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A comprehensive comparative analysis of the impact of metakaolin and fly ash additions on the mechanical performance of fiber-reinforced concrete beams

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ABSTRACT

This study explores the effects of metakaolin (MK), fly ash (FA), superplasticizer, and banana and basalt fibers on concrete's mechanical properties through a comprehensive experimental analysis. The materials employed include ordinary Portland cement (OPC) 53 grade, M-sand, coarse aggregates, 12.5% MK and FA, and superplasticizer (Sika at 0.5%), blended with banana and basalt fibers in varying proportions of 0%, 0.5%, 1%, and 1.5%. A total of 13 beam specimens, each measuring 1000 mm × 100 mm × 150 mm, were cast, including a control specimen. The primary focus of the study is to evaluate the mechanical behavior of the concrete beams under single-point load testing. Key parameters such as deflection, ductility, stiffness, energy absorption, and energy dissipation were examined. Among the various mixes, the combination with 1.5% basalt fiber and 12.5% MK (BSFM3) exhibited superior performance in terms of strength, stiffness, and overall mechanical properties. The study conducts a detailed microstructural analysis to understand the concrete mixes and performance. Comparative analysis with experimental results and existing literature underscored the enhanced performance of this mix and analyse the microstructural properties. These findings provide valuable insights for optimizing concrete mix designs, enabling engineers, architects, and construction professionals to create durable, sustainable structures.

Keywords: Metakaolin; Ductility; Stiffness; Energy Absorption; Energy Dissipation.

1. INTRODUCTION

Fibers have become essential components in the construction industry, with concrete being one of the most widely used materials worldwide. The industry's development increasingly depends on the integration of fibers, which significantly enhance concrete properties. Extensive research has focused on understanding the bonding mechanisms and characteristics of mortars reinforced with basalt and banana fibers, particularly when combined with eco-friendly alternatives like FA and MK [1, 2]. Studies have explored the use of fine recycled aggregates, banana fiber, basalt fiber, pumice powder, and other additives to create sustainable, high-performance concrete blends. Elevated temperatures can greatly influence the behavior and effectiveness of fiber-reinforced construction materials, with the distribution of fiber lengths being a key factor in their response to temperature changes. A thorough understanding of these effects, especially concerning basalt fiber, banana fiber, and MK, is essential for ensuring optimal performance and durability in various construction applications [1–3].

The performance of MK concrete at elevated temperatures is studied to understand its behavior under heat exposure, contributing to its suitability for fire-resistant construction applications [1]. Another study explores the influence of MK as a supplementary cementing material, examining its impact on the strength and durability of concrete [2]. Research also examines the effect of curing temperature on the development of the hard structure of MK-based geopolymer, providing insights into optimizing geopolymer production for enhanced material properties in construction [3]. The impact of MK and FA on the strength and efflorescence of cement-based composites is investigated, offering valuable insights into optimizing concrete mixtures for better performance

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and reduced efflorescence issues [4]. The study also investigates the synergistic effects of recycled aggregate and ground granulated blast furnace slag (GGBS) with MK on the physicochemical properties of geopolymer concrete, contributing valuable insights into sustainable construction materials [5]. The spalling behavior of MK-FA-based geopolymer concrete when exposed to elevated temperatures is explored, providing insights into the material's fire resistance and structural performance [6].

The study investigates the cracking behavior of basalt fiber reactive powder concrete beams using acoustic emission techniques to understand crack initiation, propagation, and the influence of basalt fibers on crack resistance [7]. It examines the effects of wrapping HDPE-filled concrete with basalt and geotextile fibers on compressive and flexural strengths to evaluate the mechanical benefits of fiber wrappings [8]. The research also focuses on developing empirical models for predicting compressive and tensile strength in basalt fiber-reinforced concrete, taking into account factors such as fiber content, concrete mix proportions, and curing conditions for accurate strength estimation [9]. Additionally, the durability of basalt fiber polymer in expanded clay concrete is investigated under various environmental stressors, aiming to assess long-term performance, temperature fluctuations, and chemical exposure [10]. The mechanical properties of basalt fiber-reinforced concrete with high stone powder content are examined at elevated temperatures to understand its behavior under thermal stress for structural applications [11]. Bonding between basalt fiber-reinforced polymer (BFRP) sheets and concrete in beams is assessed to evaluate load transfer effectiveness and provide insights into BFRP's structural performance in concrete [12]. The flexural performance of concrete beams with chopped basalt fibers is analyzed to assess their impact on behavior and load capacity, offering insights into the effectiveness of basalt fibers in concrete reinforcement [13]. The study also explores the development of eco-concrete for environmentally friendly construction, incorporating sustainable materials to create "green" elements with reduced environmental impact across their lifecycle [14]. The potential of waste banana fiber in various industries is reviewed, focusing on its feasibility, benefits, and challenges, with an aim to promote sustainability and reduce waste through its incorporation in diverse applications [15]. Lastly, the shear behavior of reinforced concrete (RC) beams with basalt and polypropylene fibers is assessed to understand their effectiveness as shear reinforcement and enhance structural performance [16].

The study explores the flexural performance of reinforced concrete (RC) beams strengthened with a single layer of BFRP sheets, assessing improvements in strength, stiffness, and overall structural behavior. It provides insights into the effectiveness of BFRP as a concrete strengthening material [17]. Additionally, the research examines the flexural behavior of concrete reinforced with a combination of basalt and polypropylene fibers, analyzing their collective impact on strength and ductility. A prediction model for flexural performance is developed, offering valuable insights into structural behavior and engineering applications [18]. The study also investigates the use of basalt fiber bars in concrete structures, evaluating their feasibility, effectiveness, and advantages over traditional steel reinforcement. This assessment includes an analysis of mechanical properties, durability, and overall structural performance to determine their suitability [19]. Furthermore, the seismic behavior of basalt fiber-reinforced beam-column joints under cyclic loading is examined, providing insights into the effectiveness of basalt fibers in enhancing the seismic resilience of concrete structures [20]. Parametric finite element analysis is used to study the flexural behavior of BFRP in fiber-reinforced concrete (FRC) beams, exploring how varying parameters affect the flexural response. This research aims to optimize beam structures [21]. The fracture toughness of concrete containing polypropylene and basalt fibers is also evaluated, with an emphasis on how these fibers impact crack resistance, providing insights into enhancing structural durability [22]. Mechanical properties of basalt fiber-reinforced concrete with high stone powder content are assessed at elevated temperatures, offering insights into the material's behavior under extreme conditions for fire-resistant construction applications [23]. The study focuses on structural design calculations for Basalt Fiber Polymer-Modified Reactive Powder Concrete (RPC) beams under four-point bending, analyzing load capacity and deflection behavior to optimize performance in bending applications [24]. Further research assesses the strength and durability of basalt fiber-reinforced concrete, examining the fibers' impact on material properties, environmental resistance, and long-term durability. This provides insights into its advantages and applications in construction [25]. Lastly, the effect of basalt fibers on the deflection strength of expanded clay concrete beams is analyzed, evaluating its impact on structural behavior and load capacity, with a focus on enhancing deflection strength in such structures [26].

Banana fiber combined with phenolic resin creates a strong composite, but the addition of vajram resin reduces its strength. Despite this, the all-natural approach shows promise for specific applications [27]. Research on a banana fiber-epoxy-steel mesh composite provides insights into the behavior of these materials, paving the way for future engineering applications [28]. The study also examines the influence of sisal and banana fiber hybridization on the mechanical and durability properties of polypropylene fiber-reinforced concrete [29]. This exploration aims to determine if these fibers can replace steel, aiding in the design of future

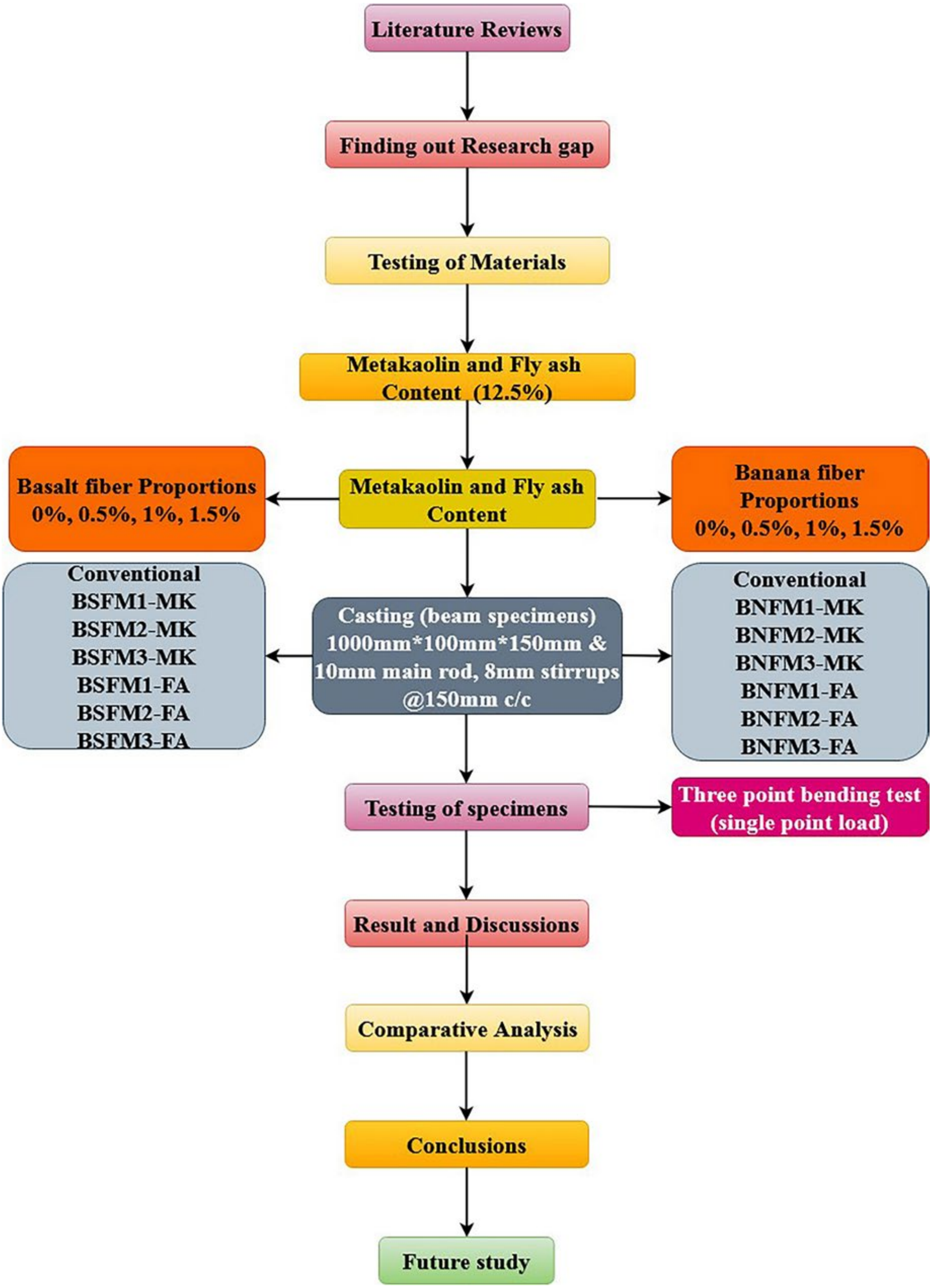

Figure 1: Research methodology.

