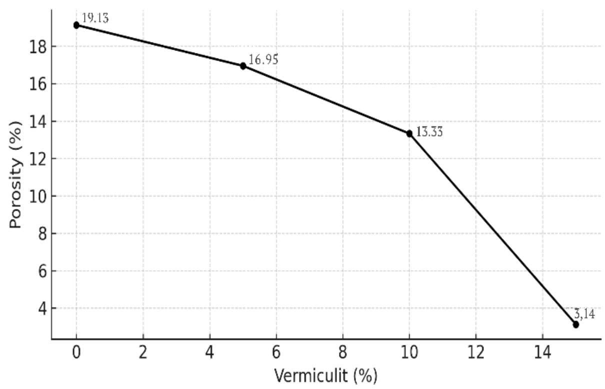

Figure 3. Porosity Test Results

3.1 Permeability Testing

Permeability testing was conducted at 28 days using the falling head method, with results expressed in cm/s, to evaluate the hydraulic functionality of the fine aggregate free pervious concrete mixtures. As shown in Figure 4, the permeability of fine-aggregate-free pervious concrete decreases consistently with increasing vermiculite content. The permeability value drops from about 0.70 cm/s at 0% vermiculite to approximately 0.55 cm/s at 5%, 0.37 cm/s at 10%, and reaches around 0.08 cm/s at 15%.

This trend indicates that the addition of vermiculite reduces the interconnected pore structure, thereby limiting water flow through the concrete matrix. Although higher vermiculite contents may contribute to other performance aspects, excessive amounts significantly compromise hydraulic functionality. The control mixture containing 0% expanded vermiculite (EV) exhibited the highest permeability value of 0.70 cm/s, confirming its suitability as a pervious concrete system. The incorporation of 5% EV resulted in a moderate reduction in permeability to 0.55 cm/s, while still remaining within the acceptable range for pervious concrete applications. In contrast, further increases in EV content led to a pronounced decline in permeability. Mixtures containing 10% and 15% EV showed permeability values of 0.37 cm/s and 0.08 cm/s, respectively. In particular, the mixture with 15% EV fell well below the minimum permeability requirement of 0.14 cm/s specified in ACI 522R-10 [19], indicating a significant loss of functional water infiltration capacity.

The observed reduction in permeability closely mirrors the porosity trends discussed in the previous section. As expanded vermiculite content increases, EV particles progressively obstruct the interconnected macro pore network, thereby reducing pore connectivity and restricting water flow. While higher EV contents contribute to improved compressive strength through matrix densification, they simultaneously compromise the drainage function that defines pervious concrete performance.

Figure 4 illustrates the sharp, non-linear decrease in permeability with increasing EV dosage. The most severe reduction occurs at higher EV contents, particularly between 10% and 15%, where the concrete behavior transitions from hydraulically functional pervious concrete to a denser, low-permeability material. This trend highlights the strong sensitivity of permeability to pore connectivity rather than total porosity alone. Overall, the permeability results confirm that expanded vermiculite incorporation should be limited to approximately 5% when hydraulic functionality is a primary design requirement. Beyond this threshold, the balance between mechanical enhancement and water infiltration shifts unfavorably, reinforcing the necessity of dosage control to achieve an optimal balance between mechanical strength and hydraulic performance in pervious concrete systems.

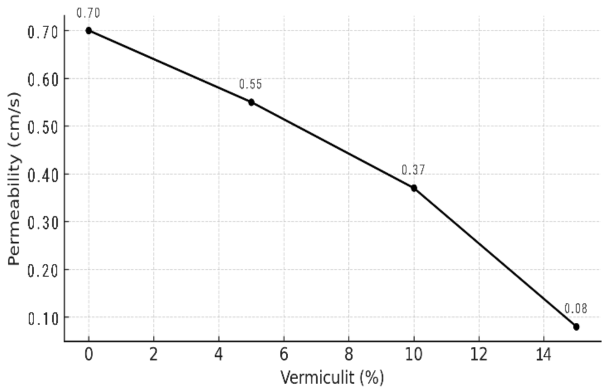

Figure 4. Permeability Test Results

4. Conclusion

This study investigated the influence of expanded vermiculite (EV) as a lightweight aggregate substitute on the performance of fine aggregate free pervious concrete, with particular emphasis on achieving a balance between mechanical strength and hydraulic functionality. Four concrete mixtures incorporating EV contents of 0%, 5%, 10%, and 15% were designed using a modified volumetric approach in accordance with ACI 522R-10, and their compressive strength, porosity, and permeability were evaluated under controlled laboratory conditions. The experimental results demonstrate that increasing EV content enhances compressive strength at both 7 and 28 days, primarily due to the internal curing effect and microstructural densification associated with EV incorporation. The highest compressive strength values were obtained for the mixture containing 15% EV.

However, this strength improvement was accompanied by a substantial reduction in porosity and permeability as EV content increased. Porosity and permeability results indicate that mixtures containing 0% and 5% EV satisfy the minimum hydraulic performance requirements specified in ACI 522R-10, while mixtures with 10% and 15% EV fall below the recommended thresholds. This behavior reflects a clear transition from hydraulically functional pervious concrete to a denser concrete structure at higher EV dosages, despite the associated strength gains. Based on the combined evaluation of compressive strength, porosity, and permeability, 5% expanded vermiculite is identified as the optimal dosage for fine-aggregate-free pervious concrete. At this level, a meaningful improvement in mechanical strength is achieved while maintaining adequate pore connectivity and water infiltration capacity. Higher EV contents, although beneficial for strength, compromise hydraulic functionality and are therefore unsuitable for infiltration-dependent applications.

Overall, the findings confirm that the performance of fine-aggregate-free pervious concrete is governed by a critical trade-off between strength enhancement and hydraulic functionality, and that careful dosage control of expanded vermiculite is essential for designing pervious concrete systems that meet both structural and drainage performance requirements.

Article Information Form

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Authors Contribution

Rahmad Pasca Try Valent contributed to the conception, experimental design, data collection, data analysis, and manuscript writing. All authors participated in interpreting the results, reviewing, and approving the final version of the manuscript.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Artificial Intelligence Statement

No artificial intelligence tools were used while writing this article.

Copyright Statement

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