Technema: Journal of Intelligent Engineering and Computing
Vol 1 No 2 June 2026, Hal 389-404
ISSN: 3163-6020 (Print) ISSN: 3163-5997 (Electronic)
Open Access: https://sovereignresearch.org/technema

Mechanical Properties Analysis of Concrete Using Grouting Cement and Wood Charcoal as Cement Substitutes

Ilham Akbar Arrafi[1*], Amin Nur Rokhim[2], Antonius[3], Muhamad Rusli Ahyar[4]
[1-4] Universitas Islam Sultan Agung Semarang, Indonesia
email: *ilhamarrafiakbar@gmail.com*[1]

Article Info :
Received:
09-06-2026
Revised:
22-06-2026
Accepted:
29-06-2026

Abstract

Concrete is one of the most widely used construction materials in infrastructure development, yet the extensive use of Portland cement contributes substantially to carbon dioxide emissions from cement production. This study investigates grouting cement and wood charcoal as partial cement substitutes in K-300 concrete to reduce conventional cement consumption while utilizing wood-derived waste. An experimental study was conducted at the Material Mechanics Laboratory, Faculty of Engineering, Universitas Islam Sultan Agung, using substitution levels of 0%, 5% (2.5% grouting cement and 2.5% wood charcoal), and 10% (7.5% grouting cement and 2.5% wood charcoal). Cylindrical specimens measuring 150 × 300 mm were used for compressive and splitting tensile tests, while 600 × 150 × 150 mm beams were used for flexural testing at 7 and 28 days. The results showed that the 5% substitution provided the best mechanical performance at 28 days, achieving an average compressive strength of 19.398 MPa, an 18.26% increase over normal concrete, splitting tensile strength of 2.900 MPa, a 45.73% increase, and flexural strength of 3.029 MPa, a 3.73% increase. The 10% substitution reduced mechanical performance, indicating that excessive carbonaceous material may hinder effective cementitious matrix development. The findings identify 5% substitution as the most favorable composition under the investigated conditions. The results provide an empirical basis for optimizing alternative cementitious materials while maintaining acceptable fresh-concrete workability and mechanical performance.

Keywords: *Concrete Compressive Strength, Concrete Flexural Strength, Concrete Splitting Tensile Strength, Grouting Cement, Wood Charcoal.*

INTRODUCTION

Concrete remains one of the most widely selected structural materials in construction because of its workability and capacity to sustain substantial loads across diverse infrastructure applications. Concrete is fundamentally formed from Portland cement, fine aggregate, coarse aggregate, and water, which develop into a dense, rock-like mass after hardening, while the characteristics of each constituent influence the resulting quality and mechanical performance. Aggregate represents the dominant fraction of a conventional concrete mixture, making the physical and mechanical characteristics of its constituent materials important considerations in concrete design. From a mechanical perspective, concrete possesses relatively high compressive strength but comparatively limited resistance to tensile and flexural stresses, creating a continuing need to optimize its constituent materials and mixture proportions. Recent concrete-material research has increasingly moved toward the utilization of alternative materials that can partially replace conventional cement while maintaining satisfactory engineering performance (Andaryati et al., 2026). This development reflects a broader transition in construction-material engineering toward resource efficiency, waste utilization, and reduced dependence on conventional cementitious materials. The central challenge is therefore no longer limited to achieving adequate concrete strength, but also involves identifying alternative constituents that can provide functional mechanical performance while contributing to more sustainable material utilization.

Environmental considerations provide an important background for this research because the extensive use of Portland cement is associated with considerable environmental burdens arising from cement production. The search for alternative materials has increasingly emphasized waste-derived resources that can be incorporated into concrete as partial cement substitutes without compromising its intended structural function. This research uses grouting cement, specifically Sika Grout New 125, which is characterized by non-shrink behavior, high flowability, and suitability for applications such as machine-foundation strengthening and repair of deteriorated concrete. Cementitious grouts possess specific composition and performance requirements because their applications demand effective filling, dimensional stability, load transfer, and mechanical integrity (da Rocha Gomes et al., 2023). Experimental research has demonstrated that the compressive strength and mechanical properties of cement-based grout are influenced by mixture characteristics and specimen dimensions, indicating that grout-based materials require specific consideration in mechanical-performance evaluation (Bing & Yuan, 2023). Alongside grouting cement, this research utilizes wood charcoal as a partial cement substitute because charcoal-derived materials represent a potentially useful biomass resource that remains insufficiently utilized in construction applications. The incorporation of charcoal is particularly relevant because its mineral constituents may participate in reactions within the cementitious matrix and potentially influence the formation and development of hydration products.

The potential of charcoal-derived materials as cement substitutes has been demonstrated by recent studies, although their effects on concrete performance vary according to material characteristics, processing conditions, and replacement levels. Chiadighikaobi et al. (2024) reported that wood black charcoal powder used as a cement replacement affected the physicomechanical properties of bio-concrete, demonstrating the feasibility of integrating charcoal-derived material into cement-based composites. Carbon-based materials have also been investigated in grout systems, where their incorporation has been associated with changes in pre-hardened shrinkage behavior, suggesting that their influence may extend to the early stages of cementitious development (Lee et al., 2024). Research on biochar has further demonstrated that carbonaceous materials can influence compressive strength and fracture performance, indicating that their role may involve both physical and microstructural interactions within concrete (Qing et al., 2023). The response of cementitious composites to charcoal-derived materials is not uniform because characteristics such as particle size, porosity, surface properties, feedstock, and processing conditions can substantially alter their interaction with cement. Hylton et al. (2024) specifically demonstrated that biochar characteristics are relevant to the compressive strength of biochar-cement mortars, reinforcing the need to consider material-specific behavior when determining suitable replacement levels. Recent evidence also indicates that char derived from different sources can modify both mechanical performance and microstructural characteristics of concrete, further emphasizing the importance of controlling material properties and mixture proportions (Dipta et al., 2025). These findings establish that charcoal-based substitution has potential as a sustainable material strategy, but its mechanical effectiveness must be established experimentally for each specific material and concrete system.

Evidence from previous studies provides a particularly important basis for examining the relationship between charcoal content and concrete strength. Irfandi et al. (2025) identified an optimum charcoal powder replacement level of 3% in K-175 concrete, at which the compressive strength reached 16.620 MPa, indicating that a relatively low substitution level may provide a favorable balance between cement reduction and mechanical performance. In contrast, Akmal (2024) reported a consistent decrease in compressive strength as wood charcoal powder substitution increased from 0% to 6%, demonstrating that increasing the proportion of charcoal does not necessarily produce a corresponding improvement in concrete strength. Research using wood charcoal ash has likewise shown that charcoal-derived material can modify the compressive strength of normal concrete, although its effect depends on the quantity and characteristics of the incorporated material (William et al., 2023). Recent research on wood ash has provided further evidence that biomass-derived ash can function as an alternative cement-replacement material and, under an optimized proportion, improve compressive and splitting tensile performance while contributing to waste utilization (Shah et al., 2025). As a comparative finding, Haslinda (2020) obtained a maximum compressive strength of 21.87 MPa from a concrete mixture incorporating trass and grouting cement, indicating that the use of grouting cement with supplementary materials can produce meaningful changes in concrete strength. Other research has explored the incorporation of charcoal into concrete together with additional wood-based materials, but the mechanical response remains dependent on the specific material combination and mixture composition (Jeni, 2025). The contrasting findings demonstrate that the optimum charcoal replacement level cannot be generalized across concrete systems and that the interaction between charcoal-derived material and specialized cementitious binders remains insufficiently established.