structures [30].Research into basalt fiber reinforcement in concrete focuses on optimizing concrete strength and understanding failure mechanisms, leading to the development of better structures [31]. The strength of banana and sisal fiber composites is also evaluated, showing promise as eco-friendly alternatives in various products [32]. Computer simulations using finite element modeling (FEM) indicate that banana and hybrid fibers could potentially replace steel in concrete beams, offering a more sustainable building option [33]. Additionally, the use of banana peels and coconut fibers in precast concrete beams is explored, promoting sustainable construction practices [34]. Further simulations reinforce the idea that banana and hybrid fibers could substitute steel in concrete, supporting greener construction methods [35]. Combining banana and snake grass fibers has shown potential for creating eco-friendly composites in engineering. Testing their mechanical properties could unlock new applications [36]. Another study tests the wrapping of concrete columns with Kevlar and banana fibers, with promising results for using these materials to strengthen columns in construction [37]. Finally, the use of concrete incorporating FA, bagasse ash, and banana fiber is explored, showing potential for a greener and stronger future in construction [38]. The effectiveness of basalt fibers in improving the mechanical properties and crack resistance of RPC beams, which are known for their high strength and durability [39,40].

This research undertakes a comprehensive investigation into modifying concrete properties by incorporating banana fiber, basalt fiber, FA, MK, and a superplasticizer. The study employs high-quality OPC53 grade cement, M-Sand, and 20 mm coarse aggregates as fundamental materials. FA and varying proportions of MK (0% to 1.5%) are combined with the fibers in the concrete mixtures, along with a constant concentration of 0.5% superplasticizer (Sika), all mixed with water. The research emphasizes a thorough evaluation of mechanical properties, specifically using a single-point load test on reinforced concrete beams (1000*100*150 mm). These mechanical properties are meticulously examined, revealing critical insights into how the materials and admixtures influence the structural performance of the concrete. Additionally, by reducing cement usage, this research aligns with global efforts to lower the construction industry's environmental footprint. The research methodology of the study is shown in Figure 1.

2. MATERIALS AND METHODS

2.1. Characterization of materials

In this experiment, OPC 53 Grade (CEM I 52.5) was used. The OPC 53 Grade cement conforms to the BIS specification IS:12269-1987, with a minimum compressive strength of 53 MPa at 28 days. Its properties were verified according to the PN-EN 197-1:2002 standard, with detailed composition and technical specifications provided in Tables 1 and 2. Coarse aggregates, consisting of larger particles of crushed stone, gravel, or slag, typically 20 mm in size, were utilized. These materials play a crucial role in concrete mixes, providing bulk, strength, and durability to the structure. The physical properties of the coarse aggregate are presented in Table 3. Manufactured sand (M-Sand), an artificial sand produced by crushing hard stones into small, angular particles (4.75 mm), was also used. This sand is washed and finely graded to serve as a construction aggregate. M-Sand enhances the compressive strength of the concrete and reduces the water demand during mixing.

Table 1: Chemical composition of cement.

COMPONENT	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl	LOS	ASH	TOTAL
%	20.65	3.36	4.38	65.25	1.14	3.10	0.21	0.37	0.080	1.31	0.25	99.97

Table 2: Physical properties of cement.

CEMENT CHARACTERISTICS	CEM I 52.5N-HSR/NA
Specific surface area (cm^2/g)	4435
Water demand (%)	35
Commencement of bonding (min)	125
End of bonding (min)	173
Volume stability according to Le Chateliere (mm)	1.8
Compressive strength after seven days (MPa)	28.5
Compressive strength after 28 days (MPa)	55.8
Tensile strength after seven days (MPa)	6.12
Tensile strength after 28 days (MPa)	8.25

Table 3: Physical properties of coarse aggregates.

AGGREGATE CHARACTERISTICS	VALUE
Density (cm^3/g)	2.62
Porosity (%)	0.89
Absorption, W_{24} (%)	0.36
Ash content (%)	0.04
Frost resistance, F (%)	0.15
Resistance to crushing, LA (%)	36
Resistance to polishing, PSV (%)	58
Shape factor, SI (%)	12.5
Crusher reduction ratio, X_{rm} (%)	14.15
Los Angeles abrasion (%)	14

MK is derived from the mineral kaolin, a common clay found in the earth's crust, with "meta-" indicating a transformation in the kaolin structure. Its primary components are silica (SiO2) and alumina (Al2O3), and it is a dehydroxylated form of kaolinite, functioning as a pozzolanic material. FA, a byproduct of combustion processes, consists of fine particles carried by flue gases. It significantly enhances concrete performance and offers numerous benefits in both cement and non-cement applications.

Banana fiber (BNF), sourced from the pseudo-stems and leaves of banana plants, is a sustainable and eco-friendly material. BNF fibers have a diameter of 20 µm, a length of 12 to 15 mm, a modulus of elasticity of 27 GPa, and a tensile strength of 550 MPa. On the other hand, basalt fibers (BSF) are 50 mm long, with an aspect ratio of 50, a modulus of elasticity of 85 GPa, and a tensile strength of 2600 MPa. Extracted from basalt rock, BSF is environmentally friendly, produced through energy-efficient processes, and fully recyclable, contributing to sustainable manufacturing. BSF improves concrete's flexural strength, limits crack propagation, and enhances durability. With a moisture content of $\leq$0.10, the concrete mix was further improved using a superplasticizer, Sika-Viscocrete-5060, to optimize workability.

2.2. Methods

The flexural behavior of a beam refers to its response when subjected to bending forces, which is a crucial factor in structural analysis and design. This behavior determines the beam's ability to carry loads without experiencing failure. Key factors such as material properties, cross-sectional shape, and support conditions play a vital role in how a beam bends and distributes stresses. These considerations are essential to ensuring beams can safely handle bending loads, contributing to the overall stability and safety of structures like buildings and bridges.

Reinforcing the concrete matrix with fibers enhances the durability and resilience of the concrete, making it more capable of withstanding various stresses and loads. This study examines the effects of optimal combinations of MK, FA, and Sika admixtures (used at 0.5%) alongside basalt and banana fibers, incorporated in moderate volume proportions of 0.5%, 1%, and 1.5%. The investigation includes tests for deflection, ductility, stress-strain relationships (via a two-point load test), compressive strength, stiffness, and energy absorption. Additionally, fiber reinforcement effectively reduces shrinkage cracking, ensuring long-term stability and structural integrity. Table 4 and Figure 2 present a rectangular beam with dimensions of 1000 mm in length, 100 mm in width, and 150 mm in depth. The design indicates that the beam is primarily intended to bear loads along its length, with the width contributing to stability and the depth providing the necessary resistance to bending forces.

To enhance the beam's load-bearing capacity and structural integrity, reinforcement is strategically incorporated into its design. This includes a primary 10 mm diameter rod running along the length of the beam for main reinforcement, complemented by 8 mm diameter stirrups spaced 150 mm apart (Figure 3) to provide lateral support and prevent buckling under load.

The mixture proportions can be adjusted to achieve the desired strength, texture, and durability of the final product. The concrete manufacturing process, detailed in Figure 4, begins with the precise mixing of components such as cement, M-sand, coarse aggregates, MK, FA, superplasticizer (Sika), basalt fiber, and banana fiber, combined with an appropriate water-cement ratio to ensure workability. For preparing the reinforced beam,

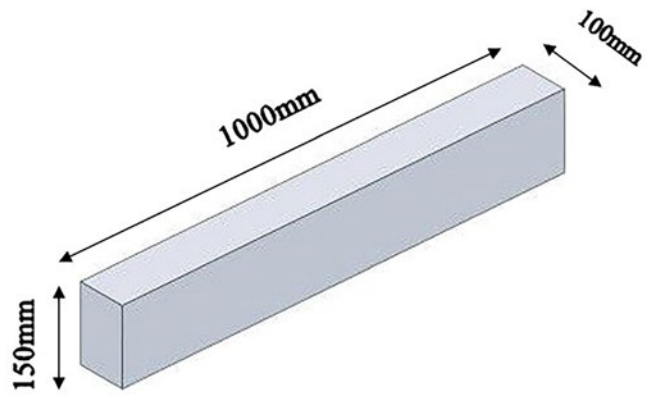

Figure 2: Geometrical details of beam.

Table 4: Geometric and reinforcement details of all specimens.

SPECIMEN ID	TYPE OF ADMIXTURE USED	DIMENSIONS OF THE SPECIMEN (mm)			REINFORCEMENT DETAILS (mm)		
		LENGTH	BREADTH	DEPTH	MAIN ROD	STIRRUPS	SPACING
C	–	1000	100	150	4#10	8	@150 c/c
BSFM1	Metakaolin	1000	100	150	4#10	8	@150 c/c
BSFM2		1000	100	150	4#10	8	@150 c/c
BSFM3		1000	100	150	4#10	8	@150 c/c
BNFM1		1000	100	150	4#10	8	@150 c/c
BNFM2		1000	100	150	4#10	8	@150 c/c
BNFM3		1000	100	150	4#10	8	@150 c/c
BSFM1	Fly ash	1000	100	150	4#10	8	@150 c/c
BSFM2		1000	100	150	4#10	8	@150 c/c
BSFM3		1000	100	150	4#10	8	@150 c/c
BNFM1		1000	100	150	4#10	8	@150 c/c
BNFM2		1000	100	150	4#10	8	@150 c/c
BNFM3		1000	100	150	4#10	8	@150 c/c

Note: BSFM – Basalt Fiber Mix, C – Conventional, BNFM – Banana Fiber Mix.

