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COMBINED EFFECT OF BAMBOO FIBER AND KAOLIN ON CONCRETE PROPERTIES: AN EXPERIMENTAL STUDY

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Abstract

Concrete is the most widely used construction material globally, but its production is energy-intensive, depletes natural resources, and contributes significantly to CO_2 emissions. This study investigates the potential of using locally sourced waste materials—calcined kaolin (CK) as a partial cement replacement and bamboo fiber (BF) as reinforcement—to develop a more sustainable concrete. An experimental program was conducted to evaluate the mechanical properties of concrete mixes with CK (4%, 8%, 12% by weight of cement) and BF (0.5%, 1%, 1.5% by volume of concrete). The compressive, splitting tensile, and flexural strengths were tested after 7, 14, and 28 days of curing. The results indicate that the combination of 8% CK and 1% BF (mix CK8BF1) yielded the optimal performance, with a 28-day compressive strength of 37.9 MPa, approximately 10.5% higher than that of the control concrete (34.3 MPa). Strength improvements were also observed in splitting tensile and flexural tests for this optimal mix. Beyond these optimum percentages, strength declined due to a reduction in cementitious content and the balling effect of fibers. This research demonstrates that the synergistic use of calcined kaolin and bamboo fiber can enhance mechanical properties while reducing the environmental footprint of concrete, offering a promising alternative for sustainable construction, particularly in regions where these materials are abundant.

Keywords: Concrete, calcined kaolin, metakaolin, bamboo fibers, mechanical properties, sustainable construction

I. INTRODUCTION

Around the world, the building sector is increasingly playing a significant role in the expansion of national economies. It is having a significant impact on social, political, and infrastructure development. The most crucial and widely utilized building material, concrete, is in great demand.

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Global infrastructure development is driving up concrete usage, which is predicted to reach 18 × 109 tons by 2050 [1]. An estimated 20 billion tons of aggregate and 1.5 billion tons of cement are used each year to make concrete [2]. The usage of concrete is not sustainable for a number of reasons; it uses a lot of natural resources, leaving no virgin material for future generations, and its primary ingredient is cement [3], [4].

About 5% to 7% of the world's CO2 emissions are caused by the cement industry; one ton of cement generates 900 kg of carbon dioxide greenhouse gases or CO2 [4]–[8]. The other challenge is the quantity of raw materials needed to make cement; 2.5 billion tons of raw natural resources, including clay and limestone, are needed to make 1.6 billion tons of cement [5]. A recent study by [9] claims that environmental concerns are crucial to the long-term viability of the concrete and cement sectors.

The cost of the materials, their impact on the environment, and their availability and durability are the primary factors that influence the choice of building materials in the construction sector. Research have been done on replacing cement in concrete production with locally accessible materials such as wood powder [10], paper slag [11], fly ash [12], wood ash [13], termite mud, rice husk ash [14], rice straw ash [15], coal fly ash [16], and sugar cane waste [17] to lower costs and lessen environmental damage. [18] investigated if metakaolin could be used to replace some of the cement in concrete and found that after 28 days, the strength of concrete containing 20% metakaolin was greater than that of regular concrete.

Additionally, customers are worried about the price of steel in addition to cement. This can be done with locally accessible materials, like bamboo fiber, rather than steel. Bamboo is a durable fiber that has a strength-to-weight ratio comparable to steel under strain and double the compressive strength of concrete [15]. [22] concluded that adding natural fibers as reinforcement to composites (such as concrete, mortar, and/or cement paste) is an affordable method of enhancing particular qualities. Research by [23] indicates that adding bamboo fiber volume content increases the splitting tensile strength of bamboo fiber reinforced concrete while having little influence on its flexural or compressive strength. In order to assess the latest proposals by [24], a thorough investigation is necessary.

