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Original research article

Balancing strength and porosity: A critical evaluation of cement substitution with metakaolin in porous concrete

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ABSTRACT

Rapid urbanization has led to increased impervious surfaces, exacerbating stormwater runoff and urban flooding. As a response, pervious concrete has emerged as an innovative solution in sustainable infrastructure due to its high porosity, enabling water infiltration and flood mitigation. This study evaluates the impact of varying percentages of metakaolin as a partial cement substitute on the mechanical properties, permeability, and porosity of pervious concrete. Metakaolin, as a reactive pozzolanic material, is expected to enhance mechanical strength while maintaining the concrete's drainage function. Five mix variations with 10%, 12.5%, 15%, 17.5%, and 20% metakaolin as a partial cement substitute were tested at concrete ages of 7 and 28 days. The results show that the optimal composition was achieved with a 15% metakaolin substitution, yielding 13.17 MPa compressive strength, 3.87 MPa splitting tensile strength, 0.469 cm/s permeability, and 24.34% porosity at 28 days. The addition of metakaolin in moderate amounts improves density and structural strength, but higher proportions significantly reduce permeability. These findings highlight the importance of achieving a balance between mechanical performance and hydraulic function in metakaolin-based pervious concrete design.

1. Introduction

Advancements in construction technology have driven innovations in building materials, including concrete. Concrete has become the primary material of choice in construction projects due to its superior characteristics, such as high strength, durability in extreme weather conditions, low water absorption, and cost-effective production [1]. Consequently, concrete is widely used in infrastructure development, including dams, bridges, irrigation systems, and roads [2]. However, due to rapid urbanization, issues related to inadequate drainage systems have arisen. Poor drainage can lead to water pooling, potentially causing flooding [3]. To address this, innovative materials are

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needed that offer high load-bearing capacity while reducing water accumulation through effective infiltration systems.

Pervious concrete offers an effective solution to this problem [4]. This concrete has high porosity, allowing water to infiltrate directly into the ground. As a result, it reduces surface water runoff and manages rainwater more effectively [5]. This is due to voids created by uniformly graded coarse aggregates, with minimal or no fine aggregates. Although pervious concrete excels in permeability, its mechanical properties are generally lower than those of conventional concrete [6]. Therefore, optimizing its constituent materials is necessary to achieve adequate strength without compromising drainage function. One approach is to minimize the water-cement ratio (W/C) and incorporate admixtures like superplasticizers [7]. Superplasticizers enhance concrete workability without reducing compressive strength, enabling easier application while maintaining performance [8].

Additionally, using supplementary materials like metakaolin as a partial cement substitute has been explored to enhance pervious concrete quality. Metakaolin, an active pozzolanic material, reacts with calcium hydroxide to form calcium silicate hydrate (C-S-H), strengthening the concrete's microstructure [9]. Studies show that 10-15% metakaolin enhances compressive strength, reduces microporosity, and improves durability while preserving macro-permeability [10]. Thus, combining metakaolin and superplasticizers holds potential for producing stronger, more stable pervious concrete while preserving its drainage functionality.

This study evaluates the effects of varying metakaolin substitution percentages on the mechanical properties, permeability, and porosity of pervious concrete. The research also applies pervious concrete to pedestrian pathways in parks to enhance rainwater infiltration and mitigate urban flooding [11]. The metakaolin substitution percentages used are 10%, 12.5%, 15%, 17.5%, and 20% of the total cement weight, based on studies showing improved compressive strength in this range [10]. This research aims to contribute to the development of sustainable, environmentally friendly construction materials.

2. Material and method

This study, conducted at the Structure and Material Construction Laboratory of Sriwijaya University, employed an experimental method to evaluate the influence of metakaolin as a partial cement substitute in pervious concrete, focusing on its mechanical and hydraulic properties. Porous concrete was prepared with five metakaolin substitution levels—10%, 12.5%, 15%, 17.5%, and 20% of the total cement content—using a fixed water-cement ratio of 0.35, a 3.54:1 aggregate-to-cement ratio, and 1% superplasticizer by binder weight to ensure workability. Cylindrical specimens (15 cm diameter × 30 cm height) were used for consistent testing.

