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Research Article

Assessing the Role of Kaolin in Cement-Based Concrete: Strength Development and Material Performance

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Abstract

This study investigated the influence of kaolin as a partial cement replacement on the fresh and mechanical properties of concrete for road pavement applications. The Research was carried out through laboratory experiments using five kaolin replacement levels: 0%; 7,5%; 15%; 22,5%; and 30% by weight of cement. The evaluated parameters included XRF testing, slump, compressive strength, and flexural strength. The XRF results of cement and Kaolin show similarities in CaO and SiO_2 in the formation of cement clinker phases. The test results showed that incorporating kaolin affected the workability of the concrete mixture. The control mixture produced the highest slump value of 6 cm, while the mixture containing 30% kaolin showed the lowest slump value of 1 cm, indicating a considerable reduction in workability at higher replacement levels. A similar trend was observed in compressive strength, which decreased from 33 MPa in the control concrete to 27 MPa, 22 MPa, 19 MPa, and 14 MPa for the 7.5%, 15%, 22.5%, and 30% kaolin mixtures, respectively. This finding suggests that excessive kaolin replacement may reduce the binder system's ability to develop compressive strength effectively. In contrast, flexural strength remained relatively consistent, ranging from 5 to 6 MPa across all mixtures. This indicates that, although kaolin reduces compressive strength, its effect on flexural performance is less pronounced. Overall, kaolin replacement levels of 7.5% to 15% appear to be the most promising range for concrete pavement materials, as they still provide acceptable mechanical performance while offering the potential to reduce cement consumption.

Introduction

Road infrastructure requires high-quality materials that can withstand repeated traffic loads, provide good durability, and meet the technical specifications for rigid pavement (Pattimura Nomor et al., 2024). Flexural strength is a key parameter for concrete road pavements, as concrete slabs are subjected primarily to tensile stress rather than compressive stress from vehicle wheels. According to the Bina Marga General

Specifications, the flexural strength requirement at 28 days is 4.7 MPa for trial concrete and 4.5 MPa for project control (Pattimura Nomor et al., 2024). In addition to flexural strength, compressive strength is also important, as it indicates concrete quality by examining the relationship between compressive strength and concrete strength (Salsabilla et al., 2025).

Continued use of Portland cement can also cause environmental damage from carbon emissions (Halim & Amiruddin, 2024; Laksono et al., 2024; Sekar et al., 2026). Therefore, this study explores alternative materials as partial replacements to support the development of more economical and sustainable concrete mixtures (Fitrawansyah, 2020; Sani et al., 2024). One material studied is kaolin clay, a local material. Kaolin clay is a clay containing aluminosilicate compounds that can be used as a partial replacement material in concrete mixtures (Febryandi et al., 2022; Mahendra et al., 2024). Pure kaolin as a concrete admixture has received limited attention, as its relatively low reactivity can reduce concrete strength (Febryandi et al., 2022; Sasongko et al., 2025). Using pure kaolin as a partial cement replacement reduces compressive strength, yet it may improve durability characteristics such as porosity and water resistance (Febryandi et al., 2022; Salsabilla et al., 2025). Consequently, research into kaolin for concrete applications remains highly viable, offering the potential for high compressive strength while also considering mechanical performance and the utilization of local materials (Salsabilla et al., 2025). Evaluating the mechanical properties of kaolin-based concrete is really important to ensure its structural performance and durability (Jiang et al., 2025). Using kaolin soil requires continuous testing across various percentage variations to achieve optimal results by monitoring changes, specifically increases or decreases, in both compressive and flexural strength. Research into using kaolin soil mixtures as a partial replacement material is highly relevant. This study aims to show how varying kaolin additions affect compressive and flexural strength and to assess the material's suitability as a locally sourced, efficient alternative for concrete pavement mixtures that still meet all required standards.

Research Method

A laboratory experimental investigation was conducted to evaluate the influence of kaolin incorporation on the compressive and flexural strength performance of concrete. In this study, kaolin was used as a partial replacement for Portland cement at different replacement levels based on the total mass of cementitious material. This study used SNI 2016 (Kementerian PUPR, 2016) and AHSP 2023 (AHSP, 2023) as references.