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According to a study by [25], bamboo fiber reinforced concrete has a tensile strength that is on par with regular concrete. [26] assessed the efficiency of bamboo fiber as a concrete strength enhancer and proposed that bamboo fibers might be utilized as novel fibers in concrete to improve the concrete's ductility and strength. [27] determined that bamboo fiber reinforced concrete has greater strength than normal concrete after finding that the addition of fiber can boost the strength of the concrete by up to 2%. [28] found that bamboo fiber reinforced concrete outperformed regular concrete in terms of mechanical performance by 26.25%. Because bamboo and bamboo-based concrete have different strengths, more research should be done. While the individual effects of metakaolin [18-21] and bamboo fiber [23-27] on concrete properties have been studied, systematic research on their combined effect is limited. The interaction between a pozzolanic material that densifies the cement matrix and a natural fiber that provides tensile reinforcement could lead to synergistic improvements not observed when using either material alone. This study aims to fill this gap by comprehensively investigating the combined effect of locally sourced calcined kaolin and bamboo fiber on the mechanical properties of concrete. The originality of this work lies in the systematic optimization of both CK and BF percentages to identify an optimal mix that maximizes strength gains, providing new insights for developing eco-friendly concrete composites.

II. MATERIALS AND METHODS

A. Materials Used and Preparations

1) Cement: For this research work, OPC with 42.5-grade cement readily available in the local market, which is compatible with Ethiopian Standard Cement and conforms to ASTM, was used.

2) Calcined Kaolin (Methakaolin): For this research, the material was locally sourced from Banssa around Dilla. It was burned for three hours at 700^0c °C to convert kaolin into calcined kaolin (metakaolin) and was processed in the Arba Minch University Foundry Laboratory. Finally, the final powder was ground, and the ashes that passed through a sieve size of 75 μm were used.

3) Bamboo Fiber: Natural bamboo fiber materials were gathered from Chencha and appropriately formed into fibers for this investigation. To determine the fiber lengths, the bamboos were divided along the horizontal axis. After that, the bamboo samples were submerged in water for seven days. In order to increase the specimen's strength and durability, it was then sun-dried for seven days.

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Various percentages of bamboo fiber, including 0.5%, 1%, and 1.5%, were employed in this experiment. The fiber is roughly 37.5 mm long.

4) Fine Aggregates (Sand): This study employed locally accessible natural (river) sand as the fine aggregate for experiments. The sand used in the experiment was gathered from the Arba Minch market, namely from supplies from the Kayle location (Konso). To assess the fine aggregate's quality and ensure that it satisfies all ASTM standards, a variety of tests were conducted.

5) Coarse Aggregates: In this investigation, well-graded crushed coarse aggregate and broken stones from nearby quarries were used. The size of the coarse aggregate utilized was 37.5 mm. It comes from Arba Minch town, which is near Bihere Mariam. Basic crushing equipment is used to break the natural rock. By following ASTM guidelines for aggregate tests of a coarse type, the coarse aggregate's physical characteristics were identified and ascertained.

6) Water: For this research, potable water was used for the experiment. Clear potable water in the construction material testing laboratory of the Faculty of Civil Engineering in Arba Minch Institute of Technology was used.

B. Mix Proportions and Sample Preparations

For concrete with grades ranging from C to 25, the mix design used in this study was approved by ACI 211.1. Bamboo fiber was added as reinforcement in proportions of 0.5%, 1%, and 1.5% of the total volume of concrete, and OPC was partially substituted with metakaolin weights of cement at 4%, 8%, and 12% to create the cubes. Calcined kaolin was used to partially replace the cement in each concrete mix, and bamboo fiber was added as a percentage of the concrete's overall volume. The concrete mix designation was presented in Table I below.

TABLE I: Concrete mix designation

Mix Code	Cement, %	Metakaolin, %	Bamboo fiber, %
CK0BF0	100	-	-
CK4BF0.5	96	4	0.50
CK4BF1	96	4	1.00
CK4BF1.5	96	4	1.50
CK8BF0.5	92	8	0.50

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CK8BF1	92	8	1.00
CK8BF1.5	92	8	1.50
CK12BF0.5	88	12	0.50
CK12BF1.5	88	12	1.00
CK12BF1	88	12	1.50

C. Test Methods Used

1) Test on Hardened Concrete: Utilizing a 150 x 150 x 150 mm cubic mold, the compressive strength was evaluated. The split tensile strength was tested using a cylindrical specimen of 150 mm in diameter by 300 mm in height, and the flexural strength was tested using a beam cast measuring 500 x 10 x 10 mm. The test dates and criteria utilized for the qualities of hardened concrete are shown in Table II.