The inconsistency in previous findings establishes a scientific and practical need to investigate grouting cement and wood charcoal within a single controlled concrete system. Existing research has predominantly evaluated charcoal, biochar, wood ash, or other carbon-based materials separately from specialized grouting cement, leaving limited empirical evidence concerning their simultaneous use as partial cement substitutes in structural concrete. This gap is important because charcoal incorporation can affect particle packing, pore structure, hydration behavior, and interfacial characteristics, whereas grouting cement possesses a formulation specifically developed for flowability and dimensional stability. The resulting mechanical behavior may therefore differ from that observed when charcoal is introduced into conventional Portland-cement concrete alone. A meta-analysis based on 606 paired observations demonstrated that biochar effects on compressive strength depend on feedstock type, pyrolysis conditions, particle size, dosage, curing conditions, and mixture design, confirming that the performance of carbon-based cement substitutes is highly context dependent (Zhao et al., 2024). Research on sustainable concrete grouts has likewise demonstrated the feasibility of incorporating alternative cementitious materials into grout-based systems, indicating the potential of specialized grout for more sustainable composite formulations (Saleh et al., 2025). Indonesian research concerning wood-derived materials has also produced varied strength responses, indicating that material utilization must be evaluated according to the specific residue characteristics, replacement level, and concrete composition rather than through generalized assumptions (Sihotang, 2025). Establishing the mechanical interaction between grouting cement and wood charcoal is therefore necessary to determine whether this combination can reduce conventional cement utilization while maintaining the performance expected from K-300 concrete.

Positioned within this research landscape, the present study investigates the combined use of grouting cement and wood charcoal as partial substitutes for cement in K-300 concrete. The study aims to analyze the influence of these substitutions on compressive strength, tensile strength, and flexural strength at concrete ages of 7 and 28 days. The experimental mixture proportions are established using the applicable Indonesian concrete mix-design provisions to ensure systematic comparison among the investigated compositions. Compressive strength is evaluated using the standardized procedure for testing cylindrical concrete specimens, while tensile performance is assessed through the applicable splitting-tensile testing method. Flexural strength is also considered to provide a broader representation of mechanical performance because the behavior of concrete under bending cannot be fully represented by compressive strength alone. The study further seeks to determine the optimum substitution composition by comparing strength development at early and later curing ages. Theoretically, this research contributes empirical evidence concerning the interaction between grouting cement and wood charcoal within a K-300 concrete matrix, while methodologically it provides a comparative framework for evaluating multiple mechanical properties across different curing periods. Practically, the findings are expected to support the development of alternative concrete formulations that utilize wood charcoal as a potential cement-replacement material while maintaining appropriate mechanical performance for construction applications.

RESEARCH METHODS

This study employed an empirical experimental design conducted at the Material Mechanics Laboratory, Faculty of Engineering, Universitas Islam Sultan Agung, Semarang, to investigate the mechanical properties of K-300 concrete incorporating grouting cement and wood charcoal as partial cement substitutes. The experimental materials consisted of Portland cement (Gresik), natural sand obtained from the Merapi area, coarse aggregate, laboratory water, Sika Grout New 125 grouting cement, wood charcoal produced through incomplete combustion, and Besmitel superplasticizer, while the main equipment included a digital balance with 1-g accuracy, vibrating aggregate sieves, measuring cylinders, cylindrical and beam molds, and a compression testing machine. Three concrete mixture groups were prepared, consisting of normal concrete as the control and two substitution variations containing different proportions of grouting cement and wood charcoal relative to the cement mass. The mixture proportions were established based on the applicable Indonesian concrete mix-design standard, with normal concrete designed as K-300 and the material quantities for each mixture maintained according to the specified job mix design (Badan Standardisasi Nasional, 2000). Cylindrical specimens measuring 150 mm in diameter and 300 mm in height were prepared for compressive and splitting-tensile strength tests, while beam specimens measuring 600 × 150 × 150 mm were prepared for flexural-strength testing. Each material was weighed according to the predetermined mixture proportions, followed by mixing until a homogeneous fresh concrete mixture was obtained, placement into the corresponding molds, and curing until the designated testing ages of 7 and 28 days. The overall implementation consisted of material preparation, aggregate preparation, material weighing, mixing, slump testing, specimen casting, curing, and mechanical testing, as illustrated in Figure 1.

Table 1. Job Mix Design for Each Concrete Variation

No.	Composition	Cement (kg)	Besmitel (L)	Sand (kg)	Wood Charcoal (kg)	Grouting Cement (kg)	Coarse Aggregate (kg)	Water (L)
1	Normal	2.189	–	3.275	–	–	5.441	1.14
2	Variation 1	2.079	0.017 (1%)	3.275	0.054725	0.054725	5.441	1.14
3	Variation 2	1.970	0.016 (1%)	3.275	0.054725	0.329	5.441	1.14

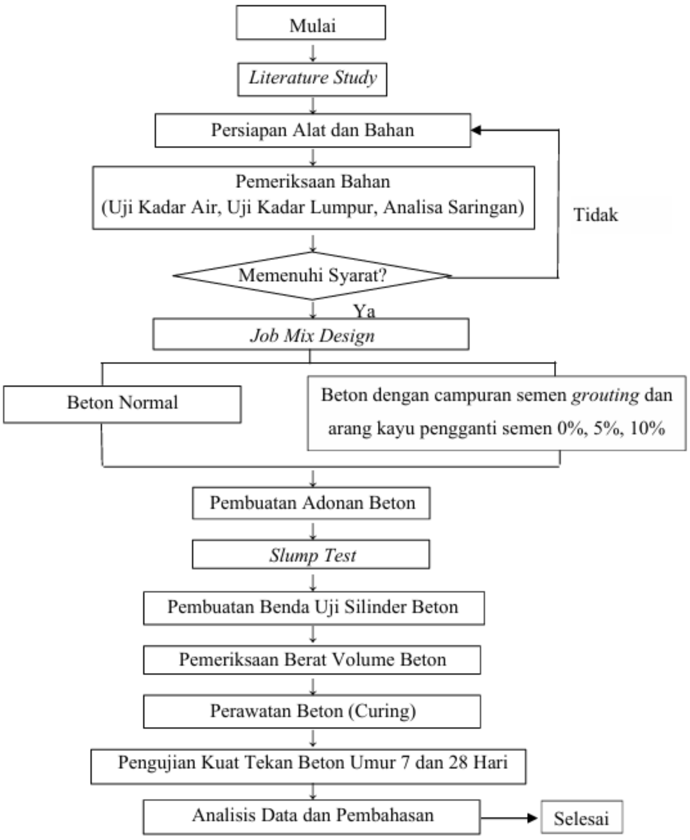

Figure 1. Research Flowchart

The experimental evaluation was conducted through compressive-strength, splitting-tensile-strength, and flexural-strength tests at 7 and 28 days to determine the mechanical development of each concrete composition. Compressive strength was measured using cylindrical specimens in accordance with SNI 1974:2011, with the maximum applied load converted into compressive stress based on the specimen cross-sectional area (Badan Standardisasi Nasional, 2011). Splitting tensile strength was determined using cylindrical specimens according to SNI 2491:2014 to quantify the tensile resistance of the concrete under indirect tensile loading (Badan Standardisasi Nasional, 2014). Flexural strength was evaluated using beam specimens with a 450-mm effective span under two-point loading, and the corresponding failure load was used to determine the flexural capacity of each mixture. Fresh-concrete workability was assessed using the slump test for all mixtures, with a target range of 8–12 cm established to ensure that the mixtures could be properly placed and compacted. Experimental validation was performed by comparing the substitution mixtures with the normal-concrete control and by examining the change in each mechanical parameter between 7 and 28 days, thereby enabling the influence of grouting cement and wood charcoal to be evaluated systematically. Performance was quantified using compressive strength, splitting tensile strength, flexural strength, and slump as the principal evaluation metrics, while the optimum composition was determined from the mixture exhibiting the most favorable overall mechanical performance while maintaining acceptable fresh-concrete workability.