The research proceeded in five stages: First, raw materials, including Portland cement, metakaolin, coarse aggregates, superplasticizer, and laboratory equipment, were collected, with metakaolin and cement characterized using X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and Scanning Electron Microscopy-Energy Dispersive Spectroscopy (SEM-EDS) for chemical composition, mineral phases, and morphology. Second, coarse aggregates were tested per ASTM standards for specific gravity and absorption (ASTM C127), bulk density and voids (ASTM C29/C29M), moisture content (ASTM C566), and sieve analysis (ASTM C136), using single-size aggregates (9.5–19 mm) to ensure high interconnected voids critical for pervious concrete's porosity and permeability. Third, concrete mixtures were developed with the specified ratios and metakaolin levels. Fourth, materials were weighed, mixed mechanically, cast into molds, manually compacted to maintain void structure, demolded after 24–48 hours, and moist-cured wrapped in plastic sheets, with specimen ends capped with sulfur before compressive strength testing. Finally, the concrete's properties were evaluated through compressive strength (ASTM C39) and splitting tensile strength (ASTM C496) tests at 7 and 28 days using a Universal Testing Machine, permeability (ASTM C1701) at 28 days using a Falling Head Permeameter, and porosity via a gravimetric method comparing oven-dry and submerged weights. These tests provided quantitative data to analyze trade-offs between mechanical strength and hydraulic performance, enabling the identification of an optimal mix design for sustainable pervious concrete applications.

Table 1 details variations in concrete mixtures incorporating metakaolin at different percentages—10%, 12.5%, 15%, 17.5%, and 20% of the cement weight. Each variation (V1 to V5) contains a different amount of metakaolin based on these percentages, while the aggregate quantity remains constant at 7.50 kg/m^3. As metakaolin content increases, the cement quantity decreases progressively from 1.910 kg/m^3 in V1 to 1.696 kg/m^3 in V5. The water content, aggregate-to-cement ratio (ACR), water-to-cement ratio (W/C), and superplasticizer (SP) are fully specified only for the V3 variation, which includes 0.742 kg/m^3 of water, an ACR of 3.54, a W/C ratio of 0.35, and 1% superplasticizer. This suggests that V3, with 15% metakaolin, serves as the primary sample for evaluating concrete mixture performance. The data indicates an optimized material proportion aimed at enhancing concrete performance by partially replacing cement with metakaolin.

Table 1
Composition of porous concrete mixture

Variations	Metakaolin (gram)					Aggregate (kg/m³)	Cement (kg/m³)	Water (kg/m³)	ACR	FAS	SP
	10%	12.5%	15%	17.5%	20%						
V1	212	-	-	-	-	7.50	1.91	0.742	3.54	0.35	1%
V2	-	265	-	-	-	7.50	1.855	0.742	3.54	0.35	1%
V3	-	-	318	-	-	7.50	1.802	0.742	3.54	0.35	1%
V4	-	-	-	371	-	7.50	1.749	0.742	3.54	0.35	1%
V5	-	-	-	-	424	7.50	1,696	0.742	3.54	0.35	1%

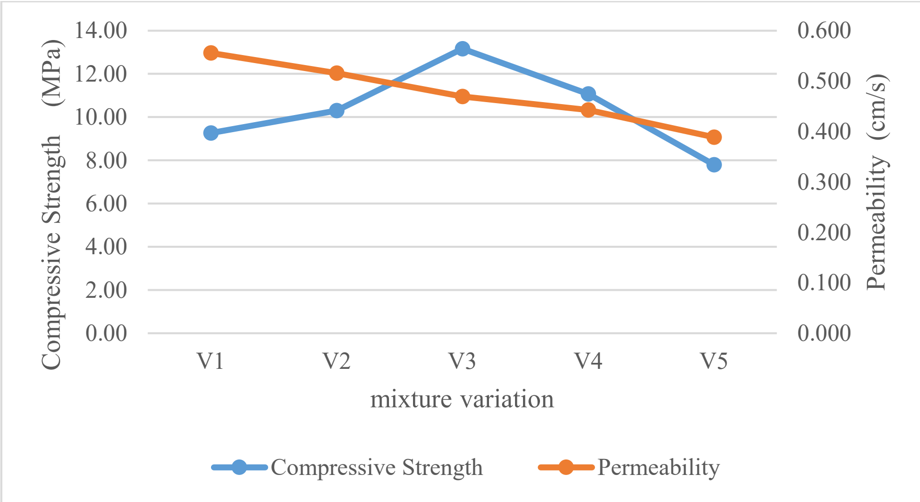

Fig. 1. Compressive strength and permeability test.