The experimental procedures included a literature review, material characterization, mix design, specimen preparation, curing or concrete maintenance, and compressive strength and flexural strength testing. The concrete mixtures were prepared using water, Portland cement, fine aggregate, coarse aggregate, and kaolin variation. A control mixture containing only Portland cement as the binder was also prepared to provide a basis for comparison. Compressive strength and flexural strength results of the kaolin-based mixtures were subsequently compared with those of the control mixture to assess the contribution of kaolin replacement to concrete strength development. The compressive strength was planned at 25 MPa. The experimental specimens consisted of cylinders (150 mm × 300 mm) and beams (100 mm × 100 mm × 400 mm), prepared for compressive and flexural strength testing, respectively. Before mixing, all constituent materials were weighed according to the designed mix proportions to ensure consistency across the concrete mixtures. Table 1 presents the specimen quantities and kaolin replacement percentages for each mixture.

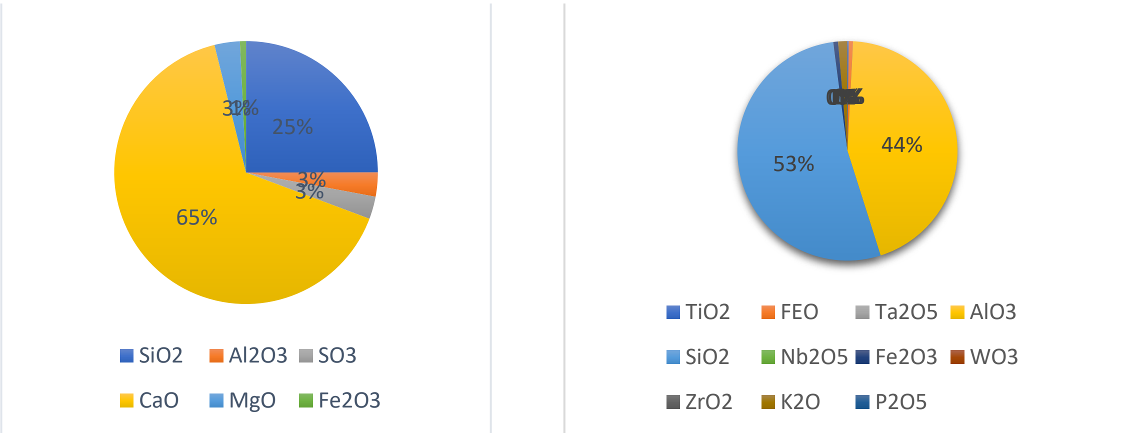
Compressive strength testing was conducted at predetermined concrete ages using a compression testing machine. The specimens were placed centrally in the machine and subjected to gradually increasing axial loads until failure. The maximum applied load was recorded and used to calculate compressive strength as the ratio of load to the specimen's cross-sectional area. Flexural strength testing was also performed to evaluate the concrete's resistance to bending. Beam specimens were placed on simple supports and loaded gradually until cracking or failure occurred. The recorded maximum load was used to determine flexural strength based on the specimen dimensions and loading configuration. The average compressive and flexural strength values of each mixture were then compared with those of the control concrete to assess the effect of kaolin replacement on the mechanical performance of concrete.

Table 1. Number of Test Objects

Kaolin Percentage	Cylinder	Beam	Time (days)
0%	3	3	28
7,50%	3	3	28
15%	3	3	28
22,50%	3	3	28
30%	3	3	28

Results and Discussion

Before using kaolin as a cement substitute in concrete mixtures, it is necessary to determine its composition, specifically whether the kaolin's constituents are comparable to those of cement so it can serve as a substitute. Consequently, we conducted XRF testing, and the results are presented in Figure 1.



(a.) (b.)

Figure 1. (a) Cement's XRF Test, and (b) Kaolin's XRF Test

XRF analysis was performed to characterize the chemical composition of kaolin soil used as a partial cement substitute in the concrete mixtures (Saputra et al., n.d.). The analysis focused on identifying major oxide contents, particularly SiO2, Al2O3, and Fe2O3, which are important indicators of kaolin's pozzolanic potential. In addition, we evaluated the presence of other oxides because they may affect cement hydration, binder formation, and the mechanical performance of concrete. Thus, XRF analysis provided a basis for understanding the relationship between kaolin's chemical characteristics and the properties of the resulting concrete.