RESULTS AND DISCUSSION

Compressive Strength of Concrete

The compressive-strength results demonstrate a distinct age-dependent response to the incorporation of grouting cement and wood charcoal, with the influence of the substitution ratio changing between the early and later curing stages. At 7 days, the normal concrete (BN) achieved the highest average compressive strength of 15.308 MPa, whereas BM 5% and BM 10% reached 13.120 MPa and 12.320 MPa, respectively. As presented in Table 2, the corresponding reductions relative to BN were 14.29% for BM 5% and 19.52% for BM 10%, indicating that the substitution system did not immediately provide a mechanical advantage during early hydration. This pattern is consistent with the general behavior of cementitious composites containing carbonaceous or biochar-based materials, whose effects depend strongly on particle characteristics, replacement level, dispersion, and the stage of cement hydration (Zhao et al., 2024). The individual specimen results also show measurable variability within each mixture, with compressive strengths ranging from 10.408 to 18.310 MPa for BN, 11.976 to 14.159 MPa for BM 5%, and 11.613 to 13.117 MPa for BM 10%. Such variation indicates that the early-age response was controlled not only by the nominal substitution percentage but also by the interaction between the modified binder phase, water availability, and specimen-level material distribution.

Table 2. Compressive Strength Test Results of Concrete at 7 Days

No.	Specimen	Age (days)	Weight (kg)	Compressive Load (P) (kN)	Actual Cylinder Strength (MPa)	Average Compressive Strength (MPa)
1	BN 1	7	12.22	183.921	10.408	15.308
2	BN 2	7	12.06	305.295	17.267	
3	BN 3	7	11.93	323.563	18.31	
4	BM 1 (5%)	7	11.99	233.742	13.227	13.120
5	BM 2 (5%)	7	11.82	250.207	14.159	
6	BM 3 (5%)	7	11.93	211.630	11.976	
7	BM 1 (10%)	7	12.12	205.224	11.613	12.320
8	BM 2 (10%)	7	11.94	216.422	12.247	
9	BM 3 (10%)	7	12.18	231.796	13.117	

The downward progression from BN to BM 5% and BM 10% at 7 days can be interpreted through the competing effects of cement dilution and the relatively slow development of secondary binding products associated with charcoal-derived silica. Wood charcoal is not equivalent to a highly reactive pozzolan solely because it contains SiO_2, since its reactivity is also governed by mineral composition, particle fineness, surface characteristics, and the proportion of carbonaceous material remaining after combustion (Hylton et al., 2024). The early reduction is therefore more plausibly associated with the replacement of a portion of Portland cement by a less immediately reactive material than with a failure of the charcoal to contribute to the hardened matrix altogether. Comparable evidence has shown that biochar and charcoal-based materials can produce either strength enhancement or strength reduction depending on their dosage and physicochemical characteristics (Qing et al., 2023). The 7-day results in Figure 2 reinforce this dosage-dependent behavior, as increasing the substitution level from 5% to 10% produced a further 6.10% reduction relative to BM 5%. This response suggests that the initial contribution of the modified binder system remained insufficient to compensate for the reduction in the amount of conventional cementitious material participating directly in early hydration.

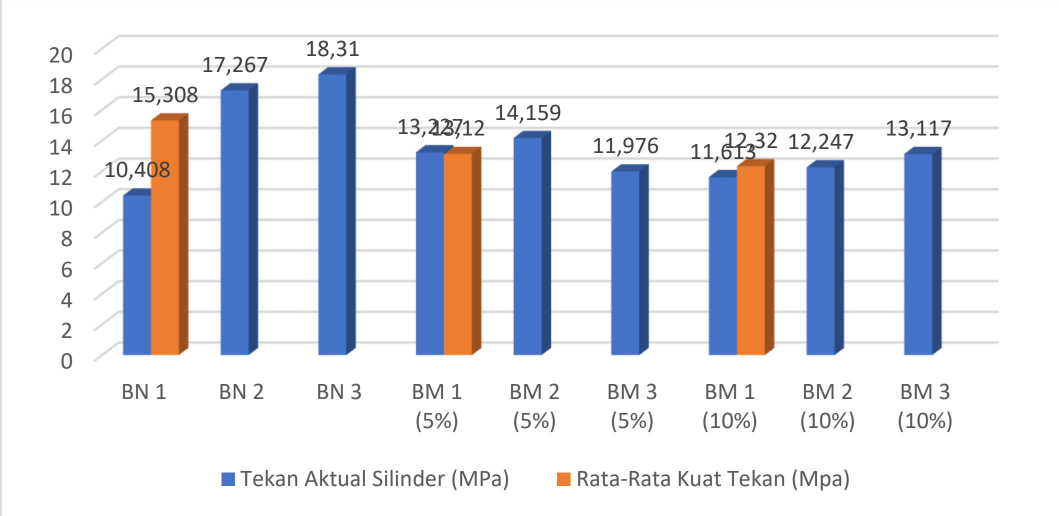

Figure 2. Comparison of Concrete Compressive Strength among Variations at 7 Days

The mechanical response changed substantially after 28 days of curing, when BM 5% became the strongest mixture rather than the control concrete. The normal concrete reached an average compressive strength of 16.403 MPa, while BM 5% increased to 19.398 MPa and BM 10% reached only 14.589 MPa. The data in Table 3 indicate that BM 5% exceeded BN by 18.26%, whereas BM 10% remained 11.06% below the control, establishing a clear optimum at the intermediate substitution level. The six BM 5% specimens produced values between 15.496 and 24.114 MPa, with the highest individual result substantially exceeding the control-group range, suggesting that the modified mixture was capable of developing a denser or more mechanically effective matrix under favorable specimen conditions. This delayed improvement is compatible with evidence that carbonaceous additions may influence cement composites through longer-term microstructural modification rather than exclusively through early-age hydration effects (Dipta et al., 2025). The reversal between the 7-day and 28-day rankings is particularly important because it indicates that evaluation based only on early-age strength would underestimate the potential contribution of the 5% substitution mixture.

Table 3. Compressive Strength Test Results of Concrete at 28 Days

No.	Specimen	Age (days)	Weight (kg)	Compressive Load (P) (kN)	Actual Cylinder Strength (MPa)	Average Compressive Strength (MPa)
1	BN 1	28	12.25	213.480	12.081	16.403
2	BN 2	28	12.21	334.809	18.946	
3	BN 3	28	12.36	309.186	17.496	
4	BN 4	28	12.44	328.165	18.570	
5	BN 5	28	12.28	298.747	16.904	
6	BN 6	28	12.10	254.808	14.419	
7	BM 1 (5%)	28	12.00	273.836	15.496	19.398
8	BM 2 (5%)	28	12.20	324.227	18.347	
9	BM 3 (5%)	28	13.35	399.054	22.582	
10	BM 4 (5%)	28	12.20	354.452	20.058	
11	BM 5 (5%)	28	12.36	426.125	24.114	
12	BM 6 (5%)	28	12.50	279.055	15.791	
13	BM 1 (10%)	28	12.63	240.478	13.608	14.589
14	BM 2 (10%)	28	12.32	262.875	14.876	
15	BM 3 (10%)	28	12.28	286.837	16.232	
16	BM 4 (10%)	28	12.44	279.956	15.842	
17	BM 5 (10%)	28	12.40	239.055	13.528	
18	BM 6 (10%)	28	12.30	237.631	13.449	

The contrasting performance of BM 5% and BM 10% at 28 days indicates that the mechanical benefit of charcoal-containing cement replacement is not linearly proportional to the amount of substituted material. At the 5% level, the combination appears to provide a favorable balance between the amount of remaining Portland cement and the secondary contribution of the charcoal-containing fraction, whereas the 10% level introduces a larger reduction in conventional cementitious content that is not sufficiently compensated by secondary reactions. Research on wood charcoal powder has similarly identified dosage as a critical determinant of concrete compressive performance, with excessive replacement capable of reversing the benefits obtained at lower proportions (Chiadighikaobi et al., 2024). The result also corresponds with the broader meta-analytic evidence that biochar effects on Portland-cement composites are highly heterogeneous and depend on material properties and incorporation conditions rather than following a universal positive or negative trend (Zhao et al., 2024). The role of grouting cement should also be considered because cementitious grouts are formulated to provide specialized flow, dimensional stability, and mechanical performance, meaning that their incorporation can alter the binder system differently from ordinary Portland cement replacement (da Rocha Gomes et al., 2023). The observed BM 5% optimum therefore reflects an interaction between substitution level and binder composition rather than the isolated effect of wood charcoal.