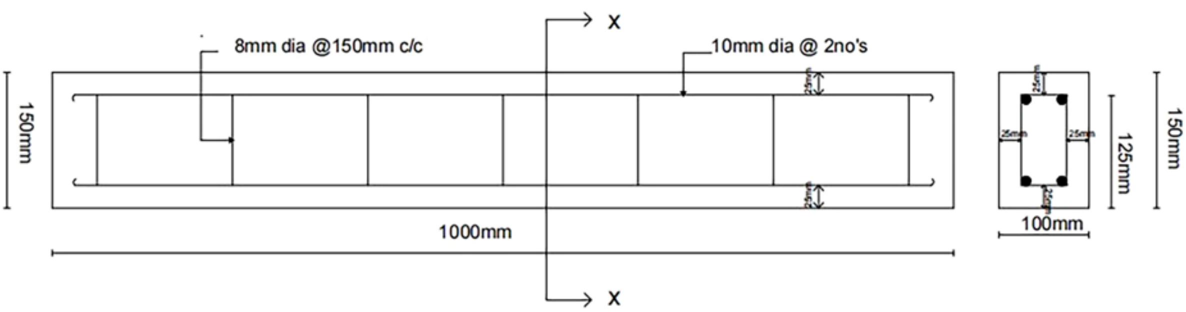

Figure 3: Reinforcement details of the beam.

Figure 4: Manufacturing process of concrete.

Figure 5: Curing and grit marked for all casted specimens.

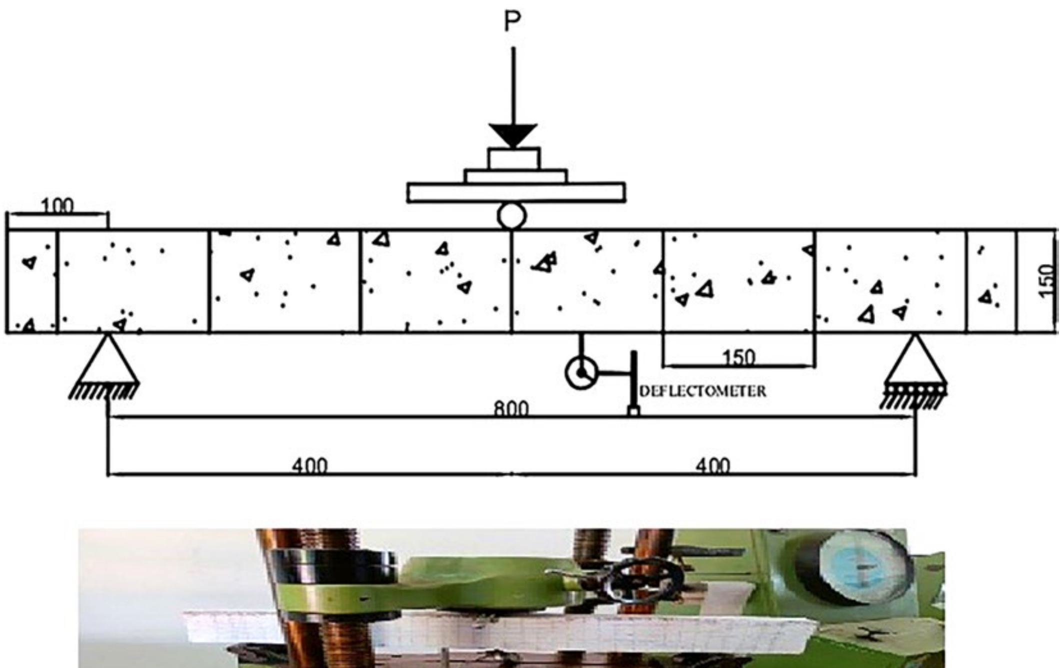

Figure 6: Experimental setup of the specimen.

the following steps are undertaken: arranging reinforcement bars within the formwork, pouring the concrete mixture to encase the bars, compacting the mixture with a vibrating machine to remove air pockets, demolding the beam once it has set, and curing the specimen to improve its strength and durability.

The specimens are cured for 28 days to achieve the desired strength and durability, effectively preventing cracking and enhancing the structural integrity of the reinforced beams. During this curing period, moisture is consistently maintained to facilitate proper setting of the specimens. Once the 28-day curing process is complete, all specimens are labeled for testing as "grit" (Figure 5).

Figure 6 illustrates the experimental setup for the three-point bending test conducted using a universal testing machine (UTM). The specimen, measuring 1000 mm in length, 100 mm in width, and 150 mm in depth, is placed horizontally on the testing platform. The clear span between the supports is 100 mm on each side, with the load applied at the center of the beam. The distance from each support to the loading point (P/2) is 400 mm.

Steel rods are positioned at the top of the specimen to evenly distribute the load across its width. These rods act as load distributors, ensuring uniform loading and reducing localized stress concentrations that could impact the accuracy of the test results. The test involves applying a controlled load until the specimen reaches a designated endpoint, such as failure or a specified displacement. During the test, data, including load-displacement curves, are recorded for subsequent analysis. This setup allows for a thorough evaluation of the specimen's mechanical properties.

3. EXPERIMENTAL INVESTIGATION

3.1. Single point load test

The single-point load test is a structural assessment designed to evaluate the load-bearing capacity and deflection characteristics of materials, components, or structures. During this test, a load is applied at a single point on the specimen, typically using a Universal Testing Machine (UTM) with a specified capacity (400 kN). This test provides critical data on the material's behavior under stress, including its yield point, ultimate strength, and failure mode. The yield point indicates the stress at which the material begins to deform plastically, meaning it undergoes permanent deformation even after the load is removed. Beyond the yield point, the material reaches its ultimate strength, which is the maximum stress it can endure before failing completely. This point represents the material's peak load-bearing capacity under the test conditions. The failure mode observed during the test reveals how the material responds to extreme stress, whether through brittle fracture, ductile deformation, or other failure mechanisms.

Table 5 displays the flexural load values for all tested beams. Figure 7 presents a comparative analysis of the flexural load testing results for concrete specimens incorporating MK and FA as partial replacements for OPC.

The control mix shows moderate load values, with the failure load slightly lower than the ultimate load. The yield load increases progressively with higher MK content, which suggests an improvement in the initial stiffness or elasticity of the concrete as MK is introduced. Ultimate and failure loads are notably higher in BSFM3, BNFM1, and BNFM3, indicating that these mixes can withstand greater stress before failure. BSFM3 has the highest ultimate and failure loads, demonstrating superior mechanical performance among the MK specimens.

Table 5: Flexural load values of all beams.

SPECIMEN ID	FIBER AND ADMIXTURE CONTENT	EXPERIMENTAL LOAD (kN) (MK USED)			EXPERIMENTAL LOAD (kN) (FA USED)		
		YIELD	ULTIMATE	FAILURE	YIELD	ULTIMATE	FAILURE
C	0	22.35	95.64	91.65	22.35	95.64	91.65
BSFM1	0.5 + 12.5	55.65	126.5	123.45	45.36	118.32	115.32
BSFM2	1 + 12.5	85.62	186.35	123.5	56.75	156.75	151.25
BSFM3	1.5 + 12.5	110.25	215.65	212.65	73.65	195.65	190.35
BNFM1	0.5 + 12.5	48.35	102.35	92.35	38.45	102.35	98.75
BNFM2	1 + 12.5	76.45	122.35	118.75	48.35	115.32	113.26
BNFM3	1.5 + 12.5	68.25	112.15	109.45	41.62	107.45	103.75

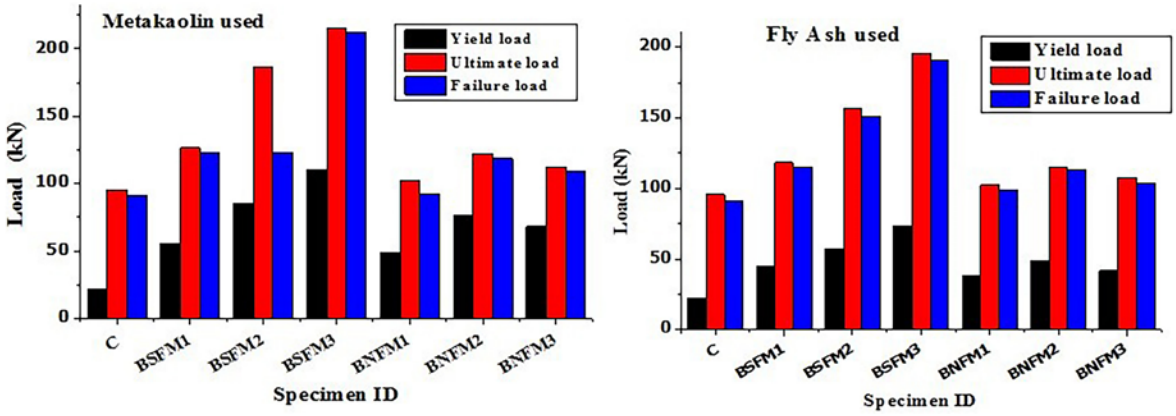

Figure 7: Flexural load carrying capacity of all beams with MK and FA.

The yield load increases as FA content increases, but the rate of improvement is not as high as in the MK specimens. Ultimate and failure loads follow a similar pattern to MK specimens, though the highest loads in FA mixes do not surpass the best-performing MK mixes. FA specimens show a slight improvement in mechanical performance, especially in ultimate and failure loads, but not as pronounced as with MK.

3.2. Deflection

Deflection measures the extent of bending or deformation that a material or structure undergoes when subjected to an applied load. In a single-point load test, assessing deflection is essential for evaluating the specimen's flexibility and stiffness under load (Table 6). This measurement involves considering factors such as material properties, geometry, and applied forces, making it a critical aspect of both mechanical and civil engineering design and analysis. By understanding deflection, engineers can identify potential weaknesses or areas of concern in the material or structure. This insight allows for necessary design modifications or reinforcements to address risks and improve structural performance. The deflection data of concrete specimens incorporating MK and FA as partial replacements for OPC, comparing their performance in terms of yield deflection, ultimate deflection, and failure deflection (Figure 8).

The control mix exhibits moderate deflection values, with ultimate deflection slightly higher than yield deflection, and failure deflection representing the highest value. The yield deflection increases from BSFM1 to BSFM3, showing an upward trend in initial stiffness reduction as MK content increases. However, the yield deflection values remain moderate. BSFM3 and BNFM2 show the highest ultimate and failure deflection, indicating these mixes have more capacity to deform before failure. This suggests a higher ductility in these specimens. The deflection range between yield, ultimate, and failure is larger in MK mixes, particularly in BSFM3 and BNFM2, indicating these specimens can undergo significant deflection before failure.

Yield deflection in FA specimens is slightly lower than in the MK specimens, indicating higher initial stiffness. The deflection values do not increase as significantly as in the MK specimens, suggesting that FA mixes are less ductile overall. BSFM3 and BNFM3 show slightly higher deflections, but still less than the corresponding MK mixes. The difference between yield, ultimate, and failure deflection is smaller in FA mixes, indicating that FA specimens exhibit less deformation and lower ductility before failure compared to MK mixes.

