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MECHANICAL PERFORMANCE OF HYBRID FIBER-REINFORCED CONCRETE: THE SYNERGISTIC EFFECT OF RAMIE AND MICRO SYNTHETIC FIBERS

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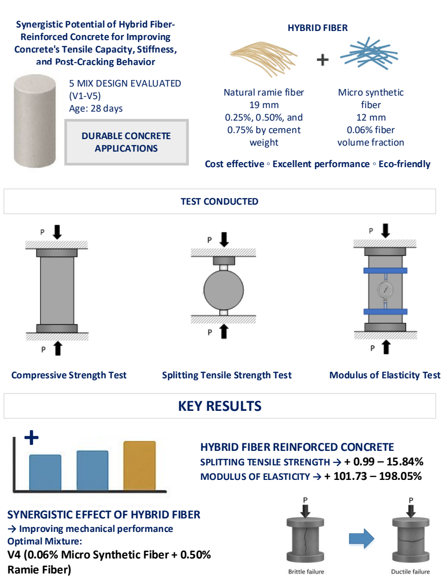
Graphical abstract



Abstract

Conventional concrete has limitations in tensile strength and crack control. Fiber-reinforced concrete improves these properties, but single fiber types can hinder performance. While steel fibers are common, synthetic and natural fibers are gaining traction due to their cost-effectiveness, performance, and eco-friendliness. This research explores hybrid fiber concrete using micro synthetic (polyamide, 12 mm, 0.06% fiber volume fractions) and natural ramie (19 mm, 0.25%, 0.50%, 0.75% by cement weight) fibers to enhance mechanical performance. Five mix designs (V1-V5) were evaluated for compressive strength, splitting tensile strength, and modulus of elasticity at 28 days. Results showed that plain concrete (V1) had the highest compressive strength of 32.44 MPa but suffered brittle failure. V2 (micro synthetic fibers only) showed the lowest strength, indicating limited effectiveness. The addition of hybrid fibers (V3-V5) significantly increased the splitting tensile strength of concrete by 0.99-15.84% and modulus of elasticity by 101.73-198.05% higher than plain concrete. Hybrid fibers also transformed the failure mode from brittle to ductile. The V4 mixture represents the most effective combination of strength, stiffness, and crack resistance. This research highlights the synergistic potential of hybrid fiber reinforcement for improving concrete's tensile capacity, stiffness, and post-cracking behavior, offering valuable insights for durable concrete applications.

Keywords: Hybrid fiber-reinforced concrete, ramie fiber, micro synthetic fiber, mechanical performance, synergistic effect

1.0 INTRODUCTION

Concrete's widespread use is underpinned by its strength and durability [1], [2]. However, its inherent disadvantages—low tensile strength, poor flexural resistance, and brittle failure results in cracking— [1], [3], [4] limit its application in structures demanding high ductility, such as large slabs and beam-column joints [5]. Fiber-reinforced concrete (FRC), which is defined by ACI 116R in Cement and Concrete Terminology [6] as concrete containing randomly dispersed and oriented fibers, has emerged as a key solution to act as internal reinforcement to significantly improve post-cracking performance, tensile capacity, and fatigue resistance [5], [7]–[11]. The use of fiber-reinforced concrete in beam-column joints has been carried out by several researchers and the results show that the structural ductility of beam-columns is improved. The addition of fibers in the cement matrix has considerable potential to be applied as it can reduce the need for reinforcement in the beam-column joint region through increased load-bearing capacity while providing easier joint design without the complexity of common ductile detailing [5].

Based on the ASTM Standard in the Standard Specification for Fiber-Reinforced Concrete (FRC), fiber concrete is classified into four different categories, namely type 1 (steel fiber), type 2 (glass fiber), type 3 (synthetic fiber), and type 4 (natural fiber) [12]. While conventional FRC often relies on steel fibers, synthetic and natural fibers are gaining prominence as sustainable and cost-effective alternatives [1], [4], [5], [13], [14]. Both types offer unique advantages; for instance, synthetic fibers provide excellent processability and usability as a reinforcement [5], [13]–[15], while natural fibers, such as ramie, are eco-friendly with neutral CO_2 emissions and possess a high specific strength [16]–[18]. The growing interest in these alternative fibers highlights a critical need to explore novel reinforcement strategies to fully leverage their potential in structural applications.