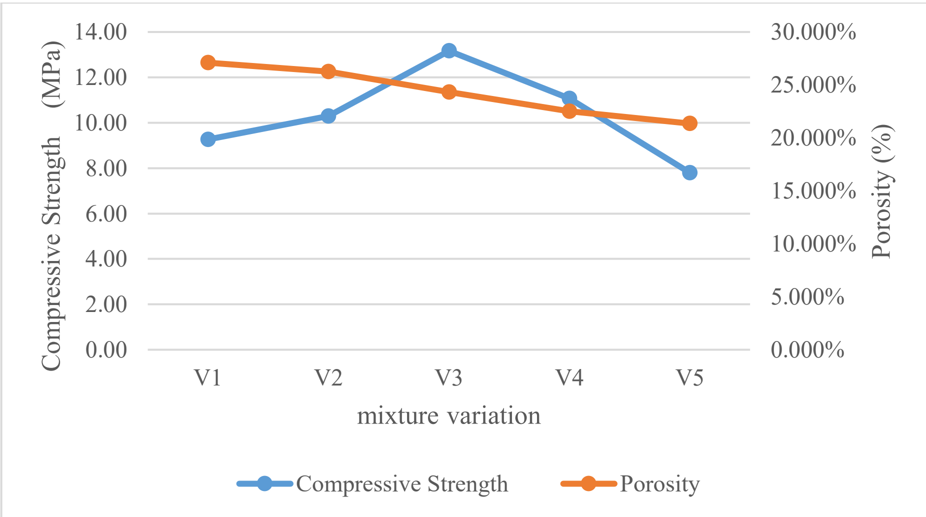

Fig. 2. Compressive strength and porosity test.

3. Results and discussion

3.1. Compressive strength and permeability test results

Fig. 1 illustrates that the relationship between compressive strength and permeability in porous concrete lacks a consistent pattern. From V1 to V3, compressive strength increases while permeability decreases. Conversely, from V3 to V5, both compressive strength and permeability decrease. Generally, higher compressive strength correlates with lower permeability, but this trend is observed only from V1 to V3. At V4 and V5, compressive strength declines due to a reduced pozzolanic reaction resulting from lower cement content.

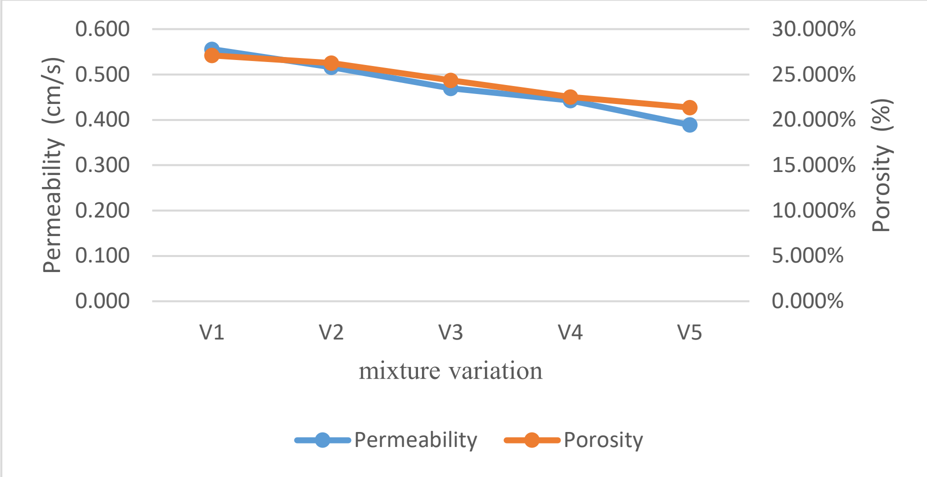

Fig. 3. Permeability and porosity test.