3.3. Ductility

In a single-point load test, ductility refers to a material's or structure's ability to undergo significant deformation before failure under an applied load. This property indicates how well a material can stretch or deform without breaking suddenly, demonstrating its resilience and capacity to absorb energy. During the test, ductility is assessed by observing how the material responds to increasing loads, which helps differentiate between gradual, ductile deformation and sudden, brittle failure. Understanding ductility is crucial in structural engineering because it enhances the overall resilience and safety of structures by enabling energy absorption and load redistribution. The single-point load test also helps determine key characteristics such as the yield point, where plastic deformation begins, and the ultimate point, which represents the maximum load the material can withstand before failing. These insights are essential for evaluating the material's performance under stress.

Table 6: Deflection values of all beams.

SPECIMEN ID	FIBER AND ADMIXTURE CONTENT	DEFLECTION (mm) (MK USED)			DEFLECTION (mm) (FA USED)		
		YIELD	ULTIMATE	FAILURE	YIELD	ULTIMATE	FAILURE
C	0	6.25	12.15	13.5	6.25	12.15	13.5
BSFM1	0.5 + 12.5	9.65	24.36	26.02	9.65	16.45	17.85
BSFM2	1 + 12.5	11.24	26.23	27.47	10.24	19.65	21.35
BSFM3	1.5 + 12.5	12.35	24.65	26.75	11.75	21.35	23.12
BNFM1	0.5 + 12.5	8.52	18.35	19.75	8.65	14.65	15.85
BNFM2	1 + 12.5	12.47	26.15	27.46	9.35	15.35	16.42
BNFM3	1.5 + 12.5	6.25	12.15	13.5	8.86	13.56	14.32

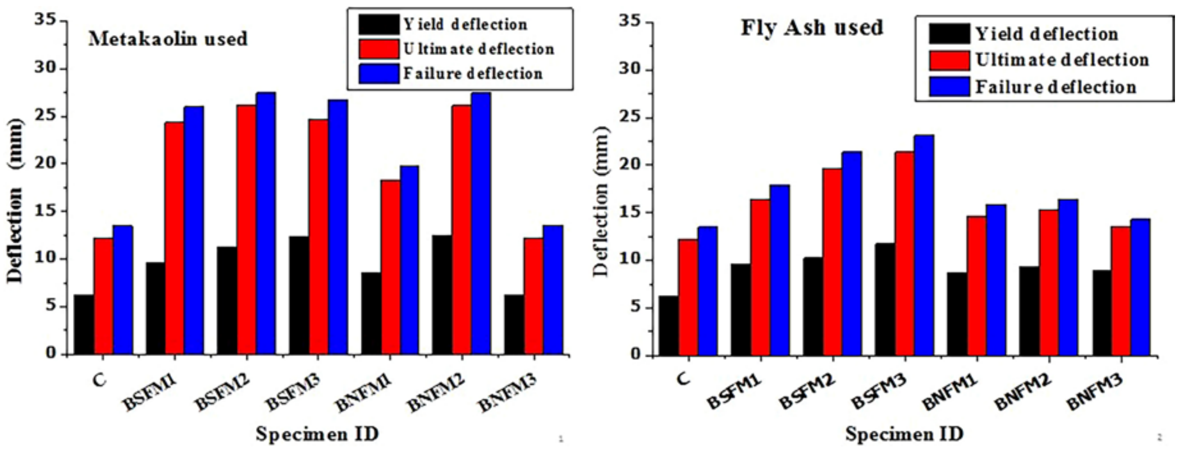

Figure 8: Deflection value of all beams with MK and FA.

Table 7: Ductility values of all beams.

SPECIMEN ID	FIBER AND ADMIXTURE CONTENT	DUCTILITY (MK USED)		DUCTILITY (FA USED)	
		YIELD	ULTIMATE	YIELD	ULTIMATE
C	0	1.94	1.11	1.94	1.11
BSFM1	0.5 + 12.5	2.52	1.07	1.70	1.09
BSFM2	1 + 12.5	2.33	1.05	1.92	1.09
BSFM3	1.5 + 12.5	2.00	1.09	1.82	1.08
BNFM1	0.5 + 12.5	2.15	1.08	1.69	1.08
BNFM2	1 + 12.5	2.10	1.05	1.64	1.07
BNFM3	1.5 + 12.5	2.14	1.04	1.53	1.06

Table 7 and Figure 9 illustrate the ductility of concrete specimens incorporating MK and FA as partial replacements for cement, with both showing data for yield ductility and ultimate ductility.

The control specimen shows a yield ductility of 1.94 and ultimate ductility of 1.11.MK specimens generally exhibit an increase in yield ductility compared to the control, with the highest value observed in BSFM1 at 2.52. This indicates that incorporating MK improves the ductility of concrete before significant cracking occurs. However, ultimate ductility remains around the control level for all MK specimens, with values ranging from

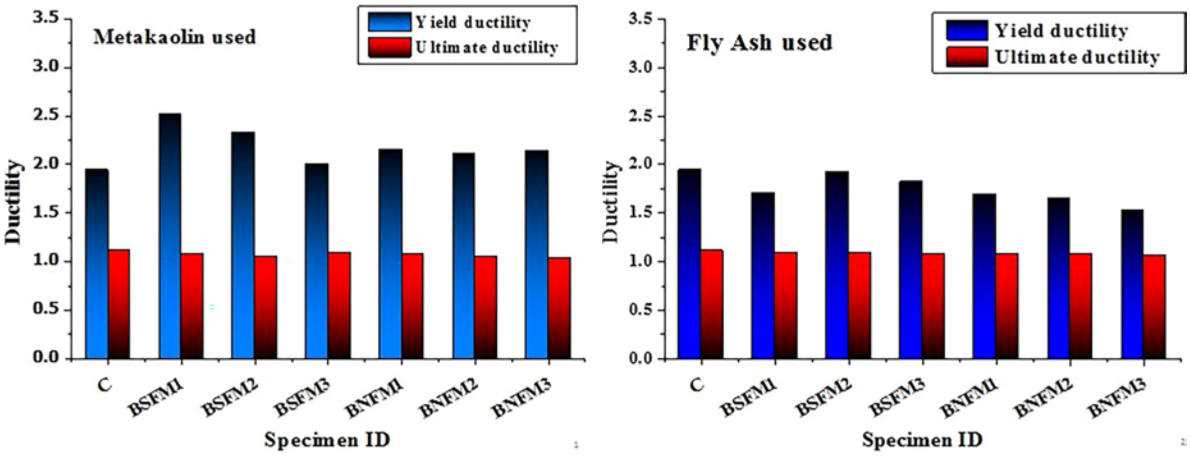

Figure 9: Ductility of all beams with MK and FA.

1.04 to 1.09. The highest ultimate ductility is in BSFM3 at 1.09, but this is only slightly better than the control. Similar to the MK control, FA control has a yield ductility of 1.94 and ultimate ductility of 1.11. The yield ductility for FA specimens is slightly lower compared to MK. The highest value is 1.92 for BSFM2, which is still below the highest MK value. The ultimate ductility for FA specimens shows less variation, with values tightly clustered around 1.06 to 1.09, similar to MK and the control.

The range of yield ductility is higher for MK specimens, varying between 2.00 and 2.52, with the control at 1.94. The increase in yield ductility indicates that MK enhances the concrete's ability to deform before yielding, making it more resilient under load. The yield ductility for FA specimens ranges from 1.53 to 1.92, indicating a less pronounced improvement compared to MK. FA specimens exhibit lower ductility, showing that FA doesn't contribute as much to deformation capacity before yielding. Both MK and FA specimens exhibit similar ultimate ductility values, ranging between 1.04 and 1.11. This indicates that neither MK nor FA significantly alters the material's behavior at the point of failure.

The MK mixes generally show a higher yield ductility compared to the control and FA mixes, indicating that MK improves the material's ability to undergo plastic deformation before cracking. The highest ductility is observed in BSFM1 with a yield ductility of 2.52. FA mixes, on the other hand, show slightly lower yield ductility and exhibit less variation in ultimate ductility, which is mostly around 1.06 to 1.09. This suggests that MK concrete mixes are more ductile and have better energy absorption capacity compared to FA mixes.

3.4. Stiffness

The stiffness test is a mechanical assessment used to measure a material's resistance to deformation under an applied load. This test involves applying a force or displacement to a material specimen, measuring the resulting deflection or strain, and calculating the material's stiffness or Young's modulus. Stiffness is a critical property in engineering, as it affects the design and performance of structures and components. Materials with high stiffness are ideal for applications requiring rigidity and stability, such as in construction materials or automotive parts. Various methods can be used to conduct the stiffness test, including bending, compression, or tension tests, depending on the material and its intended application. By evaluating a material's stiffness, engineers can assess its suitability for specific uses and ensure that it meets the required performance and durability standards. Table 8 presents the stiffness of concrete specimens incorporating MK and FA, detailing their yield stiffness and ultimate stiffness. Stiffness is a key parameter in understanding the rigidity of concrete under applied loads, defined as the material's resistance to deformation.

The control specimen has a yield stiffness of 3.58 kN/mm and an ultimate stiffness of 7.87 kN/mm. BSFM1 shows an increase in yield stiffness (5.77 kN/mm), indicating that even with 0.5% fiber and 12.5% MK, the mix becomes significantly stiffer compared to the control. BSFM2 and BSFM3 exhibit further improvements in yield stiffness, reaching values of 7.62 kN/mm and 8.93 kN/mm, respectively. This demonstrates that increasing the fiber content to 1.5% substantially enhances the material's resistance to deformation. The yield stiffness increases across the MK specimens, showing that MK improves the concrete's initial resistance to deformation. BSFM1 shows a reduction compared to the control, but BSFM2 and BSFM3 have higher values, with BSFM3

Table 8: Stiffness values of all beams.