TABLE II: Test types, standards, and curing ages of hardened concrete

S. No.	Test Types	Test Standards	Curing Ages (Days)
1	Compressive strength	ASTM C 39	7, 14 and 28
2	Flexural strength	ASTM C 78 - 02	14 and 28

The test dates and criteria utilized for the qualities of hardened concrete are shown in Table II. For each mix proportion and test age, three identical specimens were cast and tested. The results presented are the average values of these three samples.

III. RESULTS AND DISCUSSIONS

A. Mechanical Properties of Concrete

1) Compressive Strength Test: The results for the average compressive strength after 7, 14, and 28 days have been presented and extensively discussed. As shown in Table III, the calcined kaolin at 8% replacement with OPC and bamboo fiber at 1% as reinforcement, in addition, has shown a higher compressive strength value than the control throughout the testing period, i.e., 7, 14, and 28 days. The concrete work with the calcined kaolin at 12% replacement with OPC and bamboo fiber at 1.5% as reinforcement didn't show any improvement in the compressive strength value compared to the control throughout the testing period, i.e., 7, 14, and 28 days.

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TABLE III: Average compressive strength of 7th, 14th and 28th days

Mix code	Fiber Content (%)	Calcined Kaolin (%)	Average Compressive Strength at 7 Days (Mpa)	Average Compressive Strength at 14 Days (Mpa)	Average Compressive Strength at 28 Days (Mpa)
CK0BF0	0		25.7	27.8	34.3
CK4BF0.5	0.5	4	25.7	28.5	35.3
CK4BF1	1		26.4	29.3	37.6
CK4B1.5	1.5		21.6	25.3	32.7
CK8BF0.5	0.5	8	27.8	28.6	37
CK8BF1	1		29.6	32.1	37.9
CK8BF1.5	1.5		28.4	30.9	35.7
CK12BF0.5	0.5	12	24	26.8	32.3
CK12BF1	1		20.9	24.9	33.1
CK12BF1.5	1.5		19.7	22.4	27.6

B. Compressive Strength at Constant Calcined Kaolin (CK) Content

TABLE IV: The concrete mixtures with varying percentages of bamboo fibers and 4% of constant percentages of calcined kaolin

mix code	Average compressive strength of concrete, MPa		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF0.5	25.7	28.5	35.3
CK4BF1	26.4	29.3	37.6
CK4BF1.5	21.6	25.3	32.7

Table IV demonstrate that adding 4% calcined kaolin and 0.5%, 1%, and 1.5% of bamboo fiber to concrete increases its compressive strength. According to the table, as the curing age grew, so did the compressive strength of concrete prepared with kaolin and bamboo fiber.

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Compressive strength increased with CK4B0.5 (4% CK + 0.5% BF) after 7 days of curing, but there was no change compared to the control concrete. With CK4B1 (4% CK + 1% BF), the concrete improved and showed a strength of 26.4 MPa, 27.24% more modified than the control concrete. Compared to untreated concrete, the concrete enhanced with CK4B1.5 (4% CK + 1.5% BF) displayed 21.6MPa, which was 15.53% lower. The strength increased significantly from 0.5% BF to 1% BF at 4% CK, but declined at 1.5% BF. This trend is consistent with findings by [23, 27], where an optimal fiber content was identified. The initial increase is attributed to the effective bridging of micro-cracks by the dispersed fibers. The subsequent decline at 1.5% BF is likely due to the balling effect of fibers, leading to poor workability and increased porosity, which outweighs the benefits of fiber reinforcement [23].

When used in excess, bamboo fiber has detrimental effects; that is, it turns into aggregates and creates a more porous structure, which eliminates the beneficial influence of the fiber on the quality of the concrete materials.

A test of ordinary concrete that had been cured for 14 days revealed a compressive strength of 27.8 MPa. But compared to the control concrete, the concrete enhanced with 4% CK + 0.5% BF measured 28.5 MPa, 2.52% higher, and the concrete modified with 4% CK + 1% BF recorded 29.3 MPa, 5.26% higher. After adding 4% CK and 1.5% BF, the concrete's strength increased to 25.3 MPa. Consequently, compared to untreated concrete, the concrete changed with 4% CK + 1.5% BF was reduced by 8.53%.