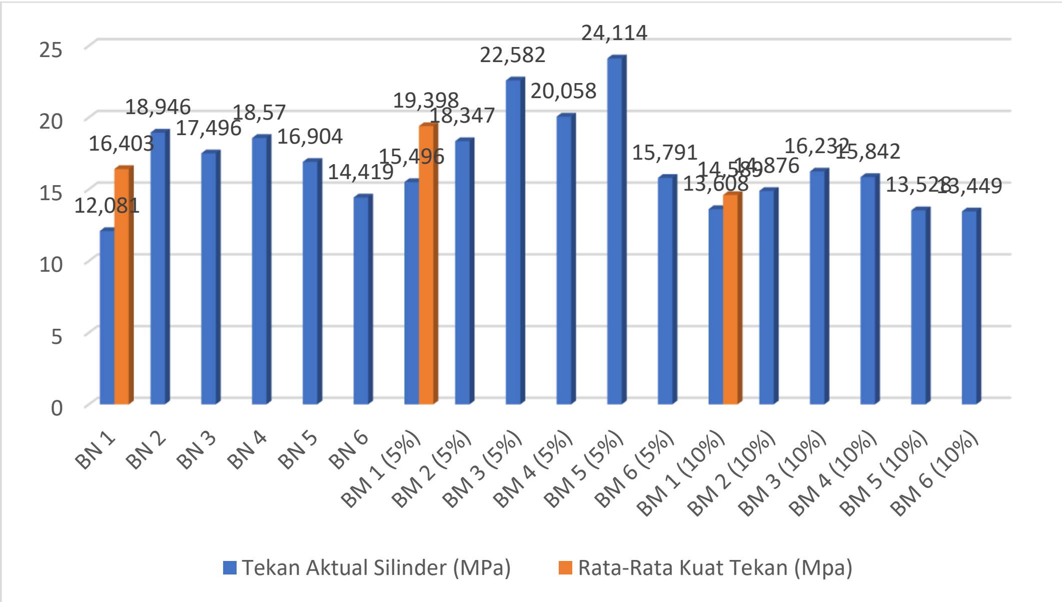

Figure 3. Comparison of Concrete Compressive Strength among Variations at 28 Days

The comparison between curing ages provides stronger evidence of the developmental mechanism underlying the observed strength pattern. BN increased from 15.308 MPa at 7 days to 16.403 MPa at 28 days, corresponding to a 7.15% increase, whereas BM 5% rose from 13.120 to 19.398 MPa, representing an increase of approximately 47.85%. BM 10% also increased from 12.320 to 14.589 MPa, but its 18.42% improvement was insufficient to surpass the control mixture. The markedly larger age-related gain in BM 5% suggests that the modified mixture experienced a delayed contribution to matrix strengthening, potentially through continued hydration and secondary reactions involving reactive mineral constituents of the charcoal fraction. Studies on biochar-cement systems have emphasized that the physical and chemical characteristics of biochar, including porosity and surface properties, can modify hydration products and the internal structure of cement-based materials (Hylton et al., 2024). The data therefore support an interpretation in which 5% substitution produces a favorable temporal balance between early cement hydration and later matrix development, whereas 10% substitution crosses a threshold at which cement dilution and possible agglomeration or pore-related effects become dominant.

The optimum compressive-strength performance at 5% substitution is also relevant when positioned against previous experimental findings using charcoal and related carbonaceous materials. Irfandi et al. (2025) reported an optimum charcoal powder replacement of 3% for K-175 concrete, while

Akmal (2024) identified a reduction in compressive performance as charcoal powder content increased under his experimental conditions. William et al. (2023) likewise demonstrated that wood charcoal ash can alter the compressive strength of normal concrete, confirming that carbonaceous cement substitutes can produce composition-dependent mechanical responses rather than a uniform effect. The present results extend these findings by demonstrating that an intermediate 5% combination of grouting cement and wood charcoal can produce a higher 28-day compressive strength than the untreated control in K-300 concrete, while a 10% substitution level reduces performance. Differences from earlier optimum levels are scientifically plausible because charcoal source, processing condition, particle characteristics, concrete strength class, binder composition, and replacement configuration differ among studies. Evidence from sustainable cement-replacement research further indicates that alternative biomass-derived materials can contribute to cement reduction when their dosage and interaction with the cementitious matrix are appropriately controlled (Shah et al., 2025). The present dataset therefore positions 5% as the experimentally supported optimum for compressive strength within the specific material combination and mix proportions investigated, rather than as a universal optimum for all charcoal-modified concrete.

Overall, the compressive-strength results establish a non-linear relationship between substitution level and mechanical performance, characterized by an initial reduction at 7 days, a substantial recovery by 28 days, and a pronounced optimum at 5% substitution. The 19.398 MPa achieved by BM 5% represents the highest average compressive strength among the tested mixtures and is 18.26% higher than the 16.403 MPa obtained by normal concrete at 28 days. The 10% mixture, in contrast, produced 14.589 MPa, confirming that increasing the replacement level beyond the optimum does not continuously improve the concrete matrix. This behavior is consistent with the principle that sustainable cement substitution requires an appropriate balance between cement reduction and the physicochemical contribution of the substitute material, rather than maximizing the replacement quantity (Andaryati et al., 2026). From a materials-engineering perspective, the findings indicate that the combined use of grouting cement and wood charcoal has potential for improving later-age compressive performance when the substitution level is carefully controlled. The experimental evidence also demonstrates why curing age must be incorporated into the assessment of alternative cementitious materials, since the relative ranking of the mixtures at 7 days differed substantially from that observed at 28 days. Within the tested formulations, the 5% mixture provides the most favorable compressive-strength response and becomes the principal candidate for further evaluation against splitting tensile strength, flexural strength, and fresh-concrete workability.

Splitting Tensile Strength of Concrete

The splitting tensile-strength test at 28 days reveals that the incorporation of grouting cement and wood charcoal produced a non-linear response across the three concrete compositions. As presented in Table 4, the normal concrete recorded an average splitting tensile strength of 1.990 MPa, while BM 5% reached 2.900 MPa and BM 10% reached 2.108 MPa. The BM 5% mixture therefore achieved an increase of approximately 45.73% relative to the normal concrete, representing the most substantial improvement among the tested compositions. The individual measurements also demonstrate that the BM 5% specimens consistently produced higher values than the control, with strengths ranging from 2.784 to 3.028 MPa. This pattern indicates that the intermediate substitution level was more effective in improving tensile resistance than the higher replacement level, suggesting the existence of a dosage-dependent interaction between the modified binder and the concrete matrix. Previous research has similarly demonstrated that the mechanical response of charcoal- and biochar-modified cement composites is strongly dependent on the quantity and characteristics of the carbonaceous material incorporated into the cementitious system (Chiadighikaobi et al., 2024).

Table 4. Splitting Tensile Strength Test Results of Concrete

No.	Specimen	Age (days)	Weight (kg)	Applied Load (P) (kN)	Actual Cylinder Strength (MPa)	Average Splitting Tensile Strength (MPa)
1	BN 1	28	11.90	146.385	2.071	1.990
2	BN 2	28	12.00	114.524	1.620	

.

3	BN 3	28	11.90	161.239	2.281	
4	BM 1 (5%)	28	11.92	205.006	2.902	2.900
5	BM 2 (5%)	28	11.82	196.668	2.784	
6	BM 3 (5%)	28	11.75	213.896	3.028	
7	BM 1 (10%)	28	12.00	155.428	2.201	2.108
8	BM 2 (10%)	28	11.62	128.033	1.813	
9	BM 3 (10%)	28	11.70	163.287	2.311	

The improvement observed at the 5% substitution level can be interpreted through the combined physical and chemical effects of the wood-charcoal fraction within the hardened cement matrix. Fine carbonaceous particles may occupy voids between cementitious particles and modify the internal packing structure, while reactive mineral constituents can participate in secondary reactions that contribute to the development of additional binding phases. Hylton et al. (2024) emphasized that biochar characteristics such as particle size, porosity, surface area, and ash composition can substantially influence the compressive behavior of biochar-cement composites, which also provides a relevant basis for interpreting tensile behavior. In the present mixture, the 5% dosage appears sufficiently low to retain an adequate quantity of Portland cement while providing a supplementary particulate phase capable of improving matrix continuity. The resulting reduction in internal discontinuities may improve stress transfer across the cement paste and aggregate interface, which is particularly relevant under indirect tensile loading. The 10% mixture, however, produced only 2.108 MPa, indicating that increasing the substitution level did not proportionally increase the beneficial effects of the charcoal fraction.