SPECIMEN ID	FIBER AND ADMIXTURE CONTENT	STIFFNESS (kN/mm) (MK USED)		STIFFNESS (kN/mm) (FA USED)	
		YIELD	ULTIMATE	YIELD	ULTIMATE
C	0	3.58	7.87	3.58	7.87
BSFM1	0.5 + 12.5	5.77	5.19	4.70	7.19
BSFM2	1 + 12.5	7.62	7.10	5.54	7.98
BSFM3	1.5 + 12.5	8.93	8.75	6.27	9.16
BNFM1	0.5 + 12.5	3.58	7.87	4.45	6.99
BNFM2	1 + 12.5	5.67	5.58	5.17	7.51
BNFM3	1.5 + 12.5	6.13	4.68	4.70	7.92

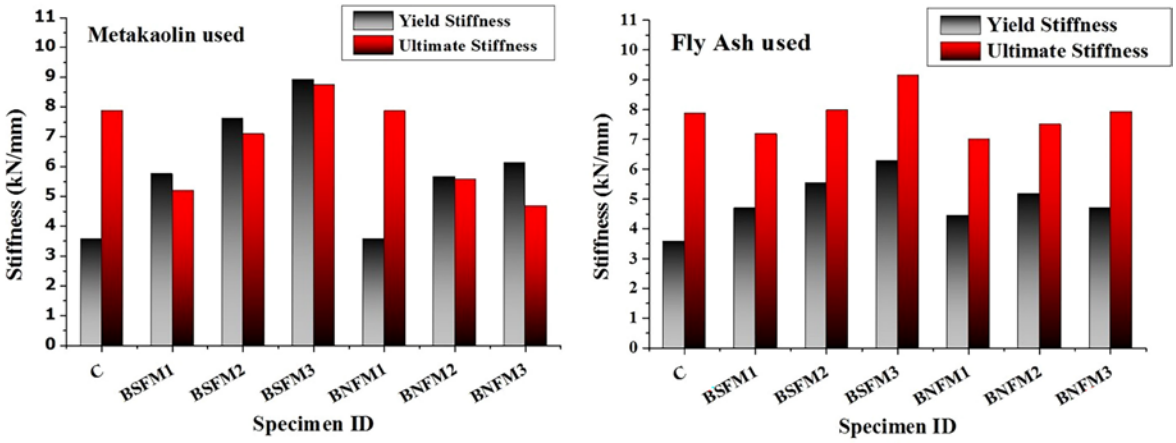

Figure 10: Stiffness of all beams with MK and FA.

achieving 8.75 kN/mm, the highest ultimate stiffness among MK specimens (Figure 10). The trend suggests that at higher MK and fiber content, both yield and ultimate stiffness increase, although the ultimate stiffness values are more variable across different mixes.

The control specimen's yield stiffness is 3.58 kN/mm and ultimate stiffness is 7.87 kN/mm, similar to MK. BSTF1 and BNFM1 exhibit improvements in yield stiffness, with values around 4.45 to 4.70 kN/mm, slightly higher than the control but lower than MK mixes. As the fiber content increases, yield stiffness also increases. BSFM3 reaches 6.27 kN/mm, the highest yield stiffness for FA mixes, but still lower than the yield stiffness for MK specimens at the same fiber content. FA specimens maintain relatively high ultimate stiffness values, with BSFM3 reaching 9.16 kN/mm, which is higher than the ultimate stiffness for most MK specimens. FA mixes tend to show better ultimate stiffness compared to yield stiffness, meaning they perform better at higher loads nearing failure. This might indicate that while FA improves the long-term deformation resistance, its effect on initial stiffness is lower than MK.

Concrete is strong in compression but weak in tension. As cracks develop, particularly at higher loads, the concrete loses its ability to resist stress, reducing overall stiffness and ductility. Once the steel reinforcement reaches its yield point, it cannot resist additional stress in the same way, contributing to a reduction in stiffness. At the ultimate stage, if the steel is fully yielded, it cannot provide additional load-carrying capacity, further decreasing ductility. As the load increases, the bond between the concrete and steel reinforcement can weaken, especially near the ultimate stage, leading to reduced load transfer efficiency and lower stiffness. At the ultimate point, deflections become large due to the reduction in stiffness, and cracks may cause localized failures in the concrete, making it less able to absorb energy through deformation (lower ductility).

3.5. Energy absorption

Energy absorption (measured in kN/mm) represents a material's capacity to absorb energy under load, which is crucial for assessing the ductility, toughness, and overall resistance to failure of concrete. Higher energy absorption means the material can sustain larger loads before failure, making it more resistant to sudden fractures or collapse, especially in structures exposed to dynamic or impact loads. Energy absorption is typically divided into two phases, like Yield Energy Absorption and Ultimate Energy Absorption. The energy absorbed by the material before significant deformation or yielding occurs. The energy absorbed until the material reaches its maximum load capacity or ultimate failure. Table 9 shows the values of energy adsorption of MK and FA used beams.

BSFM1 shows a substantial increase in yield energy absorption (290.02 kN/mm) compared to the control. Even with a low fiber content (0.5%), the energy absorption is more than 4 times higher than the control, indicating significant toughness improvement. As the fiber content increases, the energy absorption further improves. BSFM3, with 1.5% fibers, reaches 684.00 kN/mm, a tenfold increase compared to the control, illustrating that higher fiber content significantly boosts the material's ability to absorb energy before yielding. The ultimate energy absorption follows a similar trend. BSFM1 has a notable increase to 1339.71 kN/mm, while BSFM3 reaches 2004.29 kN/mm, a dramatic improvement compared to the control. The range of ultimate energy absorption for MK specimens is 1339.71 kN/mm to 2004.29 kN/mm, significantly higher than the control's 348.07 kN/mm (Figure 11), highlighting the increased toughness and durability of the MK-modified concrete under high-stress conditions.

FA mixes also show an increase in energy absorption compared to the control, but the improvement is not as significant as in MK specimens. For instance, BSFM1 shows an increase to 226.48 kN/mm, and BSFM3 reaches 424.40 kN/mm. The yield energy absorption in FA specimens remains lower than MK specimens for all

Table 9: Energy adsorption values of all beams.

SPECIMEN ID	FIBER AND ADMIXTURE CONTENT	ENERGY ABSORPTION (kN/mm) (MK USED)		ENERGY ABSORPTION (kN/mm) (FA USED)	
		YIELD	ULTIMATE	YIELD	ULTIMATE
C	0	66.83	348.07	66.83	348.07
BSFM1	0.5 + 12.5	290.02	1339.71	226.48	556.51
BSFM2	1 + 12.5	446.94	2038.42	278.76	1004.52
BSFM3	1.5 + 12.5	684.00	2004.29	424.40	1292.64
BNFM1	0.5 + 12.5	202.74	740.69	170.22	422.40
BNFM2	1 + 12.5	482.41	1359.79	223.03	491.01
BNFM3	1.5 + 12.5	391.76	1172.60	189.68	350.31

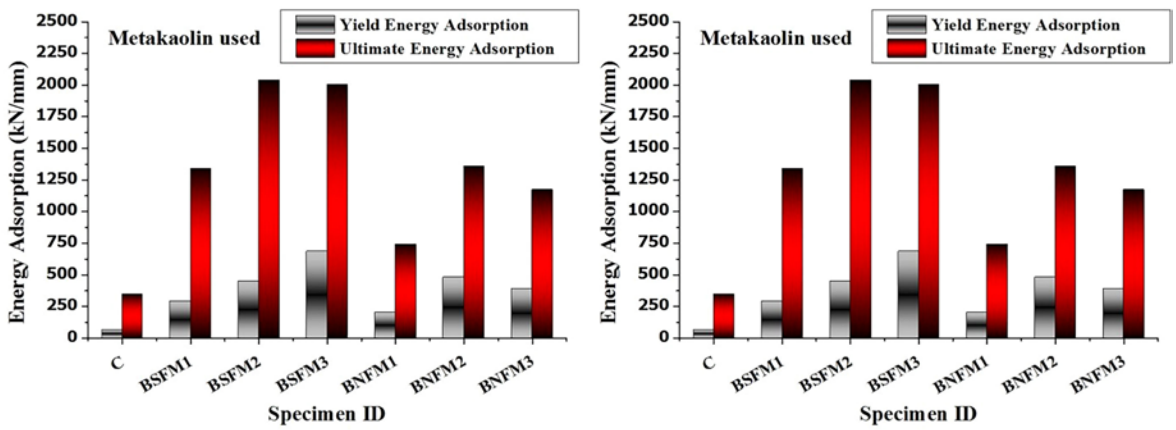

Figure 11: Energy adsorption of all beams with MK and FA.

fiber contents, indicating that MK-modified concrete has a superior capacity to absorb energy before yielding. FA specimens exhibit increased ultimate energy absorption compared to the control, though not as substantial as MK specimens. BSFM3 reaches 1292.64 kN/mm, which is still lower than the corresponding MK mix. The range of ultimate energy absorption for FA specimens is 350.31 kN/mm to 1292.64 kN/mm, a notable improvement over the control but generally lower than the MK mixes at the same fiber content.

Energy absorption in concrete beams is a measure of the material's ability to absorb energy under load, which is critical for assessing its ductility, toughness, and resistance to failure. Higher energy absorption indicates greater ability to resist sudden fractures or collapse, especially under dynamic or impact loads. The study shows that with an increase in fiber content, especially basalt fibers, there is a substantial improvement in energy absorption. For example, the energy absorption of BSFM3 (1.5% fibers) is significantly higher (684.00 kN/mm) compared to the control (lower than 100 kN/mm), demonstrating that increased fiber content boosts the material's energy absorption capacity before yielding.

3.6. Energy dissipation

Energy dissipation refers to the ability of a material or structural element to absorb and dissipate energy under load, typically during deformation or failure. In the context of fiber-reinforced concrete (FRC), energy dissipation plays a crucial role in enhancing the structural resilience of concrete under dynamic loads, such as earthquakes, impacts, or blasts. FRC incorporates fibers into the concrete matrix to improve the material's ability to resist crack propagation, thereby improving both toughness and energy absorption. By introducing admixtures like MK and FA, concrete mixes can exhibit enhanced mechanical properties and durability, as well as improved energy dissipation capacity. Table 10 represents the energy dissipation characteristics of concrete specimens that contain different combinations of fibers and admixtures required for enhancing the ductility of the concrete.

The energy dissipation values for both MK and FA mixtures span a wide range, depending on the fiber content. The control specimen without fibers or admixtures has the lowest energy dissipation at both yield (91.64 kN/mm) and ultimate (564.28 kN/mm) stages, reflecting the brittle behavior of plain concrete (Figure 12). For MK-based mixes, the energy dissipation increases with increasing fiber content. At 1.5% fiber content, the BSFM3 specimen recorded the highest energy dissipation at yield (992.25 kN/mm) and ultimate (2652.50 kN/mm), demonstrating a significant improvement compared to the control.Similarly, FA-based mixes also show an increase in energy dissipation, though generally lower than MK. The BSFM2 (1% fiber) recorded a yield value of 385.33 kN/mm and an ultimate value of 1475.02 kN/mm, while BSFM3 (1.5% fiber) reached higher values (589.20 kN/mm yield, 1878.24 kN/mm ultimate), though still less than MK counterparts.