All concrete types showed a superior strength increase when the compressive strength of 14-day-cured concrete was compared to that of 7-day-cured concrete. The improvement was caused by an excess of C-S-H gels being generated during the cement hydration process. Some extra C-H was transformed into C-S-H gels as a result of the presence of CK and the improved integrity between the cement paste and the aggregates. Additionally, C3S and C2S reactions were aided to produce additional hydration products, C-S-H gel, and CH. The addition of BF enhanced the aggregation amongst the components in addition to CK.

According to test results, the typical concrete (CK0B0) that had been cured for 28 days had a compressive strength of 34.3 MPa. However, the concrete material upgraded with 4% CK + 0.5%

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BF exhibited 35.3 MPa, which was 9.3 MPa higher than the 7-day result and 2.97% better than regular concrete. When compared to unmodified concrete, the changed concrete's compressive strength (4% CK + 0.5% BF) was 9.35% higher at 37.6 MPa, and it was 11.2 MPa higher after 7 days. The 32.7 MPa of the concrete that had been changed with 4% CK and 0.5% BF was 4.25% lower than that of the untreated concrete.

In contrast, the 1%BF modified concrete of 28 days cured increased by 2.3 MPa, or 6.38%, as compared to a constant 4% CK and 0.5%BF. This resulted from the bamboo fibers clumping together. A 4.26% decrease in BF-modified concrete from 1% to 1.5% resulted in a more porous structure and the loss of the beneficial effect on enhancing the concrete materials. The compressive strengths of control and modified by bamboo fiber and kaolin concrete samples of 7, 14, and 28 days cured are shown in the following key findings from the above table.

The following table V show compressive strength at a constant 8% CK with different percentages of bamboo.

TABLE V: Concrete mixes with different bamboo fiber ratios and constant 8% calcined kaolin

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK8BF0.5	27.8	28.6	37
CK8BF1	29.6	32.1	37.9
CK8BF1.5	28.4	30.9	35.7

From the point of the constant percentage of calcined kaolin, from 4%CK of replacement to 8%CK, the compressive strength of concrete increased compared with control with different percentages of bamboo fiber at all ages of curing. This is due to the calcined kaolin effect.

The reason behind this was that OPC, on the other hand, contains a smaller amount of silica by itself. The replacement of calcined kaolin in this cement has resulted in a higher compressive strength for 8% replacement. Because calcined kaolin reached the silica mineral, it reacted with

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the previously described cement-free C-H reaction. This is most likely due to the pozzolanic reaction of metakaolin and calcium (OH)2 from cement hydration.

The enhanced reactivity and high specific surface area resulting from the reduced particle size of the calcined kaolin critically contribute to the observed gain in compressive strength. This strength augmentation exhibited its most significant rate of increase during the initial two weeks of hydration, specifically at the 7-day and 14-day testing intervals.

A faster pozzolanic reaction is caused by a larger surface area of calcined kaolin, which results in the early development of high strength. On the other hand, compared with modified concrete, the concrete CK8BF1 (8%CK+1.5%BF) decreased. This is the balling effect of bamboo fiber.

TABLE VI: The concrete mixtures with varying percentages of bamboo fibers and 12% of constant percentages of calcined kaolin

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK12BF0.5	24	26.8	32.3
CK12BF1	20.9	24.9	33.1
CK12BF1.5	19.7	22.4	27.6

Table VI illustrate the 7, 14, and 28 days compressive strength made by constant 12%CK and different percentages of bamboo fiber, i.e. 0.5%, 1%, and 1.5%BF.

The compressive strength was decreased at a constant 12%CK with different percentages of bamboo fiber through the curing ages. The probable reason for this is the high replacement of cement by calcined kaolin, thus reducing the cement content of the mixture, which in turn causes a reduction in the hydration reaction.

In addition to this, the high content of calcined kaolin resulted in a higher water requirement, making the water unavailable for the hydration of the cement. The decreasing compressive strength was a cluster effect of the materials due to the reduced workability of the concrete and the absorption of water by the bamboo fiber.