The difference between BM 5% and BM 10% is particularly informative because both mixtures contain the same wood-charcoal quantity in the reported job mix design but differ substantially in the amount of grouting cement replacing Portland cement. BM 5% contains 0.054725 kg of grouting cement, whereas BM 10% contains 0.329 kg, while the wood-charcoal content remains 0.054725 kg for both formulations. This compositional difference indicates that the decline in tensile performance at BM 10% cannot be attributed solely to an increase in wood-charcoal content and should instead be interpreted as a consequence of the overall binder modification. Cement-based grout systems possess specific compositional and rheological characteristics that influence their interaction with the cementitious matrix, and their performance depends on mixture formulation and application conditions (da Rocha Gomes et al., 2023). The BM 5% composition may therefore provide a more favorable balance between conventional cement hydration and the contribution of the modified grout-charcoal system. The result also supports the interpretation that partial cement replacement should be optimized through the interaction of all substituted constituents rather than evaluated from the charcoal proportion in isolation. Such an interpretation is important because previous studies have reported both strength enhancement and strength deterioration depending on the proportion and processing characteristics of carbon-based cement substitutes (Qing et al., 2023).

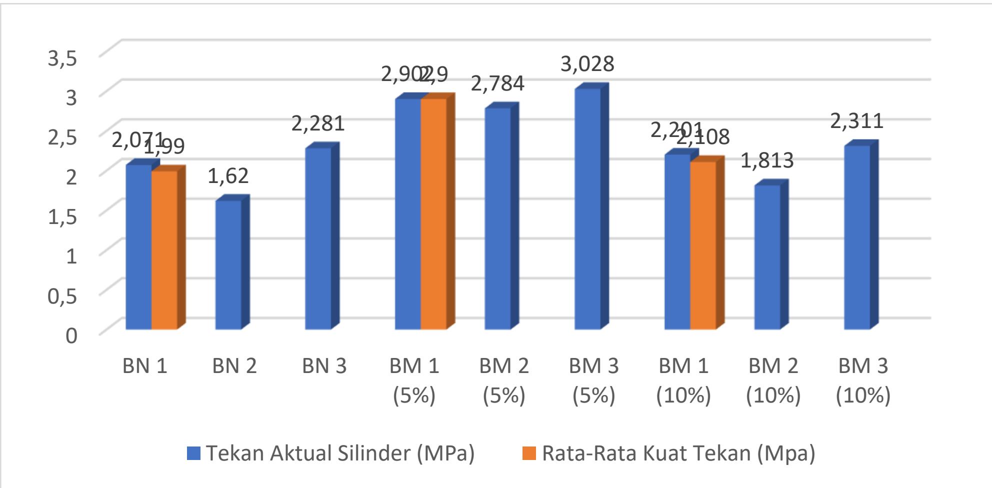

Figure 4. Comparison of Concrete Splitting Tensile Strength among Variations

The tensile-strength pattern also corresponds closely with the compressive-strength behavior observed at 28 days, where BM 5% was the strongest composition and BM 10% exhibited a substantial reduction. The normal concrete recorded 1.990 MPa, BM 5% reached 2.900 MPa, and BM 10% reached 2.108 MPa, producing a clear ranking of BM 5% > BM 10% > BN. The consistency between the two mechanical indicators suggests that the BM 5% mixture developed a more effective hardened matrix rather than improving only one isolated failure mode. This interpretation is supported by the finding that carbonaceous materials can affect both pore characteristics and cement-matrix development, with their influence depending strongly on dosage and material properties (Zhao et al., 2024). The BM 10% mixture remained slightly stronger in tension than the normal concrete, but its performance was approximately 27.31% lower than BM 5%, demonstrating that the mechanical advantage obtained at the intermediate composition was not maintained when the binder modification was increased. The result provides evidence of an optimum region rather than a monotonic relationship between substitution and mechanical resistance. It also highlights the importance of assessing tensile properties independently because compressive strength alone cannot fully represent the cracking resistance of concrete.

Comparison with earlier studies further supports the dosage-dependent interpretation of the present findings. Akmal (2024) reported that wood-charcoal powder substitution can substantially influence both compressive and splitting tensile strength, with the response dependent on the substitution level and material characteristics. William et al. (2023) similarly demonstrated that wood-charcoal ash affects the compressive behavior of normal concrete, indicating that carbon-derived materials can modify the cement matrix through mechanisms extending beyond simple cement dilution. Research on other biomass-derived charcoal materials has also shown that partial cement replacement can modify concrete performance when the replacement proportion is appropriately controlled (Jeni, 2025). The 45.73% improvement obtained by BM 5% in the present study is therefore consistent with the broader evidence that moderate incorporation of carbonaceous materials can improve selected mechanical properties, although the magnitude of improvement varies substantially among materials and mix designs. The difference between the present optimum and optimum levels reported elsewhere is scientifically reasonable because the current system combines Sika Grout New 125 with wood charcoal rather than evaluating charcoal as an isolated cement substitute. The findings consequently extend existing evidence by showing that the optimum mechanical response can emerge from a specific interaction between grouting cement and wood charcoal rather than from the charcoal content alone.

The tensile results establish BM 5% as the most effective composition for improving the resistance of the concrete to indirect tensile loading at 28 days. Its average strength of 2.900 MPa exceeded the normal mixture by 0.910 MPa, while BM 10% provided only a marginal improvement of 0.118 MPa over the control. The pronounced difference between BM 5% and BM 10% suggests that the beneficial effect of the modified binder is constrained by an optimum composition at which matrix densification and secondary binding effects can compensate for the reduction in Portland cement content. Evidence concerning sustainable cement alternatives indicates that successful replacement strategies depend on controlling the physical and chemical characteristics of the substitute and maintaining an appropriate binder balance (Shah et al., 2025). From a structural-material perspective, the BM 5% result is important because tensile resistance is closely related to crack initiation and propagation, making the improvement relevant to the service behavior of concrete subjected to tensile stresses. The result also reinforces the compressive-strength finding that an intermediate substitution level provides the most favorable mechanical response within the tested formulations. Further interpretation of the overall material performance requires consideration of flexural strength, because tensile and flexural behavior may respond differently to changes in matrix composition.

Flexural Strength of Concrete

The flexural-strength results demonstrate that the influence of grouting cement and wood charcoal on concrete bending resistance was strongly dependent on curing age and substitution level. At 7 days, normal concrete exhibited the highest average flexural strength of 2.740 MPa, followed by BM 10% at 2.540 MPa and BM 5% at 2.114 MPa. As shown in Table 5, BM 5% experienced a reduction of approximately 22.85% relative to the normal concrete, whereas BM 10% was 7.30% lower than the control. This early-age pattern differs from the compressive-strength response, where BM 5% and BM

10% also remained below the control but with a different relative ranking. The results indicate that the modified binder system had not yet developed sufficient matrix continuity to translate the presence of charcoal and grouting cement into improved resistance against flexural loading. Similar age-dependent behavior has been reported for carbonaceous cement composites, where the contribution of biochar to mechanical performance depends on the development of the cementitious matrix and the physicochemical characteristics of the carbon-based particles (Qing et al., 2023).