3.7. Microstructural analysis

The SEM analysis (Figure 13) revealed valuable insights into the microstructure of basalt fiber reinforced concrete incorporating metakaolin. The presence of basalt fibers was clearly observed, dispersed throughout the concrete matrix. These fibers acted as crack-bridging elements, preventing the propagation of larger, critical cracks. The formation of large CSH gel formations was also evident, indicating a strong bond between the fibers and the surrounding matrix. The addition of metakaolin and fly ash to the concrete mix influenced the formation and properties of the interfacial transition zone (ITZ) and the distribution of CSH. The incorporation of basalt fibers, metakaolin, and fly ash into concrete resulted in significant improvements in mechanical

Table 10: Energy dissipation values of all beams.

SPECIMEN ID	FIBER AND ADMIXTURE CONTENT	ENERGY DISSIPATION (kN/mm) (MK USED)		ENERGY DISSIPATION (kN/mm) (FA USED)	
		YIELD	ULTIMATE	YIELD	ULTIMATE
C	0	91.64	564.28	91.64	564.28
BSFM1	0.5 + 12.5	378.42	1860.82	307.99	804.58
BSFM2	1 + 12.5	649.86	2793.39	385.33	1475.02
BSFM3	1.5 + 12.5	992.25	2652.50	589.20	1878.24
BNFM1	0.5 + 12.5	293.48	1006.10	234.16	614.10
BNFM2	1 + 12.5	714.81	1673.75	301.22	691.92
BNFM3	1.5 + 12.5	587.63	1457.95	258.46	505.02

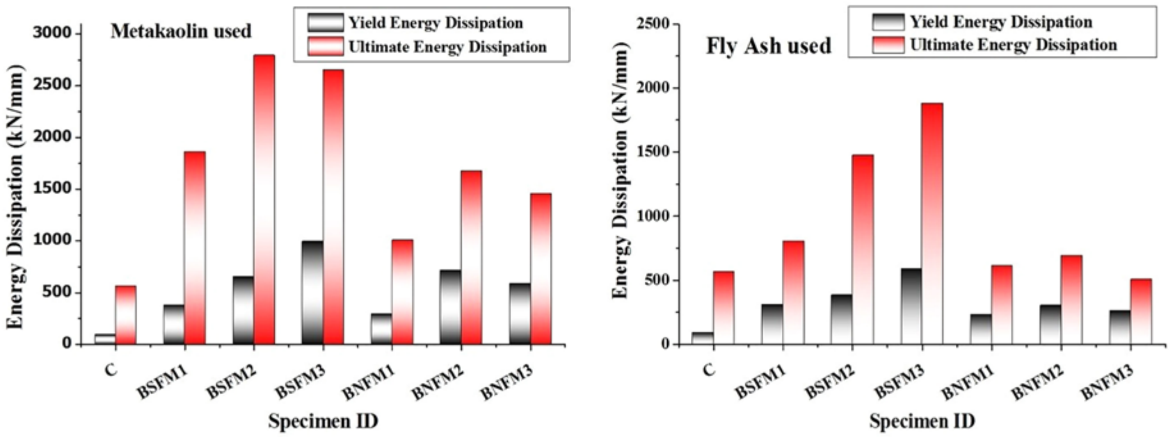

Figure 12: Energy dissipation of all beams with MK and FA.

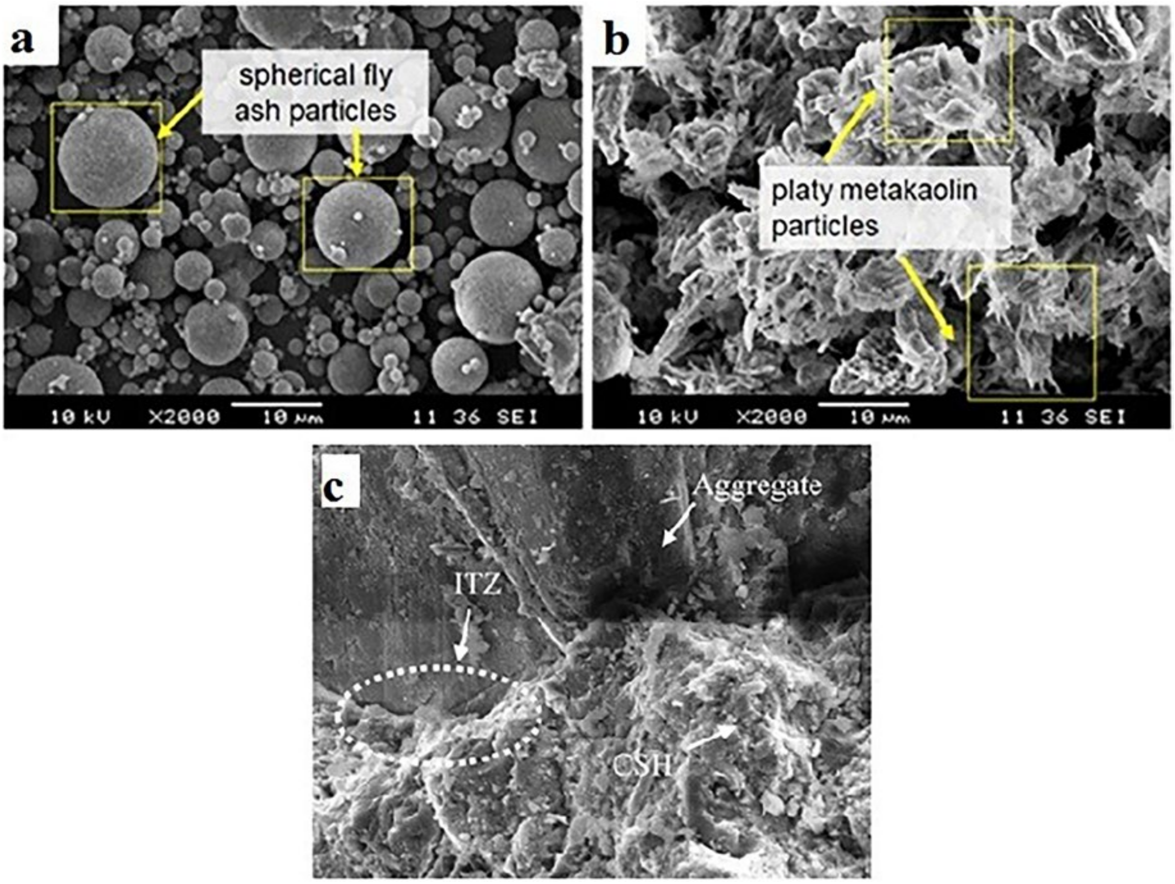

Figure 13: SEM images of the material observation and ITZ for BSFM3.

properties. The fibers provided a mechanism for bridging cracks and distributing stress, preventing the formation of larger, critical cracks. The pozzolanic properties of metakaolin and fly ash contributed to enhanced strength by reacting with calcium hydroxide to form additional CSH gel. This increased CSH formation enhanced the overall matrix strength and improved the bond between the fibers and the surrounding concrete. The combined effect of these factors led to increased flexural and compressive strength, as well as improved durability.

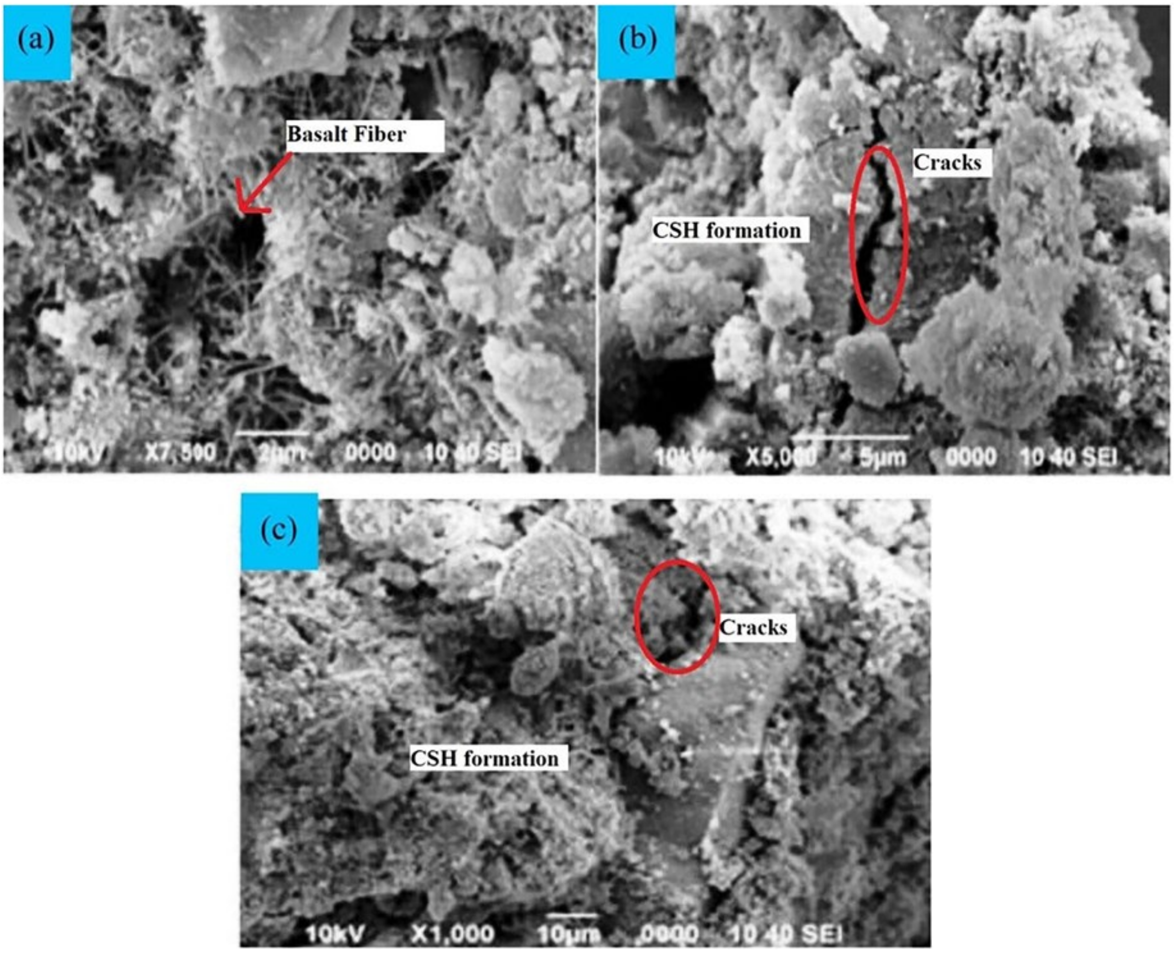

Figure 14: SEM images of the formation CSH gel and cracks in BSFM3 mix.