The primary limitation of using a single type of fiber in FRC is its restricted ability to bridge cracks across a wide range of scales—as it is restricted by the cracking zone and the limited volume fraction that can be added. Microfibers excel at controlling micro-cracks, while macro-fibers are more effective in bridging larger cracks [5]. Natural and synthetic fibers, in both macro and micro sizes, have their own advantages in bridging cracks on various scales and increasing tensile strength [5], [19]. This functional gap, along with the adverse effect of high fiber volume fractions on workability [20], has led to a growing interest in hybrid fiber systems. While recent studies have explored hybridizing different types of synthetic fibers or different types of natural fibers, there is a distinct lack of research on the synergistic effects of combining synthetic and natural fibers, particularly in the context of their mechanical performance. To the best of the authors' knowledge, no prior research has investigated the hybrid effect of micro synthetic fibers and ramie fibers on the mechanical properties of concrete. This research specifically addresses this knowledge gap by exploring the potential of such a hybrid system.

Natural ramie fiber and micro synthetic fiber were selected for this research due to their distinct characteristics and documented performance. Micro synthetic fibers, with their small diameter, are highly effective in increasing tensile strength, toughness modulus, elastic linear fracture energy, and controlling micro-crack propagation, where this fiber size also has good compatibility and workability for application in concrete of various size, as evidenced by previous studies with polyamide-based (12 mm length, 27 µm, tensile strength 900 MPa, fiber volume fraction of 0.06%) and polypropylene-based (19 mm length, tensile strength 570-660 MPa, fiber volume fraction of 0.30%) micro synthetic fibers [1], [2], [5], [21]. Ramie fiber, on the other hand, offers a unique combination of high tensile strength, lightweight, biodegradability, and eco-friendly properties [1], [22], [23]. Ramie fiber comes from the Boehmeria nivea plant where the bark of the plant is separated with a decorticator [24]. Ramie fiber has various advantages over other natural fibers such as high tensile strength and water absorption, light weight, good resistance to moisture, bacteria, and heat, and is environmentally friendly [25]. Ramie fiber has a tensile strength of about 1050 MPa, modulus of elasticity of 61.5 GPa, strain of 3.6 - 3.8%, diameter of 40 - 80 µm, flexural strength and density of 1.5 - 1.6 gr/cm^3, where the tensile strength of ramie fiber and modulus of elasticity are higher than other natural fibers such as kenaf fiber, coconut fiber, banana fiber, pineapple fiber, and cotton fiber [22]. While studies have shown its effectiveness in improving tensile and flexural strength (0.5% and 0.75% by the weight of cement) [22], [26], the synergistic interaction of ramie with micro synthetic fibers remains largely unexplored. This combination is particularly promising as it may allow for a dual-scale crack bridging mechanism: micro synthetic fiber addressing early-stage micro-cracks and ramie fiber bridging larger macro-cracks, thereby enhancing the overall ductility and energy absorption capacity. However, based on Mahendra & Risdianto (2019) [22] excessive amounts of ramie fiber in concrete mixtures can reduce the mechanical properties of concrete due to the water-absorbing nature of the fiber so that the water needed in the concrete hydration process is reduced and the bonding process is disrupted. The treatment of ramie fiber can be carried out by washing it in a 10% NaOH solution to reduce the lignin content in the ramie fiber. The utilization of ramie fibers as a composite material such as in concrete construction can increase the function of natural materials and the development of research and technology on this material is a good step to increase the market value of local materials.

In addition to diameter, another factor to consider is the length of the fiber used in the concrete. The crack area formed in the concrete will be held by fibers of a certain length where the fiber length will have a significant effect on the ability to withstand cracks that occur. Based on research conducted by Noorvand et al. (2022) [27] related to fiber-reinforced concrete with varying fiber lengths, fibers with a length of 19 mm provide better performance than fibers with lengths of 10 mm and 38 mm. It was also noticed that short fibers affect microcrack bridging and tensile strength improvement, while long fibers have an impact on microcrack bridging and ductility enhancement [28].