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C. Compressive Strength at Constant Bamboo Fiber (BF) Content

The 7th, 14th, and 28th-day average compressive strength test results obtained from three representative samples are separately presented for 0.5%, 1%, and 1.5% BF addition as reinforcement with different CK content as cement replacement, respectively. Results of the compressive strength of concrete at constant fiber content with variable calcined kaolin percentage are shown in table VII.

TABLE VII: Average compressive strength results with varying percentages of calcined kaolin and 0.5% of constant percentages of bamboo fibers

mix code	Average compressive strength (MPa)		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF0.5	25.7	28.5	35.3
CK8BF0.5	27.8	28.6	37
CK12BF0.5	24	26.8	32.3

TABLE VIII: Average compressive strength results with varying percentages of calcined kaolin and 1% of constant percentages of bamboo fibers

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF1	26.4	29.3	37.6
CK8BF1	29.6	32.1	37.9
CK12BF1	20.9	24.9	33.1

TABLE IX: Average compressive strength results with varying percentages of calcined kaolin and 1.5% of constant percentages of bamboo fibers

mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK4BF1.5	21.6	25.3	32.7
CK8BF1.5	28.4	30.9	35.7
CK12BF1.5	19.7	22.4	27.6

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Table VII demonstrate the average compressive strength of 0.5%BF content with variable calcined kaolin content, i.e., 4%, 8%, and 12%CK at 7, 14, and 28 days of curing. Compared to conventional concrete, the compressive strength of modified concrete increased at 7th and 14th curing days. The calcined kaolin was replaced from 4%CK to 8%CK. The strength is not insignificant, whereas the maximum strength is achieved at 8% calcined kaolin content.

Table VIII exhibit the average compressive strength of 1%BF content with variable calcined kaolin content, i.e., 4%, 8%, and 12%CK at 7, 14, and 28 days of curing. Results show that strength increases by increasing the CK content. Overall maximum strength was obtained at 1% fiber content. The increase in 28 days' strength is greater from 4% to 8% replacement, whereas a lesser gain in strength is observed from 8% to 12% replacement. Previous research has shown that a decrease in strength is observed after a 12% replacement level.

Table IX exhibit the average compressive strength of 1.5%BF content with variable calcined kaolin content, i.e., 4%, 8%, and 12%CK at 7, 14, and 28 days of curing. It can be seen that the overall increase in strength is less than that obtained at 1.0% BF. The maximum strength is 4.1% greater than that of the control mix, which is obtained at 8%CK replacement.

D. Average Maximum Compressive Strength Results Among Different Replacement Levels

TABLE X: Average maximum compressive strength of each replacement with different percentages of bamboo fiber

Mix code	Average compressive strength		
	7 day	14 day	28 day
CK0BF0	25.7	27.8	34.3
CK8BF0.5	27.8	28.6	37.0
CK8BF1	29.6	32.1	37.9
CK8BF1.5	28.4	30.9	35.7

As seen in Table X it demonstrate the maximum compressive strength from each replacement level with different fiber content at 7, 14, and 28 days. A comparison between maximum strength and each replacement level is done to find out the optimum mix for maximum strength. The graphical description shows that overall maximum strength was achieved with 8% CK replacement and 1% fiber content, but the increase in strength was not as significant from 4% to 8% replacement.

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The main points noted in this experiment are the following. Results of compressive strength are shown in Table X .At 1% bamboo fiber and 8% metakaolin, the 28-day compressive strength is greatest at 1% bamboo fiber and 8% metakaolin. Hence, 1% bamboo fiber and 8% metakaolin are more suitable for improving the compressive strength of structural concrete.

E. Splitting Tensile Strength Test

The tensile strength at which failure occurs is the tensile strength of concrete. In this investigation, the test is carried out on the cylinder by splitting along its middle plane parallel to the edges by applying the compressive load to opposite edges. The 14th and 28th days of curing for bamboo fiber reinforced with calcined kaolin replaced cement concrete. . The tensile strength of the concrete was tested at 14th and 28th days, and the variation of split tensile strength concerning fiber content and metakaolin is shown in Table XI.

TABLE XI: Average splitting tensile strength performance of concrete at 14 days

mix code	Average splitting Tensile strength (N/mm2)		
	0.5% BF	1% BF	1.5% BF
CK4	1.775	1.66	1.375
CK8	1.725	1.375	1.325
CK12	1.7	1.45	1.26

The 28-day average splitting tensile strength of control concrete was 2.52Mpa.