The optimal fiber content for achieving maximum strength benefits in basalt fiber reinforced concrete with metakaolin and fly ash may vary depending on factors such as the fiber type, size, and distribution. Experimental studies are necessary to determine the optimal fiber content for specific applications. Additionally, the properties of the concrete matrix, including its water-cement ratio and curing conditions, can also influence the effectiveness of fiber reinforcement. Future research can explore the potential of using other types of fibers or combining different types of fibers to further enhance the mechanical properties of concrete. Additionally, investigating the long-term performance of basalt fiber reinforced concrete with metakaolin and fly ash under various environmental conditions is essential to assess its durability and suitability for different applications.

MK and FA enhance the microstructure of concrete by improving the ITZ between the aggregates and the cement matrix. MK and FA are pozzolanic materials that react with calcium hydroxide in the concrete to form additional calcium silicate hydrate CSH gel, which increases the overall strength of the matrix. The SEM analysis showed that basalt fibers dispersed throughout the concrete matrix helped bridge cracks, preventing their propagation and distributing stress. The incorporation of MK and FA also enhanced the bond between the fibers and the surrounding concrete, resulting in improved mechanical properties like flexural and compressive strength, as well as better durability and resistance to cracking.

Figure 14 offer valuable insights into the microstructure of basalt fiber reinforced concrete incorporating metakaolin. In image (a), the presence of basalt fibers is clearly visible, dispersed throughout the concrete matrix. Image (b) highlights the formation of cracks within the concrete, which are likely mitigated by the presence of the fibers. Additionally, the development of large CSH gel formations is observed, indicating a strong bond between the fibers and the surrounding matrix. Image (c) further emphasizes the crack-bridging effect of the fibers, as they are seen to span across the cracks and contribute to overall structural integrity.

The observed improvements in strength properties can be attributed to several factors. The addition of basalt fibers provides a mechanism for bridging cracks and distributing stress, preventing the formation of larger, critical cracks. Moreover, the presence of metakaolin, a pozzolanic material, contributes to enhanced strength by reacting with calcium hydroxide to form additional CSH gel. This increased CSH formation enhances the overall matrix strength and improves the bond between the fibers and the surrounding concrete.

4. RESULT AND DISCUSSION

The MK-enhanced specimens demonstrate a more significant increase in yield, ultimate, and failure loads compared to FA specimens, aligning with MK's properties of improving flexural strength. The highest-performing MK mix (BSFM3) suggests that optimized MK content greatly enhances load-bearing capacity (Figures 13 and 15). While FA specimens exhibit modest improvements, they do not match the performance of MK mixes, particularly in early strength gains. MK and FA increase yield load, delaying crack formation, but MK mixes (BSFM3) achieve the highest ultimate and failure loads, indicating superior structural resilience. FA's improvements are more subdued but still beneficial compared to the control.

MK-enhanced concrete shows greater ductility, particularly in mixes like BSFM3 and BNFM2, which can sustain larger deflections before failure, suggesting higher energy absorption. FA mixes, while stiffer, exhibit less ductility, indicating lower energy absorption but greater rigidity. This may be beneficial in situations requiring high stiffness. The greater deflection range in MK specimens suggests a more ductile failure mode, while FA mixes exhibit more brittle behavior, showing narrower deflection ranges and faster failure once the ultimate load is reached.

In terms of ductility, MK specimens show significant improvement in yield ductility, with mixes like BSFM1 and BSFM2 showing enhanced deformation capacity before cracking. FA specimens, in contrast, offer limited improvements in yield ductility, aligning with their known properties of enhancing workability and long-term durability rather than ductility (Figure 14 and 16). MK's broader range in yield ductility makes it more suitable for applications requiring flexibility, whereas FA offers benefits in stiffness without significantly affecting ductility [15].

The yield stiffness of MK specimens increases significantly with higher fiber content, ranging from 5.77 kN/mm to 8.93 kN/mm, compared to 3.58 kN/mm in the control, indicating better resistance to early-stage deformation. FA specimens show moderate stiffness improvement, with values between 4.45 kN/mm and 6.27 kN/mm. MK specimens also exhibit higher ultimate stiffness, with BSFM3 achieving 8.75 kN/mm. While FA specimens show consistent ultimate stiffness, some, like BSFM3, reach 9.16 kN/mm, highlighting FA's potential to improve stiffness under high load conditions, likely due to its long-term pozzolanic reaction.

MK-modified concrete shows a significant improvement in yield energy absorption, ranging from 290.02 kN/mm to 684.00 kN/mm, compared to the control. FA-modified concrete also shows improvements, but the range (226.48 kN/mm to 424.40 kN/mm) is less impressive than MK. MK specimens also demonstrate superior ultimate energy absorption, ranging from 1339.71 kN/mm to 2004.29 kN/mm, while FA-modified specimens show lower values (350.31 kN/mm to 1292.64 kN/mm). In terms of energy dissipation, MK specimens (BSFM series) show a clear trend of improvement with increased fiber content, with BSFM3 recording the highest values. FA specimens (BNFM series) also improve energy dissipation, though their performance remains lower than the MK-based mixes.

4.1. Comparative analysis

Table 11 represents the comparing the proposed work with the literature, several key distinctions and advancements stand out, particularly in terms of load-bearing capacity and the synergistic effects of different fiber types combined with supplementary materials like MK and FA.

The proposed RC beams, reinforced with Basalt Fiber Mix (BSFM) and Banana Fiber Mix (BNFM) in combination with MK and FA, exhibit notably higher load capacities than most beams reported in the literature. For instance, the highest load achieved in the proposed work (BSFM3-MK at 215.65 kN) significantly surpasses the basalt fiber-reinforced beams from the literature, which reported maximum loads of 135.15 kN (2022) and 145.65 kN (2023). This indicates that the integration of MK and FA, particularly with BSFM mixes, has a pronounced positive effect on structural performance. The use of MK and FA as partial replacements for OPC in the proposed work has resulted in substantial improvements in the load-bearing capacity. For example, the BSFM2-MK (186.35 kN) and BSFM3-FA (195.65 kN) mixes significantly outperform fiber-reinforced beams from previous studies, even those using advanced fiber combinations like basalt-polypropylene [17] (142.30 kN in 2022). This suggests that the proposed work not only introduces new material combinations but also enhances the sustainability of the beams by reducing reliance on traditional cement while improving their mechanical properties.

Table 11: Comparative (statistical) analysis of proposed work and literature.

YEAR	SPECIMEN	TYPE OF FIBER	EXP. LOAD (kN)	THEOR. LOAD (kN)	REF.
2024	RC Beam	Basalt fiber	180	179.52	[39]
2023	RC Beam	Basalt and Geo-Textile Fiber	52.35	51.50	[20]
2023	Beam	Basalt fiber	145.65	144.85	[22]
2023	Beam	Banana fiber	40.25	38.85	[23]
2022	RC Beam	Basalt fiber	125.65	124.50	[31]
2022	RC Beam	Basalt fiber	135.15	135.25	[30]
2022	Beam	sisal and banana fiber	105.32	104.96	[29]
2022	Beam	chemically treated banana fiber	122	121.35	[27]
2022	RC Beam	basalt fiber/polypropylene fiber	142.30	141.60	[17]
2021	RC Beam	basalt fiber polymer	125.65	125.10	[19]
2019	RC Beam	Banana-Jute Hybrid Fiber	95.54	95.10	[15]
2020	RC Beam	banana/glass fiber	86.26	85.80	[9]
Proposed	RC Beam	BSFM1-MK	126.5	125.86	Author
	RC Beam	BSFM2-MK	186.35	185.65	
	RC Beam	BSFM3-MK	215.65	214.65	
	RC Beam	BNFM1-MK	102.35	101.85	
	RC Beam	BNFM2-MK	122.35	122.10	
	RC Beam	BNFM3-MK	112.15	110.32	
	RC Beam	BSFM1-FA	118.32	117.56	
	RC Beam	BSFM2-FA	156.75	155.63	
	RC Beam	BSFM3-FA	195.65	195.12	
	RC Beam	BNFM1-FA	102.35	101.85	
	RC Beam	BNFM2-FA	115.32	114.65	
	RC Beam	BNFM3-FA	107.45	105.98	
	Mean		125.72	124.98	
	Standard Deviation		40.15	40.08	
	Coefficient of variation %		32.62	32.45	

The literature demonstrates that different fiber types yield varying structural results, with basalt fibers generally outperforming banana and hybrid fibers like banana-jute [15] and banana-glass [9]. However, the proposed work elevates performance through hybrid fiber mixes (BSFM and BNFM), where the BSFM mixes consistently achieve higher load capacities. For instance, the BSFM1-MK (126.5 kN) outperforms most banana fiber-reinforced beams from the literature, such as the banana-glass fiber [9] beam (86.26 kN in 2020) and the banana-jute hybrid fiber [15] beam (95.54 kN in 2019). This deep comparison underscores the effectiveness of fiber hybridization and optimization in enhancing RC beam performance in the proposed work.

The proposed research significantly improves upon the findings in the literature by achieving superior load-bearing capacities with fiber-reinforced RC beams. The inclusion of MK and FA further enhances mechanical properties, demonstrating a more sustainable and high-performance solution compared to traditional fiber-reinforced concrete beams. The results of the proposed work suggest a clear advancement in structural performance, particularly with the Basalt Fiber Mix (BSFM) reinforced beams.

4.2. Failure pattern

The beams tested still fail under the three-point loading; the failure specimens are depicted in Figure 15. According to the experimental study, the standard mode of failure observed from all beams is a concrete crushing failure. The control beams failed with concrete crushing, flexural behaviour, and shear failure. Similarly, the addition of the banana and basalt fibre on beams leads to an increase in the tensile strength of the specimens.