Based on the identified knowledge gap, this research aims to investigate the synergistic effects of a hybrid fiber system combining micro synthetic and natural ramie fibers on the mechanical properties of concrete. This research will develop hybrid fiber-reinforced concrete using micro synthetic fibers made from polyamide (Kratos MicroFiber with a length of 12 mm) and natural fibers made from ramie (length of 19 mm). The concrete materials were formulated through mix design with a target concrete strength of 30 MPa according to SNI 7656-2012 [29].This research was conducted by varying 5 concrete mix designs, namely V1 (0% synthetic fiber; 0% ramie fiber); V2 (0.06% synthetic fiber; 0% ramie fiber); V3 (0.06% synthetic fiber; 0.25% ramie fiber); V4 (0.06% synthetic fiber; 0.5% ramie fiber); and V5 (0.06% synthetic fiber; 0.75% ramie fiber). The proportion of synthetic fiber is to the overall volume fraction of concrete and the proportion of ramie fiber is to the weight of cement. The study will experimentally determine the optimal proportion of ramie fiber by evaluating compressive strength, splitting tensile strength, and modulus of elasticity at the age of 28 days where each concrete variation and test variation is made in 3 test specimens, cracks and failure modulus will also be evaluated. The significance of this work lies in providing a novel, sustainable, eco-friendly, and cost-effective solution for producing high-performance concrete with excellent tensile capacity and ductility. By validating the synergistic benefits of this hybrid system, this research provides crucial insights for developing concrete materials specifically tailored for structural applications like slabs and beam-column joints, which require enhanced crack resistance and toughness.

2.0 METHODOLOGY

2.1 Materials and Properties

In this research, a conventional concrete mix design was formulated as a control with a target 28-day compressive strength of 30 MPa and a slump value of 75 – 100 mm according to SNI 7656-2012 [29]. The concrete composition was made of fine aggregate in the form of sand, coarse aggregate in the form of gravel, cement, water, and superplasticizer (Variation 1 - V1). Then, from the mix design at a later stage, micro synthetic fibers were added with a fiber volume fraction of 0.06% (V2). The proportion was taken from previous research by the author and team [2], [21]. The effect of hybrid fiber addition was observed starting at variations V3, V4, and V5 by adding 0.25%, 0.50%, and 0.75% ramie fiber to the cement weight, respectively. The composition is based on previous research by Mahendra & Risdianto (2019) [22] and Yudha Kusuma (2018) [26].

The cement used in this research is Dynamix Serbaguna Cement, a type of Portland Composite Cement (PCC) equipped with micro filler particles that will perfectly fill the voids to provide strength from the inside to reduce cracking. This type of cement has a 32% reduction in CO_2 emissions compared to Ordinary Portland Cement (OPC) [30]. The fine aggregate used was sand passing a 4.75 mm sieve tested according to ASTM C40, ASTM C117, ASTM, C128, ASTM C136 [31]–[34] with properties as presented in Table 1. The coarse aggregate used was gravel passing the 19 mm sieve and retained on the 12.5 mm sieve tested under ASTM C127, ASTM C131, and ASTM C136 [34]–[36] with properties as presented in Table 2.

Table 1 Properties of fine aggregate (sand)

Type of Testing	Test Result	Standard
Water absorption	7,20%	ASTM C.128
Apparent specific gravity	2.73 gr/cm^3	ASTM C.128
Bulk specific gravity	2.28 gr/cm^3	ASTM C.128
Bulk specific gravity SSD	2.50 gr/cm^3	ASTM C.128
Material finer than 75-µm	4.90%	ASTM C.117
Organic impurities	Reddish yellow	ASTM C.40
Fineness modulus	2.14	ASTM C.136

Table 2 Properties of coarse aggregate (gravel)

Type of Testing	Test Result	Standard
Abrasion	32.98%	ASTM C.131
Water absorption	3.17%	ASTM C.127
Apparent specific gravity	2.64 gr/cm^3	ASTM C.127
Bulk specific gravity	2.44 gr/cm^3	ASTM C.127
Bulk specific gravity SSD	2.51 gr/cm^3	ASTM C.127
Fineness modulus	4.97	ASTM C.136