The slump test is crucial for determining the workability of the concrete mix and serves as a control measure, as it influences compressive strength. Table 1 presents the slump results graphically. Figures 2 and 3 show the slump test. The slump test results indicate that increasing the proportion of kaolin reduced the workability of the fresh concrete, as reflected by the lower slump values. This reduction can be explained by kaolin's finer particle size and greater specific surface area, which increase water demand by absorbing some of the free water in the mixture. Consequently, the amount of water available to lubricate the cement and aggregate particles decreases, resulting in a stiffer mixture. However, at higher kaolin replacement levels, the rate of slump reduction became less pronounced. This may be due to the filler effect of fine kaolin particles, which can occupy voids between cement particles and fine aggregates, improve particle packing, and partially stabilize mixture consistency.

Table 1. The Result of Slump Test

Code	Slump Test
BN 0%	6 cm
BK 7,5%	4 cm
BK 15%	4,5 cm
BK 22,5%	5 cm
BK 30%	1 cm

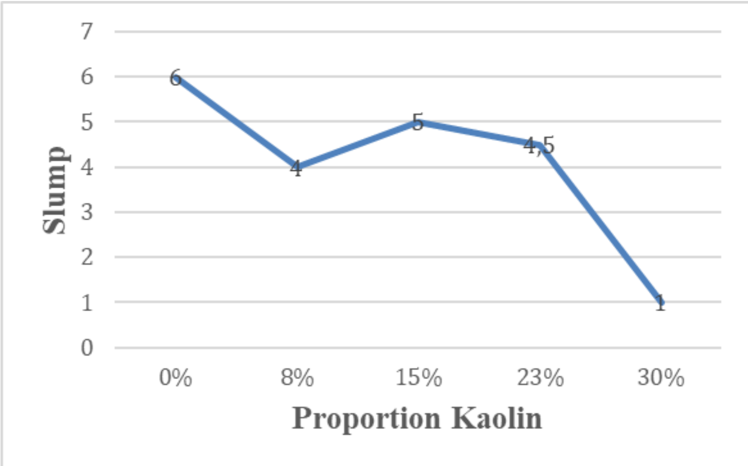


Figure 2. Slump Test

(a)

(b)

Figure 3. (a) Example Slump Test Normal Concrete, and (b) Slump Test with Kaolin 22,5%

The concrete compressive strength test results are presented in Table 2 and in the form of a graph, as shown in Figure 4 above. The result of compressive strength test showed that This study investigates the partial subtitution of cement with kaolin in concrete reduced the compressive strength of concrete. The control concrete exhibited the highest average compressive strength of 33 MPa, while the mixtures containing 7.5%, 15%, 22.5%, and 30% kaolin showed average compressive strengths of 27 MPa, 22 MPa, 19 MPa, and 14 MPa, respectively. A gradual loss of compressive strength is observed as the amount of kaolin increases. The reduction may be attributed to the result of dilution which are caused by the lower Portland cement content in the mixture, which reduced the formation of hydration products responsible for strength growth. In addition, the fine particle measure and high surface area of kaolin may have increased water demand and affected the compactness of the cementitious matrix. Although kaolin at low replacement levels may contribute to a filler effect, higher replacement levels appear to reduce the binding capacity of the mixture, resulting in lower compressive strength. Among the kaolin-based mixtures, the

7.5% replacement level produced the highest compressive strength and therefore showed the most favorable performance compared with the other kaolin variations.

Table 2. The Result of Compresive Strenght (Mpa)

Code	Test Object Fc' (Mpa)			Average Fc'
	1	2	3	
BN	36,72	30,31	30,64	33
BK 7,5%	26,68	29,01	24,84	27
BK 15%	22,47	21,57	22,44	22
BK 22,5%	20,68	16,16	19,12	19
BK 30%	13,77	13,33	15,18	14

Dalam penelitian ini, BN (Normal Concrete) digunakan sebagai beton kontrol tanpa penambahan kaolin, sedangkan variasi beton dengan substitusi kaolin dinyatakan sebagai BK 7,5%, BK 15%, BK 22,5%, dan BK 30%, yang masing-masing menunjukkan penggunaan kaolin sebesar 7,5%, 15%, 22,5%, dan 30%.