Table 5. Flexural Strength Test Results of Concrete at 7 Days

No.	Specimen	Age (days)	Weight (kg)	Applied Load (P) (kN)	Actual Strength (MPa)	Average Flexural Strength (MPa)
1	BN 1	7	29.40	13.098	1.746	2.740
2	BN 2	7	29.20	14.921	1.989	
3	BM 1 (5%)	7	30.35	16.964	2.262	2.114
4	BM 2 (5%)	7	30.04	14.747	1.966	
5	BM 1 (10%)	7	30.45	18.825	2.514	2.540
6	BM 2 (10%)	7	30.20	19.272	2.570	

The lower flexural performance of BM 5% at 7 days can be related to the relatively early stage of cement hydration, when the substituted binder components have not yet produced sufficient secondary bonding to compensate for the reduced Portland cement fraction. The presence of carbonaceous particles may also modify the moisture distribution and internal pore structure of the fresh and hardening matrix, producing effects that are not necessarily beneficial during early curing. Hylton et al. (2024) identified particle characteristics and biochar morphology as important factors controlling the interaction between carbonaceous materials and cementitious matrices, particularly through their influence on water demand and microstructural development. In the present experiment, BM 10% nevertheless produced a higher flexural strength than BM 5%, indicating that the relationship between substitution level and early flexural resistance was not monotonic. This difference suggests that the grouting-cement fraction may have contributed to the early mechanical response through its specialized cementitious properties, although its larger proportion did not translate into superior performance at 28 days. The early-age results therefore demonstrate that flexural behavior cannot be inferred directly from the charcoal dosage without considering the complete binder composition.

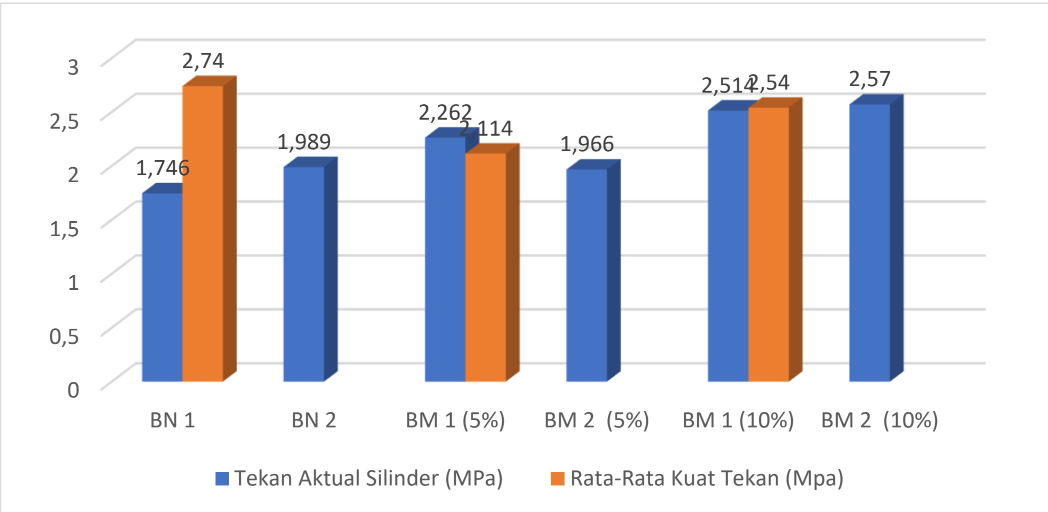

Figure 5. Comparison of Concrete Flexural Strength among Variations at 7 Days

A substantially different pattern emerged after 28 days of curing, when BM 5% became the mixture with the highest average flexural strength. The normal concrete achieved 2.920 MPa, whereas BM 5% reached 3.029 MPa and BM 10% reached only 2.420 MPa. As reported in Table 6, BM 5%

therefore exceeded the normal concrete by approximately 3.73%, while BM 10% was 17.12% lower than the control. The relatively modest improvement of BM 5% compared with the much larger tensile-strength improvement indicates that the influence of the modified binder is mechanical-mode dependent. The increase in flexural resistance at 28 days can be associated with continued hydration and the development of a more integrated cementitious matrix, while the carbonaceous fraction may contribute through pore filling and modification of the interfacial structure. Research on biochar-cement composites indicates that the contribution of carbonaceous materials to hardened properties is sensitive to dosage and microstructural characteristics, which can produce positive effects at moderate replacement levels but adverse effects at excessive levels (Zhao et al., 2024). The reversal in ranking between the early and later curing stages confirms that the mechanical effect of the substitution should be evaluated over an adequate curing period rather than based exclusively on early-age measurements.

Table 6. Flexural Strength Test Results of Concrete at 28 Days

No.	Specimen	Age (days)	Weight (kg)	Applied Load (P) (kN)	Actual Strength (MPa)	Average Flexural Strength (MPa)
1	BN 1	28	30.56	23.539	3.139	2.920
2	BN 2	28	31.66	20.371	2.716	
3	BM 1 (5%)	28	30.15	22.750	3.033	3.029
4	BM 2 (5%)	28	29.33	22.698	3.026	
5	BM 1 (10%)	28	30.23	17.423	2.373	2.420
6	BM 2 (10%)	28	30.19	18.542	2.472	

The comparison between 7- and 28-day flexural strength provides an important indication of the temporal development of the modified concrete matrix. Normal concrete increased from 2.740 to 2.920 MPa, corresponding to a 6.57% increase, while BM 5% increased from 2.114 to 3.029 MPa, representing an increase of approximately 43.28%. BM 10% decreased slightly from 2.540 to 2.420 MPa based on the reported average values, showing that its early flexural advantage over BM 5% did not persist during longer curing. The strong increase observed in BM 5% suggests that the mixture benefited from later-age matrix development that was not yet fully expressed at 7 days. The behavior is compatible with findings that carbon-based additives can affect cement hydration and microstructural characteristics over time, with their final mechanical contribution depending on the interaction between particle properties and cementitious reactions (Dipta et al., 2025). The substantially smaller change in the normal mixture further emphasizes that the modified BM 5% system developed a distinctive curing-age response rather than simply following the ordinary strength-growth trajectory of Portland-cement concrete.

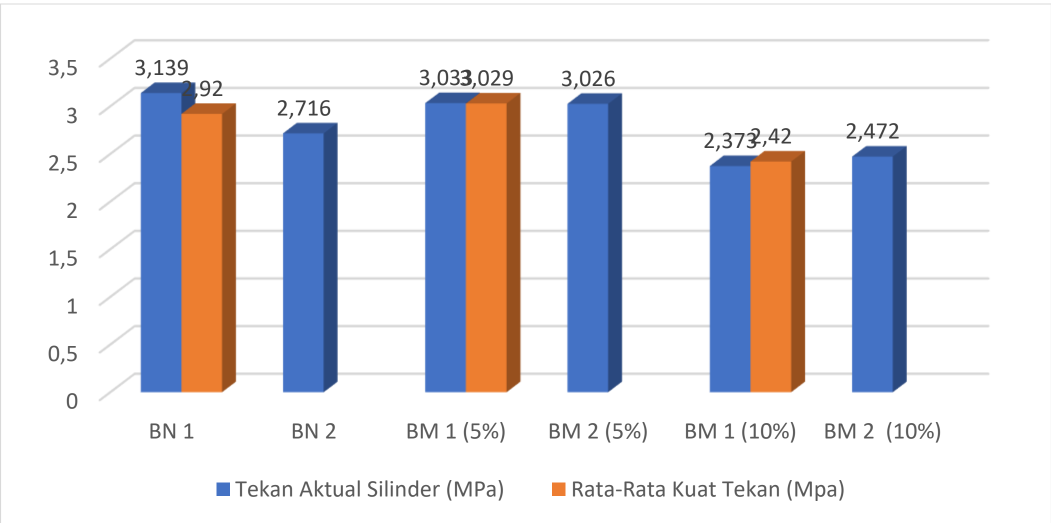

Figure 6. Comparison of Concrete Flexural Strength among Variations at 28 Days

The 28-day flexural results also demonstrate that increasing the substitution level beyond 5% was not beneficial for bending resistance. BM 10% produced an average of 2.420 MPa, which was 20.10% lower than BM 5% and 17.12% lower than the normal concrete. Such a reduction suggests that the higher level of binder modification may have introduced a less favorable balance between cementitious continuity and the physical presence of carbonaceous particles. Previous investigations have shown that excessive carbon-based replacement can reduce mechanical performance when the substitute material does not provide sufficient reactive binding capacity to compensate for the reduction in conventional cement (Akmal, 2024). The present result is also consistent with the broader observation that biochar effects on cement composites vary considerably with dosage, feedstock, processing, and material characteristics (Zhao et al., 2024). BM 5%, in contrast, retained sufficient Portland-cement content while incorporating the modified constituents at a level that produced a small but measurable improvement in flexural capacity. The difference between the two modified mixtures indicates that optimization is more important than maximizing the amount of alternative material incorporated into the concrete.