TABLE XII: Average splitting tensile strength performance of concrete at 14 days

Mix	Average splitting Tensile strength (N/mm2)		
	0.5% BF	1% BF	1.5% BF
CK4	3.04	2.79	2.31
CK8	2.9	2.84	2.2
CK12	2.86	2.33	1.72

Tables XI and XII above show the average splitting tensile strength of concrete made with 4%, 8%, and 12% calcined kaolin and a combination of 0.5%, 1%, and 1.5% bamboo fiber after 14th and 28th days of curing, respectively.

The splitting tensile strength of 14-day cured normal concrete showed 1.49MPa. But, the concrete improved with (0.5 BF + 4 % CK) showed 1.78MPa, which was 19.46% more modified than the

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normal concrete. In comparison to the control concrete, the concrete that had been improved with (1 % BF + 4% CK) displayed 1.73MPa, which was 16.11% more modification. And, concrete modified with (4%CK + 1.5%) showed 1.70MPa, which was 14.09% more modified than plain concrete. The concrete modified with (8%CK + 0.5%BF) showed 1.66MPa, which was 11.47% more modified than the control concrete. Concrete modified with (8%CK + 1%) showed 1.68MPa, which was 12.75% more modified than plain concrete. And, concrete modified with (8%CK + 1.5%) showed 1.45MPa, which was 2.68% less than plain concrete. However, the splitting tensile strength was slightly reduced from 1%BF to 1.5%BF and from 4% to 12% due to collection effects. However, from 1% BF to 1.5% BF, the splitting tensile strength was somewhat decreased.

The splitting tensile strength of 28-day cured unmodified concrete showed 2.51 MPa. However, the concrete modified with (4% BF + 0.5% CK) demonstrated a 3.04MPa, which was 21.12% higher than the control concrete, and it was 1.27MPa, or 1.92% higher when compared to the 7-day test. (1%BF + 4%CK) showed 2.79MPa, which was 11.16% more modified than control concrete, and when compared with the 7-day result, it was 1.06 MPa, or 0.31% decreased. And, concrete modified with (4%CK + 1.5%) showed 2.31MPa, which was 7.97% more unmodified than plain concrete. The concrete modified with (8%CK + 0.5%BF) showed a 2.90MPa, which was 15.54% more modified than the control concrete. Concrete modified with (8%CK + 1%) showed 2.84MPa, which was 13.15% more modified than plain concrete. And, concrete modified with (8%CK + 1.5%) showed 2.20MPa, which was 12.35% less than plain concrete. However, the splitting tensile strength was slightly reduced from 1%BF to 1.5%BF and from 4% to 12% due to cluster effects.

F. Flexural Strength Test Results

The flexural strength test gives another way of estimating the tensile strength of concrete. During pure bending, the member resisting the action is subjected to internal stresses (shear, tensile, and compressive). For a bending force applied downward to a member simply supported at its two ends, fibers above the neutral axis are generally subjected to compressive stresses, and those below the neutral axis undergo tensile stresses. The following tables XIII investigate detailed test results of flexural strength at the ages of 14th and 28th days for bamboo fiber reinforced concrete. They are presented in Appendix D3 at the end of this document.

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TABLE XIII: 14-day flexural strength test results

Mix code	Calcined kaolin (%)	Bamboo fiber (%)	Average flexural Strength 14 days (Mpa)
CK0BF0	0	0	6.88
CK4BF0.5	4	0.5	7.15
CK4BF1	4	1	7.57
CK4BF1.5	4	1.5	7.66
CK8BF0.5	8	0.5	8.71
CK8BF1	8	1	8.20
CK8BF1.5	8	1.5	7.17
CK12BF0.5	12	0.5	7.67
CK12BF1	12	1	7.31
CK12FB1.5	12	1.5	7.50