Based on SNI 7656-2012 [29] for a target compressive strength of 30 MPa and a slump value of 75 – 100 mm, the target water-to-cement ratio (w/c) was set at 0.54. This ratio corresponded to a total design water content of approximately 205 kg/m^3. However, the final amount of water physically added to the mix was adjusted to compensate for the moisture content in the aggregates. Given the high absorption values of the fine aggregate (7.20%) and coarse aggregate (3.17%), the water supplied by the aggregates was accounted for, resulting in a net added water of only 113.67 kg/m^3. Therefore, the Effective w/c ratio that governs hydration and strength remains 0.54, as the total water available for cement hydration is 205 kg/m^3.

The superplasticizer used was Sika Viscocrete 1003, which is a type F superplasticizer (high-range water reducer) with a dosage of 0.35% by the weight of cement, based on trial results, across all variations to maintain the target slump and ensure adequate workability. The added material in this research is polymer-based monofilament micro synthetic fiber (Kratos) which is 100% polyamide 6.6 EN 14889-2 Class 1 based fiber with specific gravity 1.14 gr/cm^3, with a length of 12 mm, diameter of 27 µm and tensile strength of 900 MPa. This fiber has a failure strain of 17.55% and a melting point of 260°C with excellent alkali resistance and corrosion resistance [37], as shown in Figure 1. The natural fiber used is ramie fiber, as shown in Figure 2, derived from the *Boehmeria nivea* plant with a specific gravity of 1.5 gr/cm^3, length of 19 mm, tensile strength of 1,050 MPa, strain of 3.7%, diameter of 40 µm, and good moisture resistance. Before use, the ramie fibers were treated by soaking them in 10% NaOH solution for 24 hours and drying them in the oven for 24 hours. This process is done to remove the lignin content of the natural fibers. As previously mentioned, the micro synthetic fiber content was fixed at 0.06% by fiber volume fraction (V_f) while the ramie content was varied (0.25%, 0.50%, and 0.75% by weight of cement). For consistency in comparison, all fiber contents are uniformly reported as the fiber volume fraction (V_f) in Table 3, with the corresponding mass provided for mass balance verification. The recapitulation of the hybrid fiber concrete mix design can be seen in Table 4 as follows.

Figure 1 Micro synthetic fiber

Figure 2 Ramie fiber

Table 3 Micro synthetic fiber (MSF) and ramie fiber (RF) content

Variation	MSF (%V_f)	MSF (kg/m^3)	RF (% Weight of Cement)	RF (%V_f)	RF (kg/m^3)
V1	0.00	0	0.00	0.00	0.00
V2	0.06	0.60	0.00	0.00	0.00
V3	0.06	0.60	0.25	0.09	0.95
V4	0.06	0.60	0.50	0.19	1.90
V5	0.06	0.60	0.75	0.28	2.85

Table 4 Mix design of 1 m³ hybrid fiber-reinforced concrete

Material	Amount kg/m³	Amount Weight Percentage (%)
Variation 1 (V1) – 0,00% MSF 0,00% RF		
Cement	379.63	16.18
Water (Net Added Water)	113.67	4.84
Superplasticizer	1.33	0.06
Fine Aggregate (Sand)	963.90	41.08
Coarse Aggregate (Gravel)	887.80	37.84
Micro Synthetic Fiber	0.00	0.00
Ramie Fiber	0.00	0.00
Total	2346.33	100.00
Variation 2 (V2) – 0,06% MSF 0,00% RF		
Cement	379.63	16.18
Water (Net Added Water)	113.67	4.84
Superplasticizer	1.33	0.06
Fine Aggregate (Sand)	963.90	41.07
Coarse Aggregate (Gravel)	887.80	37.83
Micro Synthetic Fiber	0.60	0.03
Ramie Fiber	0.00	0.00
Total	2346.93	100.00
Variation 3 (V3) – 0,06% MSF 0,25% RF		
Cement	379.63	16.17
Water (Net Added Water)	113.67	4.84
Superplasticizer	1.33	0.06
Fine Aggregate (Sand)	963.90	41.05
Coarse Aggregate (Gravel)	887.80	37.81
Micro Synthetic Fiber	0.60	0.03
Ramie Fiber	0.95	0.04
Total	2347.88	100.00
Variation 4 (V4) – 0,06% MSF 0,50% RF		
Cement	379.63	16.16
Water (Net Added Water)	113.67	4.84
Superplasticizer	1.33	0.06
Fine Aggregate (Sand)	963.90	41.04
Coarse Aggregate (Gravel)	887.80	37.80
Micro Synthetic Fiber	0.60	0.03
Ramie Fiber	1.90	0.08
Total	2348.83	100.00
Variation 5 (V5) – 0,06% MSF 0,75% RF		
Cement	379.63	16.16
Water (Net Added Water)	113.67	4.84
Superplasticizer	1.33	0.06
Fine Aggregate (Sand)	963.90	41.02
Coarse Aggregate (Gravel)	887.80	37.78
Micro Synthetic Fiber	0.60	0.03
Ramie Fiber	2.85	0.12
Total	2349.78	100.00