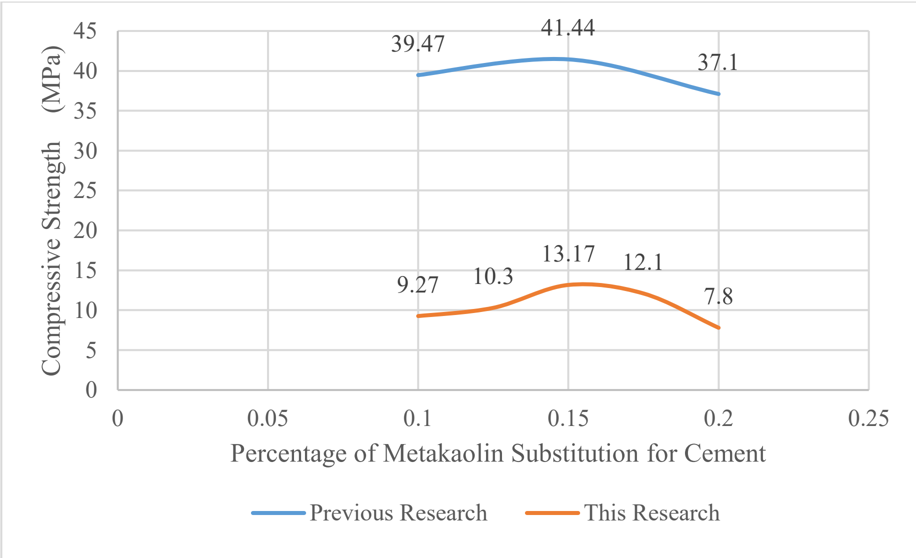

Fig. 4. Comparison of compressive strength test with previous research.

3.2. Compressive strength and permeability test results

Fig. 2 shows that from V1 to V3, compressive strength increases while porosity decreases. In contrast, from V3 to V5, both compressive strength and porosity of porous concrete decrease. Typically, higher compressive strength corresponds to lower porosity due to fewer voids in the concrete matrix. This relationship holds only from V1 to V3. At V4 and V5, compressive strength decreases due to a diminished pozzolanic reaction caused by reduced cement content.

3.3. Permeability and porosity test results

Fig. 3 demonstrates a direct correlation between permeability and porosity, with both parameters increasing or decreasing together. In this study, both permeability and porosity decrease as the percentage of metakaolin substitution for cement increases.

3.4. Compressive strength test results with previous research

Previous research [10] reported increased compressive strength in porous concrete with metakaolin substitutions of 10% to 15%, consistent with this study's findings. However, both studies observed a decrease in compressive strength at substitutions of 15% to 20%, attributed to a reduced pozzolanic reaction due to lower cement content. Fig. 4 confirms that the compressive strength patterns in this study align with those in prior research. A 15% metakaolin substitution was identified as the optimal proportion for achieving maximum compressive strength in this study.

Table 2
Compressive strength 7 days.

No	Mixture variation	Weight (kg)	Compressive strength (MPa)	Average compressive strength (Mpa)
1	V1	9.68	6.1	6.43
2	V1	9.72	6.5	6.43
3	V1	9.81	6.7	6.43
4	V2	9.98	6,8	7.20
5	V2	9.85	7.3	7.20
6	V2	9.8	7.5	7.20
7	V3	10	9.3	9.43
8	V3	9.9	9.4	9.43
9	V3	10.18	9.6	9.43
10	V4	10.1	7.7	8.17
11	V4	10.15	7.9	8.17
12	V4	10.3	8.9	8.17
13	V5	10.4	5.1	5.43
14	V5	10.25	5.5	5.43
15	V5	10,38	5.7	5.43

Table 3
Compressive strength 28 days.

No	Mixture variation	Weight (kg)	Compressive strength (MPa)	Average compressive strength (Mpa)
1	V1	9.75	8.9	9.27
2	V1	9.68	9.1	9.27
3	V1	9.65	9.8	9.27
4	V2	9.86	9.8	10.30
5	V2	9.69	10.3	10.30
6	V2	9.95	10.8	10.30
7	V3	9.95	12.7	13.17
8	V3	10.05	13.2	13.17
9	V3	10.2	13.6	13.17
10	V4	10.2	10.2	11.07
11	V4	10.2	10.9	11.07
12	V4	10.3	12.1	11.07
13	V5	10.2	7.5	7.80
14	V5	10.48	7.7	7.80
15	V5	10.5	8.2	7.80

3.5. Compressive strength testing

Table 2 presents the compressive strength test results for concrete at 7 days for five variations (V1 to V5) with varying metakaolin proportions. Each variation was tested on three samples, with weights ranging from 9.68 kg to 10.4 kg. The V3 variation (15% metakaolin) achieved the highest average compressive strength of 9.43 MPa, indicating optimal early strength. In contrast, the V5 variation (20% metakaolin) recorded the lowest average compressive strength of 5.43 MPa, suggesting that excessive metakaolin reduces early strength. These results indicate an optimal metakaolin substitution of 15% for maximizing compressive strength at 7 days.