TABLE XIV: 28-day flexural strength test results

Mix code	Calcined kaolin (%)	Bamboo fiber (%)	Average flexural Strength 28 days (Mpa)
CK0BF0	0	0	8.95
CK4BF0.5	4	0.5	9.09
CK4BF1	4	1	9.13
CK4BF1.5	4	1.5	9.32
CK8BF0.5	8	0.5	11.41
CK8BF1	8	1	10.35
CK8BF1.5	8	1.5	9.40
CK12BF0.5	12	0.5	9.34
CK12BF1	12	1	8.63
CK12FB1.5	12	1.5	7.99

The above tables XIV reveal the 14 and 28-day of average flexural strength test results of the concrete. It can be seen from Table XIII that the flexural strength of 14 days of cured unmodified concrete (CK0BF0) showed 6.88 MPa. However, the flexural strength of concrete modified with (0.5 % BF + 4% CK) showed 7.15 MPa, which was 23.11 % higher than unmodified concrete. The

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*Corresponding author- **Feseha Sahile***

modified flexural strength concrete (1% BF + 4% CK) had a 7.57MPa, which was 51.74% higher than the unmodified concrete. The concrete modified with (1.5 % BF + 4 % CK) showed 7.66 MPa, which was 17.20 % modified. Moreover, Table XIV show that the flexural strength of concrete made by 0.5%, 1%, and 1.5% bamboo fiber in volume of concrete with 4%, 8%, and 12% of calcined kaolin of 28-day curing was 8.95. Another pertinent point is that the 28-day average flexural strength was increased by 8%CK with various percentages of BFs, and the optimum flexural strength is 11.41MPa, which was 27.45% from conventional concrete.

G. Discussion of Optimal Mix and Practical Implications

The experimental results consistently demonstrate that the mix CK8BF1 (8% CK + 1% BF) provides the optimum mechanical performance across compressive, splitting tensile, and flexural strength tests. The governing parameter for determining this optimum is the peak strength value achieved before a decline is observed due to two main factors: (1) excessive cement replacement by CK (e.g., 12%), which reduces the core cementitious content and can increase water demand, hindering complete hydration; and (2) excessive bamboo fiber content (e.g., 1.5%), which leads to fiber agglomeration (balling), creating weak zones and increasing porosity.

From a practical perspective, the CK8BF1 mix shows a 28-day compressive strength of 37.9 MPa, making it suitable for a range of applications. In non-structural applications such as paving blocks, kerbstones, and low-load-bearing walls, this mix offers a sustainable and potentially lower-cost alternative. For structural applications like secondary beams, slabs, and rural housing, the enhanced tensile and flexural properties are particularly beneficial. However, long-term durability aspects such as resistance to sulfate attack, carbonation, and the susceptibility of bamboo fiber to degradation in the alkaline concrete environment require further investigation before widespread structural implementation.

The use of these locally available materials aligns with the principles of sustainable construction by reducing the carbon footprint associated with cement production and utilizing renewable bamboo resources. This approach is especially significant for developing economies like Ethiopia, where cost reduction and local material availability are critical drivers.

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IV. CONCLUSION

This study experimentally investigated the combined effect of calcined kaolin (CK) as a partial cement replacement and bamboo fiber (BF) as reinforcement on the mechanical properties of concrete. Based on the results, the following conclusions are drawn:

- The incorporation of calcined kaolin and bamboo fiber significantly influences the mechanical properties of concrete. An optimal combination exists beyond which strength properties decline.
- The mix with 8% CK and 1% BF (CK8BF1) was identified as the optimum, demonstrating the highest compressive strength (37.9 MPa) that is approximately 10.5% higher than the control mix. This mix also showed superior splitting tensile and flexural strength performance.
- The improvement in strength is attributed to the synergistic effect of the pozzolanic reaction of CK, which densifies the cement matrix, and the crack-bridging action of the BF, which enhances tensile resistance.
- Replacement levels exceeding 8% CK led to a reduction in strength due to dilution of cementitious materials, while BF content above 1% caused a decline in properties due to fiber balling and increased porosity.

The findings of this research promote the use of industrial and agricultural waste products in concrete production, contributing to more sustainable and economical construction practices. The CK8BF1 mix presents a viable option for both non-structural and certain structural applications in regions where kaolin and bamboo are readily available. Future work should focus on evaluating the long-term durability, shrinkage, and workability of this modified concrete to facilitate its broader adoption in the construction industry.

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare no conflict of interest.

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