The flexural-strength findings are broadly consistent with the compressive and splitting-tensile results in identifying BM 5% as the most favorable composition at 28 days. The mixture achieved 3.029 MPa in flexural strength, 19.398 MPa in compressive strength, and 2.900 MPa in splitting tensile strength, placing it above the normal concrete for all three reported hardened mechanical indicators at the corresponding testing ages. The consistency across these properties suggests that the 5% mixture developed a more effective load-transfer matrix than the control under the experimental conditions. Research concerning sustainable cement substitution has emphasized that alternative materials can improve concrete performance when their incorporation produces an appropriate balance between cement reduction, particle packing, and secondary binding mechanisms (Shah et al., 2025). The present flexural results further indicate that the benefit of BM 5% is not restricted to compressive loading but extends to resistance against bending-induced tensile stresses. The comparatively small 3.73% improvement in flexural strength should nevertheless be interpreted more conservatively than the 45.73% improvement observed in splitting tensile strength because the flexural dataset contains only two specimens per mixture. Within the limitations of the experimental dataset, BM 5% provides the most balanced flexural response, while BM 10% demonstrates that excessive modification of the binder system can compromise later-age bending performance.

Workability of Fresh Concrete

The workability characteristics of the fresh concrete mixtures were evaluated using the slump test to determine whether the incorporation of grouting cement and wood charcoal altered the consistency of the concrete during placement. The target slump range was established at 8–12 cm, providing a practical reference for assessing whether each mixture could be placed and compacted without excessive difficulty. As presented in Table 7, the normal concrete and BM 5% mixture both recorded a slump of 8 cm, while BM 10% produced a slightly higher value of 9 cm. The relatively narrow variation of only 1 cm indicates that the substitution materials did not substantially disrupt the fresh-state consistency under the experimental proportions. This result is relevant because alternative cementitious materials may modify water demand and particle interaction, making workability an important parameter when evaluating their suitability for concrete production (Andaryati et al., 2026). The measured values also demonstrate that all mixtures remained within the predetermined workability range, indicating that the use of Besmitel was sufficient to maintain an acceptable fresh-concrete condition.

Table 7. Slump Test Results

Composition	Besmitel (L)	Slump (cm)
Normal	–	8
5% Variation	0.017	8
10% Variation	0.016	9

The identical 8 cm slump values of the normal and BM 5% mixtures indicate that the introduction of 5% grouting cement and wood charcoal did not produce a measurable reduction in fresh-concrete consistency relative to the control. This behavior suggests that the quantity of substituted material at this level remained sufficiently compatible with the water and admixture proportions used in the mix design. Wood-derived carbonaceous materials can influence the internal distribution of mixing water because of their porous structure and surface characteristics, which may increase water demand when their proportion becomes excessive (Hylton et al., 2024). In the present mixture, however, the use of Besmitel appears to have moderated this potential effect and maintained the measured slump at the same level as the control. The result is particularly relevant because a mixture that achieves improved hardened mechanical properties but loses adequate workability may require additional water or admixture adjustment, potentially changing the resulting strength characteristics. The BM 5% mixture therefore demonstrates a favorable relationship between fresh-state consistency and the hardened mechanical performance reported previously.

The BM 10% mixture exhibited a slump of 9 cm, which was marginally higher than both the normal and BM 5% mixtures despite containing a greater proportion of substituted binder components. The increase should not be interpreted as evidence that a higher substitution level inherently improves workability because the mixture also contained a slightly different Besmitel dosage, namely 0.016 L compared with 0.017 L for BM 5%. The measured difference was only 1 cm and remained comfortably within the specified 8–12 cm range, indicating that the change in consistency was relatively limited. Research on cementitious grouts emphasizes that fresh-state behavior is governed by the interaction among binder composition, particle characteristics, water content, and admixture dosage rather than by a single replacement material alone (da Rocha Gomes et al., 2023). The result therefore suggests that the combined use of grouting cement and wood charcoal at the investigated dosage did not create a critical workability constraint. This finding is important for interpreting the lower 28-day mechanical performance of BM 10%, because the reduction in strength cannot reasonably be attributed to a failure to achieve the target slump.

The relationship between slump and hardened strength provides further insight into the behavior of the three concrete compositions. BM 5% maintained the same slump as the normal concrete while achieving higher 28-day compressive, splitting-tensile, and flexural strengths, whereas BM 10% exhibited a slightly higher slump but substantially lower mechanical performance. This contrast indicates that increased fresh-state fluidity was not accompanied by proportional improvement in hardened properties. The result is consistent with studies showing that the mechanical response of biochar-containing cement composites depends on particle characteristics, replacement level, and matrix development rather than workability alone (Qing et al., 2023). The data suggest that BM 5% achieved a more favorable balance between fresh-state handling and hardened-state structural performance than BM 10%. Such a balance is particularly relevant for sustainable concrete development because replacing conventional cement should not compromise the practical requirements of mixing, casting, and compaction. The present findings therefore support the interpretation that the 5% substitution level represents a technically more balanced composition under the investigated experimental conditions.

The stability of the measured slump values also indicates that the experimental mix design was sufficiently controlled to permit meaningful comparison of mechanical properties among the mixtures. The normal concrete established an 8 cm reference, BM 5% retained the same value, and BM 10% increased only slightly to 9 cm, producing a maximum difference of 12.5% relative to the control. Such limited variation reduces the likelihood that major differences in compressive, tensile, and flexural strength originated solely from uncontrolled fresh-concrete consistency. The use of a controlled mix-design procedure is important because changes in water-to-binder conditions can substantially affect the development of cementitious strength and pore structure (Badan Standardisasi Nasional, 2000). The workability results consequently provide supporting evidence that the observed mechanical differences primarily reflect the interaction between grouting cement, wood charcoal, and the cementitious matrix rather than pronounced differences in fresh-concrete consistency. The experimental control is further strengthened by the fact that all three mixtures satisfied the predetermined slump criterion.

From an engineering perspective, the slump results indicate that the investigated substitution strategy can be implemented without requiring major modifications to fresh-concrete workability within the tested dosage range. The 5% mixture is particularly notable because its 8 cm slump was identical to the control while its 28-day mechanical properties were consistently superior across the principal hardened-state indicators. The 10% mixture also remained workable at 9 cm, but its lower compressive and flexural strengths demonstrate that satisfactory workability alone does not guarantee favorable structural performance. This distinction supports the broader principle that sustainable concrete formulation requires simultaneous consideration of fresh-state behavior and hardened-state mechanical characteristics rather than optimizing a single performance indicator (Shah et al., 2025). The experimental evidence therefore positions BM 5% as the most promising composition among the investigated alternatives because it combines acceptable workability with the strongest overall mechanical response. Within the limits of the tested materials, proportions, and curing conditions, the slump measurements confirm that the use of grouting cement and wood charcoal at the selected replacement levels remained practically feasible for concrete production.