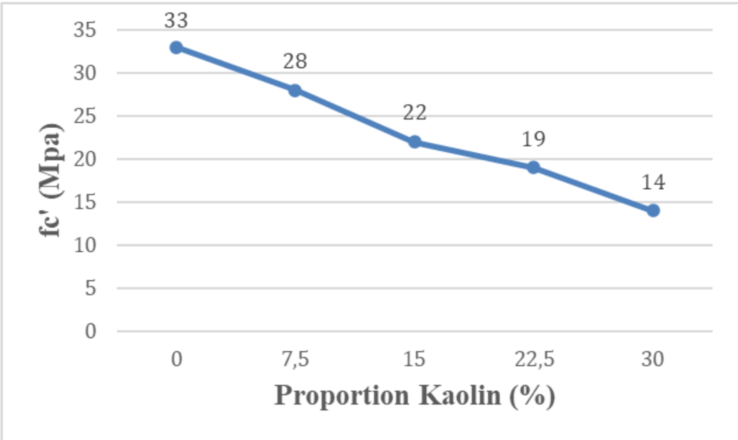


Figure 4. Result Compressive Strength (Fc')

The flexural strength test results are presented in Table 3 and plotted in the graph shown in Figure 5 above. The result of flexural strength test showed that the incorporation of kaolin as a partial cement replacement did not significantly reduce the flexural performance of concrete. The control mixture exhibited an average flexural strength of approximately 6.38 MPa, while the mixtures containing 7.5%, 15%, 22.5%, and 30% kaolin achieved average flexural strengths of approximately 5.26 MPa, 5.35 MPa, 5.23 MPa, and 5.77 MPa, respectively. Although a slight reduction was observed in the kaolin-modified mixtures, all flexural strength values remained within a range suitable for rigid pavement applications. This is important because concrete pavement slabs are primarily governed by flexural behavior under repeated wheel loading. The relatively stable flexural strength may be attributed to the filler effect of fine kaolin particles, which can improve particle packing and reduce microvoids within the concrete matrix. However, the decrease in flexural strength at several replacement levels indicates that the dilution of Portland cement may reduce the generation of hydration product and weaken the adhesion between the paste and aggregates. Among the kaolin mixtures, the 30% replacement showed the highest flexural strength, suggesting that the filler effect may contribute positively to bending resistance. Nevertheless, considering the compressive strength reduction at higher kaolin contents, the use of kaolin in rigid pavement concrete should be optimized by balancing both compressive and flexural performance. Kaolin as a 30% cement replacement usually shows small pores filled with fine kaolin particles. This filling effect can help support flexural strength. Kaolin acts as a filler that can improve the bond between cement paste and aggregates. The voids become denser at levels above 30%, which happens because the excess fine particles interfere with cement hydration. This lowers compressive strength due to the formation of new micro-pores. From several studies, SEM results can improve flexural resistance, but it needs to be optimized so that compressive strength doesn't drop (Ali et al., 2025; Jiang et al., 2025).

Table 3. The Result of Flexural Strenght (Mpa)

Code	Test Object Fs' (Mpa)			Average Fs'
	1	2	3	
BN 0%	6,78	5,58	6,78	6
BK 7,5%	5,29	6,1	4,4	5
BK 15%	6,17	4,3	5,58	5
BK 22,5%	5,29	5,31	5,1	5
BK 30%	6,17	5,58	5,56	6

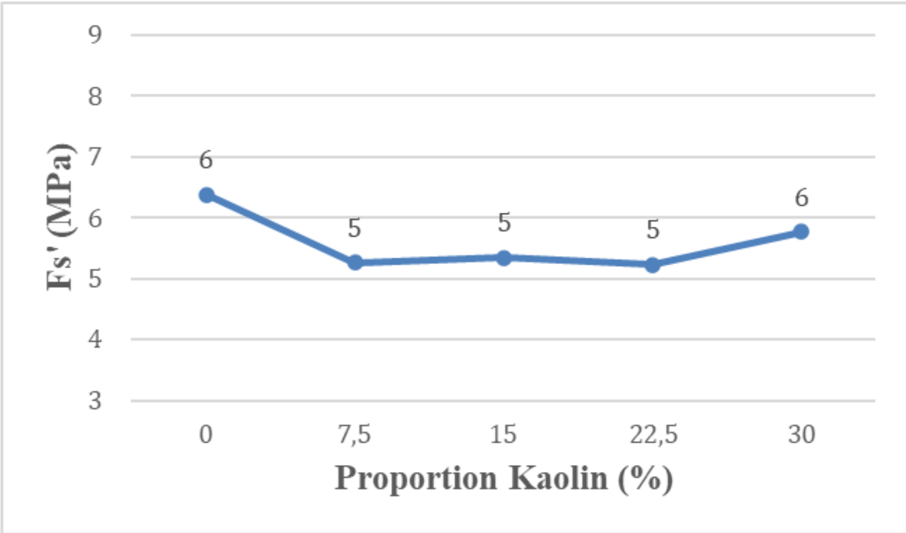


Figure 5. Result Flexural Strenght (Fs')