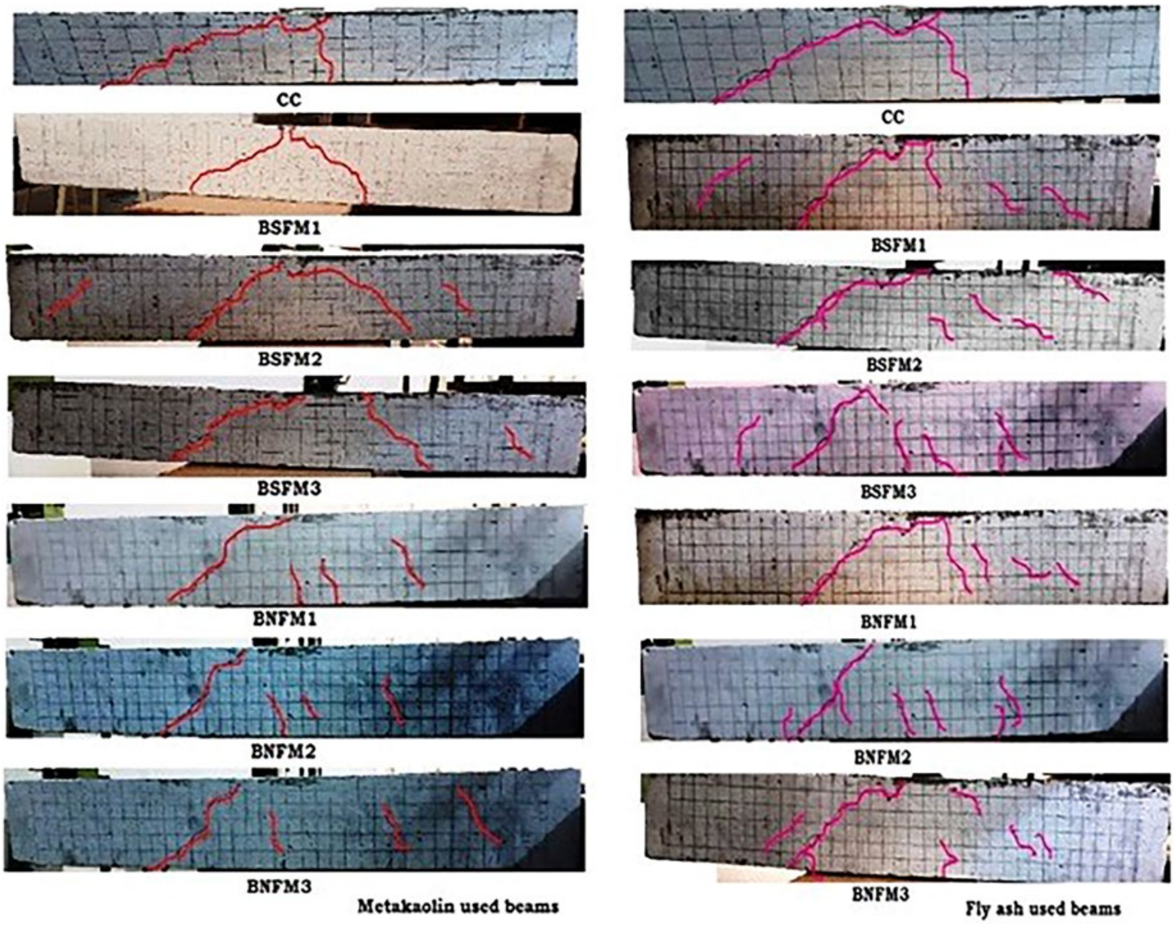

Figure 15: Failure mode of all beams.

The mode of failure of the specimens is commonly divided into three parts: the load-deflection response linear behaviour up to the yield point of the beams [33–35]. In the second stage, the specimens reach the elastic to the plastic stage. In this stage, minor cracks are propagated throughout the specimens. In the third stage, the specimens are failed after reaching the ultimate load. The ductility and stiffness are determined for all specimens, as reported in Table 7 and 8.

5. CONCLUSION AND FUTURE STUDY

1. MK-enhanced concrete shows superior mechanical performance compared to FA-enhanced concrete, particularly in yield, ultimate, and failure loads. The highest-performing MK mix, BSFM3, achieved the greatest load-bearing capacity, highlighting MK's significant impact on structural resilience.
2. FA specimens provide modest improvements over the control but fall short of MK mixes, especially at early curing stages. FA primarily enhances workability and long-term durability rather than immediate strength. Both MK and FA surpass the control in yield load, with MK consistently demonstrating greater load-carrying capacity across all stages.
3. MK produces more ductile concrete with higher deflection capacity before failure, making it ideal for applications requiring energy absorption and flexibility. In contrast, FA contributes to stiffness and rigidity, suited for applications where high rigidity is necessary. The increased deflection range in MK mixes emphasizes their superior deformation resistance.
4. MK significantly enhances yield ductility, making it suitable for structures that must endure large deformations before cracking. Although its impact on ultimate ductility is minor, MK improves concrete behavior under stress. FA offers more modest improvements in ductility, particularly at the yield stage, and may be preferred where workability or long-term durability is prioritized.

5. MK improves both yield and ultimate stiffness, with higher values as fiber and MK content increase. MK provides increased early-stage stiffness and improved ultimate stiffness, though performance varies. FA also enhances stiffness, particularly under ultimate loads, and sometimes exceeds MK mixes in this regard, reflecting its benefits in long-term durability.
6. MK-modified concrete demonstrates superior energy absorption, especially with higher fiber content, making it highly effective for enhancing toughness and durability. FA-modified concrete shows moderate improvements in energy absorption and is less effective than MK, making it suitable for applications where moderate toughness is sufficient.

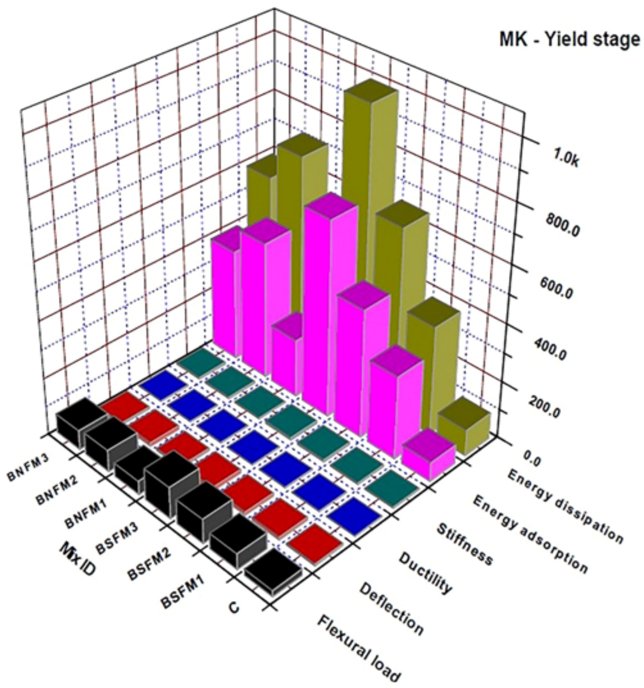

Figure 16: Comparison graph of mechanical properties of all beams at yield stage using MK.

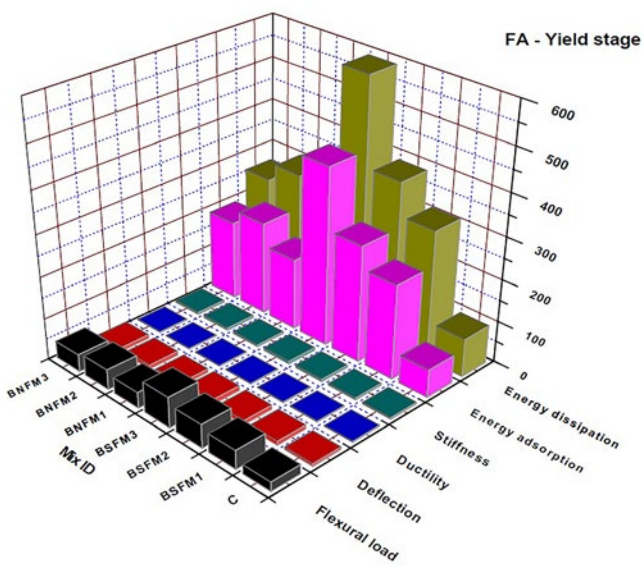

Figure 17: Comparison graph of mechanical properties of all beams at yield stage using FA.

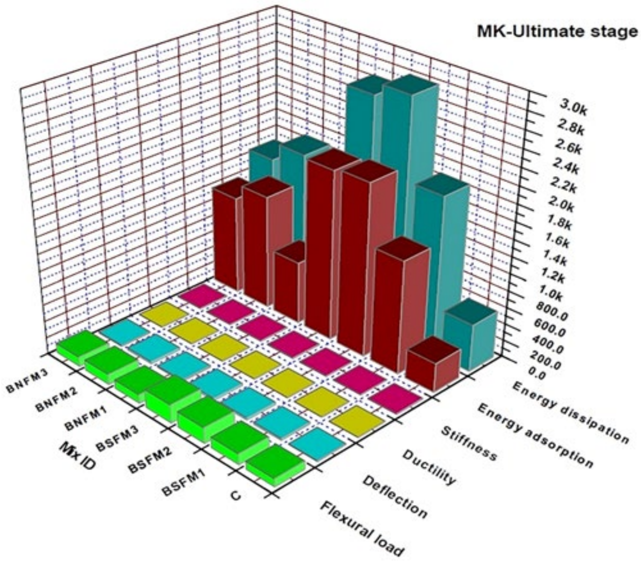

Figure 18: Comparison graph of mechanical properties of all beams at ultimate stage using MK.

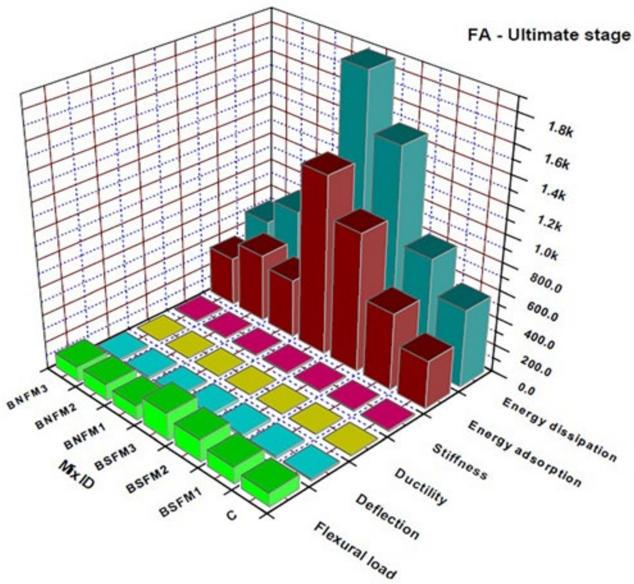

Figure 19: Comparison graph of mechanical properties of all beams at ultimate stage using FA.

7. Both MK and FA significantly improve energy dissipation, with MK-based mixes consistently showing superior performance, particularly at higher fiber contents. The BSFM3 mix, combining 1.5% fiber with 12.5% MK, is most effective in optimizing energy absorption and load resistance.

MK significantly improves yield, ultimate, and failure loads, with the BSFM3 mix demonstrating the highest load-bearing capacity (Figure 16–19). MK also enhances ductility and deflection capacity before failure, making it ideal for applications requiring high flexibility and energy absorption. In contrast, FA offers modest improvements in strength and stiffness, with notable benefits in workability and long-term durability, but does not match MK's performance, especially at early curing stages. Both MK and FA increase yield load, delaying crack formation, but MK consistently shows superior load-carrying capacity. MK's ability to enhance energy absorption further underscores its effectiveness in improving concrete toughness and resilience.

6. ACKNOWLEDGMENTS

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