CONCLUSION

The optimal composition of grouting cement and wood charcoal as partial cement substitutes was identified at the 5% substitution level, consisting of 2.5% grouting cement and 2.5% wood charcoal. At 28 days, this composition produced an average compressive strength of 19.398 MPa, representing an 18.26% increase compared with the normal concrete. The same mixture achieved a splitting tensile strength of 2.900 MPa, corresponding to a 45.73% increase, while its flexural strength reached 3.029 MPa, increasing by 3.73% relative to the control mixture. The results demonstrate that the mechanical contribution of the substitution was strongly dependent on curing age, as the modified mixtures showed lower compressive and flexural strengths than normal concrete at 7 days but developed superior performance at 28 days. The 5% composition provided the most balanced response across compressive, tensile, and flexural properties while maintaining an acceptable slump of 8 cm. These findings indicate that controlled incorporation of grouting cement and wood charcoal can provide a technically viable approach for modifying concrete while reducing dependence on conventional Portland cement.

The 10% substitution containing 7.5% grouting cement and 2.5% wood charcoal consistently produced lower compressive, splitting tensile, and flexural strengths than the 5% mixture, indicating that increasing the replacement level beyond the optimum was not beneficial under the investigated mix conditions. At 7 days, the lower strength of the substituted mixtures can be associated with the incomplete development of pozzolanic and cementitious reactions, whereas the 5% mixture exhibited substantial mechanical improvement after 28 days. The results also suggest that the amount and distribution of wood charcoal are important factors because excessive incorporation of carbonaceous material may interfere with matrix continuity and the formation of effective interparticle bonding. Further research should investigate a wider range of proportions between grouting cement and wood charcoal, particularly within the 10% total-substitution level, to determine whether alternative internal ratios can produce more favorable mechanical performance. Future experimental work should also control the crushing and particle-size distribution of wood charcoal more precisely to improve its dispersion within the cementitious matrix and reduce variation among specimens. Additional investigations involving microstructural characterization, longer curing periods, and durability-related properties would provide stronger evidence concerning the mechanisms governing the performance of grouting-cement and wood-charcoal concrete.

REFERENCES

Akmal, M. A. A. (2024). *Pengaruh Penggunaan Serbuk Arang Kayu Sebagai Bahan Substitusi Parsial Semen terhadap Kuat Tekan dan Kuat Tarik Belah Beton* (Tugas akhir, Universitas Islam Indonesia). https://dspace.uii.ac.id/handle/123456789/49918?show=full

Andaryati, A., Suharso, A. B. K., Raharja, D. S., & Saurina, N. (2026). Analysis of Alternative Substitute Materials for Concrete Production Using Word Cloud. *JRST (Jurnal Riset Sains dan Teknologi)*, 11-A. https://doi.org/10.30595/jrst.v10i1.26434

Badan Standardisasi Nasional. (2000). *SNI 03-2834-2000: Tata Cara Pembuatan Rencana Campuran Beton Mormal*.

Badan Standardisasi Nasional. (2011). *SNI 1974:2011: Cara Uji Kuat Tekan Beton dengan Benda Uji Silinder yang Dicetak*.

Badan Standardisasi Nasional. (2014). *SNI 2491:2014: Metode Uji Kekuatan Tarik Belah Spesimen Beton Silinder*.

.

Bing, H., & Yuan, H. (2023). Experimental Research on Compressive Strength-Size Effect and Mechanical Properties of Cement-Based Grout. *Construction and Building Materials*, 373, 130882. https://doi.org/10.1016/j.conbuildmat.2023.130882

Chiadighikaobi, P. C., Qais, Q. A. A., Ajani, A. A., Vanus, D. S., Hammood, M. N., & Saffia-Doe, O. (2024). Effect of Wood Black Charcoal Powder as Cement Replacement and Carbon Fiber Textile On The Physicomechanical Properties Of Bio-Concrete. *Cogent Engineering, 11*(1), 2368713. https://doi.org/10.1080/23311916.2024.2368713

da Rocha Gomes, S., Ferrara, L., Sánchez, L., & Moreno, M. S. (2023). A Comprehensive Review of Cementitious Grouts: Composition, Properties, Requirements and Advanced Performance. *Construction and building materials*, 375, 130991. https://doi.org/10.1016/j.conbuildmat.2023.130991

Dipta, I. A., Ng, K., Lau, C. K., & Yu, H. (2025). Coal-derived char for improving mechanical performance and microstructural characteristics of concrete. *Journal of Sustainable Cement-Based Materials, 14*(4), 780-798. https://doi.org/10.1080/21650373.2025.2465979

Fatriady, M. R., Rachman, M. R., Jamal, M., Muliawan, I. W., Mustika, W., & Mabui, D. S. S. (2022). *Teknologi Bangunan dan Material*. Tohar Media.

Haslinda. (2020). *Analisis Kuat Tekan Beton dengan Variasi Trass dan Semen Grouting* (Tugas akhir, Universitas Bosowa). https://repositori.unibos.ac.id/handle/123456789/9717

Hylton, J., Hugen, A., Rowland, S. M., Griffin, M., & Tunstall, L. E. (2024). Relevant Biochar Characteristics Influencing Compressive Strength of Biochar-Cement Mortars. *Biochar, 6*, Article 87. https://doi.org/10.1007/s42773-024-00375-6

Ihsanu, A. A. (2022). Pengaruh Penambahan Abu Arang Kayu Sebagai Pengganti Sebagian Semen Terhadap Beton Normal Untuk Penerapan Pada Konstruksi Jalan Rigid Pavement. *KURVA MAHASISWA, 12*(2), 37-52. http://ejurnal.untag-smd.ac.id/index.php/TEK/article/view/5992

Irfandi, A. Y., Ali, A. H., & Setiyawan, P. (2025). Efektifitas Penggunaan Serbuk Arang Sebagai Bahan Pengganti Semen Terhadap Kuat Tekan Beton K-175. *Jurnal Teknik SILITEK, 5*(2), 791–799. https://doi.org/10.51135/8g516k12

Jeni, M. L. A. (2025). Enhancing the Properties of Concrete Mixture for Construction by Partially Replacing Mangrove Charcoal in Cement and Including Sawdust as an Additive with Sand. *Progress in Engineering Application and Technology, 6*(1), 376-385. https://periodical.uthm.edu.my/index.php/peat/article/view/19002

Lee, J. B., Kim, S. S., Lee, Y. J., Jang, I. S., & Kim, J. Y. (2024). A Study on the Pre-Hardened Shrinkage Reduction of Grout Using Carbon Materials. *Materials, 17*(15), 3775. https://doi.org/10.3390/ma17153775

Mulyono, T. (2005). Teknologi Beton. Andi Offset.

Qing, L., Zhang, H., & Zhang, Z. (2023). Effect of biochar on compressive strength and fracture performance of concrete. *Journal of Building Engineering, 78*, 107587. https://doi.org/10.1016/j.jobe.2023.107587

Saleh, M. A., Isleem, H. F., Su, Z., Zhang, S., & Zhang, J. (2025). Innovative use of Portland limestone cement and date palm ash in sustainable preplaced aggregate concrete grouts. *Structural Concrete, 26*(3), 2666-2687. https://doi.org/10.1002/suco.202401323

Shah, S. A., Tantray, M. A., & Bhat, A. R. (2025). Wood ash as an eco-friendly alternative for sustainable cement replacement in concrete. *Cleaner and Circular Bioeconomy*, 12, 100178. https://doi.org/10.1016/j.clcb.2025.100178

Sihotang, J. B. (2025). *Pengaruh Substitusi Serbuk Kayu Sisa Pengergajian terhadap Kuat Tekan Beton* (Doctoral dissertation, Universitas Medan Area). https://repositori.uma.ac.id/jspui/handle/123456789/27895

William, M. R., Sembiring, K., Bangun, S., & Naibaho, P. R. T. (2023). Effect of the Use of Wood Charcoal Ash on the Compressive Strength of Normal Concrete. *International Journal of Civil Engineering and Infrastructure, 3*(2), 32-39. https://doi.org/10.24853/ijcei.3.2.32-39

Zhao, Z., El-Naggar, A., Kau, J., Olson, C., Tomlinson, D., & Chang, S. X. (2024). Biochar Affects Compressive Strength of Portland Cement Composites: A Meta-Analysis. *Biochar, 6*, Article 21. https://doi.org/10.1007/s42773-024-00309-2