Table 3 presents the compressive strength test results at 28 days for five variations (V1 to V5), with sample weights ranging from 9.65 kg to 10.5 kg. The V3 variation (15% metakaolin) achieved the highest average compressive strength of 13.17 MPa, confirming its optimal performance. Conversely, the V5 variation (20% metakaolin) exhibited the lowest average compressive strength of 7.80 MPa, indicating that excessive metakaolin negatively affects long-term strength. These findings reinforce the 7-day results, highlighting 15% metakaolin as the most effective substitution for compressive strength.

Table 4 presents the tensile strength test results at 7 days for five variations (V1 to V5), with sample weights ranging from 9.68 kg to 10.4 kg. The V3 variation (15% metakaolin) achieved the highest average tensile strength of 3.13 MPa, demonstrating optimal early tensile performance. In contrast, the V5 variation (20% metakaolin) recorded the lowest average tensile strength of 1.90 MPa, indicating that excessive metakaolin reduces tensile strength. These results confirm that 15% metakaolin optimizes early tensile strength.

Table 4
Tensile strength 7 days.

No	Mixture variation	Weight (kg)	Compressive strength (MPa)	Average compressive strength (Mpa)
1	V1	9.68	2.1	2.03
2	V1	9.72	1.8	2.03
3	V1	9.81	2.2	2.03
4	V2	9.98	2.7	2.53
5	V2	9.85	2.4	2.53
6	V2	9.8	2.5	2.53
7	V3	10	3.2	3.13
8	V3	9.9	3	3.13
9	V3	10.18	3.2	3.13
10	V4	10.1	3.1	2.73
11	V4	10.15	2.6	2.73
12	V4	10.3	2.5	2.73
13	V5	10.4	2	1.90
14	V5	10.25	2.1	1.90
15	V5	10.38	1.6	1.90

Table 5
Tensile strength 28 days.

No	Mixture variation	Weight (kg)	Compressive strength (MPa)	Average compressive strength (Mpa)
1	V1	9.75	2.8	2.63
2	V1	9.68	2.7	2.63
3	V1	9.65	2.4	2.63
4	V2	9.86	2.7	3.03
5	V2	9.69	3.1	3.03
6	V2	9.95	3.3	3.03
7	V3	9.95	4.4	3.87
8	V3	10.05	3.7	3.87
9	V3	10.2	3.5	3.87
10	V4	10.2	3.5	3.47
11	V4	10.2	3.7	3.47
12	V4	10.3	3.2	3.47
13	V5	10.2	2.5	2.30
14	V5	10.48	2.2	2.30
15	V5	10.5	2.2	2.30

Table 5 presents the tensile strength test results at 28 days for five variations (V1 to V5), with sample weights ranging from 9.65 kg to 10.5 kg. The V3 variation (15% metakaolin) achieved the highest average tensile strength of 3.87 MPa, followed by V4 (3.47 MPa) and V2 (3.03 MPa). The V5 variation (20% metakaolin) recorded the lowest average tensile strength of 2.30 MPa, confirming that excessive metakaolin diminishes tensile strength. These findings indicate that 15% metakaolin is the most effective substitution for optimizing tensile strength at 28 days.

3.6. Summary of findings on metakaolin-cement blended concrete performance

This study evaluated the mechanical performance of concrete with varying metakaolin substitution levels (10%, 12.5%, 15%, 17.5%, and 20%) for cement. X-Ray Fluorescence (XRF) analysis of metakaolin revealed primary oxides of SiO_2 (52.1%), Al_2O_3 (36.7%), and Fe_2O_3 (2.3%), meeting ASTM C618 criteria for Class N pozzolans. The cement used was Ordinary Portland Cement (OPC) Type I, complying with ASTM C150 specifications. All mechanical tests followed standardized procedures: compressive strength and splitting tensile strength were tested per ASTM C39 and ASTM C496, respectively.