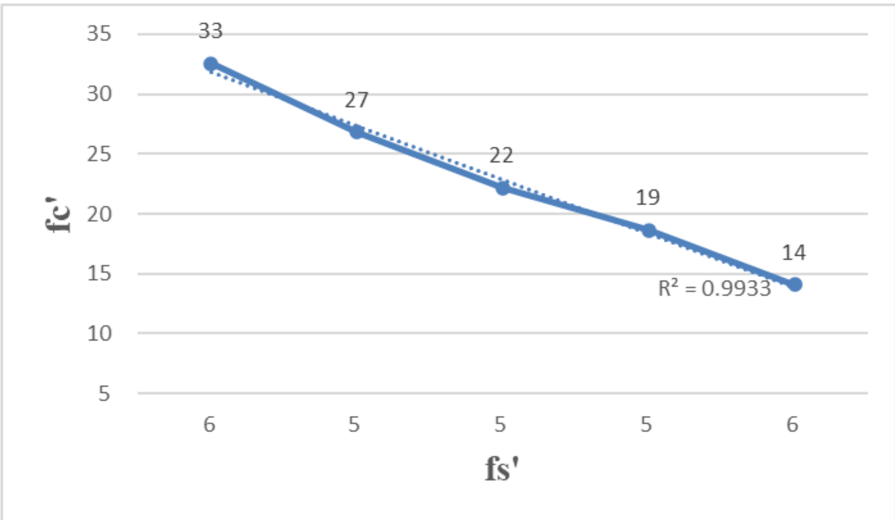


Figure 6. The Corelation between flexural strength and compressive strength

The graph indicates a marked reduction in compressive strength as the kaolin content in the mixture increased. However, the flexural strength remained relatively stable within the range of 5–6 MPa. This suggests that the decrease in compressive strength was not accompanied by a proportional reduction in flexural strength. Compressive strength is generally more sensitive to the quality and density of the cementitious matrix, which may be affected by the reduced formation of hydration products and the partial replacement of cement with kaolin. In contrast, flexural strength is more strongly influenced by crack-bridging capacity, aggregate distribution, and the interfacial bond between the cement paste and aggregates. Therefore, although the incorporation of kaolin reduced compressive strength, the flexural performance of the concrete was relatively preserved.

Conclusion

The use of kaolin as a partial cement replacement affected the fresh concrete mix and its mechanical properties. The slump values decreased with increasing kaolin content, indicating reduced workability due to the fine particles size and high specific surface area of kaolin, which increased the water demand of the mixture. The compressive strength also decreased as the kaolin replacement level increased, from 33 MPa in the control mixture to 27 MPa, 22 MPa, 19 MPa, and 14 MPa for the 7.5%, 15%, 22.5%, and 30% kaolin mixtures, respectively. Adding 7.5% kaolin still meets the planned compressive strength, but more research is needed on kaolin proportions less than 7.5%. Increasing the proportion of kaolin can reduce compressive strength; this is attributed to a decrease in active cement content and an increase in porosity.

This trend suggests that raw kaolin was not able to fully substitute Portland cement as themain binder, especially at higher replacement levels. However, the flexural strength remained relatively stable within the range of 5–6 MPa, indicating that kaolin did not significantly impair the bending performance of concrete. This behavior may be associated with the filler effect of fine kaolin particles, which can fill voids within the concrete matrix and help maintain its internal compactness and flexural resistance.

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Author Contributions

Conceptualization, D.S.L.W.G.; Methodology, W.S.; Software, W.S and D.L.G.; Validation, W.S and D.L.G.; Formal Analysis, W.S.; Investigation, D.S.L.W.G.; Resources, W.S and D.L.G.; Data Curation, D.L.G.; Writing – Original Draft Preparation, D.S.L.W.G.; Writing – Review & Editing, D.S.L.W.G.; Visualization, D.L.G.; Supervision, W.S.; Project Administration, D.L.G.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

The datasets generated during and/ or analyzedduring the current study are available from the corresponding author on reasonable request.

Use of Generative AI

No generative AI was used.

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