The mechanical performance of the concrete mixes was assessed through compressive and splitting tensile strength tests at 7 and 28 days. Of all mixes, the 15% metakaolin mix (V3) achieved the highest compressive strengths (9.43 MPa at 7 days, 13.17 MPa at 28 days) and splitting tensile strengths (3.13 MPa at 7 days, 3.87 MPa at 28 days). This indicates enhanced early and long-term strength development, attributed to the pozzolanic reaction between metakaolin and calcium hydroxide, forming additional calcium silicate hydrate (C-S-H) gel, which improves concrete matrix density and aggregate-paste bond strength.

Table 6
Summarizes the key numerical data.

No	Variation	Metakaolin (%)	Compressive strength		Tensile strength	
			7-Day	28-Day	7-Day	28-Day
1	V1	10	6.43	9.27	2.03	2.63
2	V2	12.5	7.20	10.30	2.53	3.03
3	V3	15	9.43	13.17	3.13	3.87
4	V4	17.5	8.17	11.07	2.73	3.47
5	V5	20	5.43	7.80	1.90	2.30

The optimum performance at 15% metakaolin results from balanced cement hydration and pozzolanic activity. At lower substitution levels (10–12.5%), the pozzolanic reaction is not maximized, resulting in moderate strength gains. Conversely, at higher substitution levels (17.5–20%), the dilution effect reduces cement clinker content, lowering strength. Thus, 15% of the substitution provides sufficient reactive aluminosilicates to enhance the microstructure without excessively displacing cement. Table 6 summarizes the key numerical data for each mix. These findings highlight the impact of metakaolin content on concrete's mechanical behavior and identify the 15% substitution level as the most effective for balancing strength, durability, and cost-effectiveness.

3.7. Relationship between compressive strength and permeability

This study demonstrates that the addition of metakaolin to porous concrete significantly impacts its compressive strength and permeability. At lower metakaolin contents, there is an increase in compressive strength accompanied by a decrease in permeability [12]. This is due to the pozzolanic reaction between metakaolin and calcium hydroxide, which enhances concrete density but reduces the pore space necessary for water flow, thereby affecting the drainage capacity of porous concrete [13].

Excessive metakaolin addition leads to a decline in concrete performance, both in terms of strength and permeability [14]. In mixtures with higher metakaolin content, the effectiveness of the pozzolanic reaction decreases, reducing the formation of C-S-H, which is essential for enhancing concrete strength [15]. As a result, the concrete's strength decreases, and its function as a drainage medium is compromised.

This study confirms that the relationship between compressive strength and permeability in metakaolin-based porous concrete is not linear. In the design of porous concrete, achieving a balance between these two parameters is critical, as an increase in concrete strength is often inversely related to a decrease in permeability [16]. High metakaolin substitution further reduces the concrete's ability to channel water, which is a primary characteristic of porous concrete [17].

This study emphasizes that the use of metakaolin as a partial cement substitute in porous concrete must be carefully controlled. The optimal metakaolin proportion should be considered to ensure that the concrete is not only strong but also maintains its function as an effective drainage material [18]. Further research is needed to determine the precise metakaolin proportion to optimize the performance of porous concrete in real-world applications.

3.8. Relationship between compressive strength and porosity

This study reveals that the relationship between compressive strength and porosity in metakaolin-based porous concrete follows an interrelated pattern. At lower metakaolin contents, there is an increase in compressive strength accompanied by a decrease in porosity [19]. This can be explained by the increased concrete density due to the pozzolanic reaction between metakaolin and cement, which strengthens the concrete structure and reduces pore space [20]. At higher metakaolin contents, there is a significant decrease in both compressive strength and porosity [21]. This decline is caused by the reduced cement content, which diminishes the pozzolanic reaction, consequently lowering the formation of C-S-H, a critical component for concrete strength [22]. As a result, despite the increased metakaolin content, the concrete loses much of its strength.

This study indicates an inverse relationship between compressive strength and porosity in porous concrete [23]. Higher compressive strength corresponds to lower porosity, and vice versa. In porous concrete, high porosity is generally associated with numerous voids that allow water infiltration [24]. However, these voids lead to a reduction in compressive strength, compromising structural integrity.

The study confirms that achieving a balance between compressive strength and porosity is crucial in the design of metakaolin-based porous concrete. The metakaolin proportion must be carefully selected, as exceeding the optimal threshold reduces the pozzolanic reaction and impairs concrete performance [25]. Therefore, selecting the appropriate metakaolin proportion is essential to achieve optimal porous concrete in terms of both strength and permeability.

3.9. Relationship between permeability and porosity

This study demonstrates a clear relationship between permeability and porosity in metakaolin-based porous concrete. The graph indicates that both parameters are directly correlated, decreasing together. An increase in metakaolin substitution for cement is associated with a reduction in both permeability and porosity values [26]. The decrease in permeability and porosity results from the denser concrete structure formed by the pozzolanic reaction [27]. As the metakaolin content increases, the concrete structure becomes denser, reducing the available pore space for water flow, thereby lowering permeability [28]. This relationship suggests that higher permeability corresponds to greater porosity, as more voids in the concrete allow water flow. Conversely, increased metakaolin substitution leads to a reduction in both parameters, reflecting improved concrete strength but diminished water-flow capacity [29]. The study confirms that increasing the percentage of metakaolin substitution can reduce both permeability and porosity in porous concrete. Therefore, achieving the right balance in metakaolin use is crucial to ensure the concrete maintains good structural quality while preserving its optimal drainage function.

3.10. Strong connection between this study and previous studies

This study aligns with previous research, which found that metakaolin substitution between 10% and 15% increased the compressive strength of porous concrete [10]. These findings indicate that within this range, metakaolin enhances concrete strength through an effective pozzolanic reaction. Similar to previous research, when the metakaolin substitution percentage exceeds 15% (i.e., 15% to 20%), a decrease in compressive strength occurs. This decline results from reduced cement content, which weakens the pozzolanic reaction and lowers C-S-H formation, critical for concrete strength [30]. The pattern of increasing and decreasing compressive strength closely resembles that found in previous studies. This reinforces the understanding that a 15% metakaolin substitution is the optimal point for achieving maximum concrete strength, consistent with prior findings indicating that this proportion provides the best balance between mechanical strength and concrete stability [31]. This study confirms that metakaolin substitution in porous concrete should be limited to a moderate level, around 15%, to achieve optimal performance. Excessive metakaolin addition can disrupt the pozzolanic reaction necessary for enhancing concrete strength.

4. Conclusions

Based on the test results, it can be concluded that substituting cement with metakaolin in porous concrete significantly affects the mechanical properties, permeability, and porosity of the concrete. The optimal composition was achieved with a mixture of 85% cement and 15% metakaolin, yielding the best results with a compressive strength of 13.17 MPa and a splitting tensile strength of 3.87 MPa at 28 days, complying with ACI 522R-10 standards. However, adding more than 15% metakaolin led to a decrease in compressive strength due to a reduced pozzolanic reaction.

Increasing metakaolin substitution also resulted in decreased permeability and porosity, with the lowest values observed in the 80% cement and 20% metakaolin mixture. This reduction is attributed to increased concrete density, which decreases voids and the concrete's ability to channel water. Nevertheless, this mixture still meets ACI 522R-10 standards.

Future research is recommended to explore a wider range of metakaolin percentages, the use of finer and more uniform aggregates, and variations in the water-cement ratio (W/C) to optimize the performance of porous concrete in terms of strength, permeability, and porosity. This approach is expected to produce more efficient and high-performing porous concrete mixtures.

Declaration statement

Auliya Rahmadillah: Original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bimo Brata Adhitya**: Writing - Original draft, Supervision, Methodology. **Fitria Putri Lintang Sari**: Writing, validation, data curation, review and editing.

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Disclosure statement

The authors declare no conflict of interest. Not applicable, as this study did not involve human participants or animals.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

AI Usage Statement

This research did not involve the use of generative artificial intelligence (AI) tools in the processes of data analysis, interpretation, or manuscript writing. All content presented in this article was generated, written, and reviewed solely by the authors, based on original research and findings. Any tools or software used were limited to conventional statistical or engineering applications and did not involve AI-assisted content generation.

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