2.2 Specimen Testing

Hybrid fiber-reinforced concrete in 5 variations (V1, V2, V3, V4, and V5) with 3 specimens each were prepared for testing of compressive strength, split tensile strength, and modulus of elasticity of concrete. Observations for crack patterns and failures were also carried out. All specimens were cast on cylindrical molds with a diameter of 150 mm and a height of 300 mm. Specimens were demolded 24 hours after casting. Subsequently, they were immediately immersed in a curing water tank maintained at a controlled temperature of 24 ± 2 °C (applied to the lab air). The specimens remained immersed for a period of 26 days (until the 27th day). One day before the 28-day testing (i.e., on the 27th day), all specimens were removed from the water and air-dried in the laboratory environment at an ambient temperature of 24 ± 2 °C before mechanical testing was performed at 28 days.

Compressive strength testing was conducted based on ASTM C39 "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" [38]. Before conducting the test, the ends of each cylinder were prepared to ensure they were smooth and perpendicular to the axis of the cylinder. The diameter of each cylinder was measured at two locations perpendicular to each other at mid-height, and the average was used to calculate the cross-sectional area. Each specimen was then centered on the bearing block of a Compression Testing Machine (CTM). The rate of loading was meticulously controlled to be within the range of 0.25 ± 0.05 MPa/s until the specimen failed. The maximum load sustained by the specimen was recorded. The compressive strength value of concrete can be obtained based on equation (1) as follows:

$$f_c' = \frac{P}{A} \tag{1}$$

where fc' is the compressive strength of concrete in N/mm² or MPa, P is the maximum load at failure in N, and A is the cross-sectional area of concrete in mm². The crack exhibited by each cylinder was also observed and recorded to provide additional qualitative data on the concrete's behavior under compression.

The splitting tensile strength of concrete cylinders was determined in accordance with ASTM C496/C496M "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens" [39]. For this investigation, each cylinder specimen was carefully positioned horizontally in the Compression Testing Machine (CTM), centered on bearing strips (steel plate). The steel plates were placed along the top and bottom of the cylinder to ensure uniform load distribution and minimize stress concentrations. A continuous and uniform compressive load was applied along the length of the cylinder's diametral plane until failure. The loading rate was carefully controlled to be within the range of 0.7 to 1.4 MPa/min (0.012 to 0.023 MPa/s). The maximum load at failure was recorded. The failure mode of each specimen was also observed and recorded to provide additional insights into the tensile behavior. The splitting tensile strength value of concrete can be obtained based on equation (2) as follows:

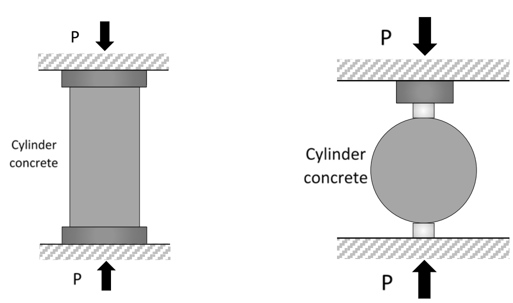
$$f_t' = \frac{2P}{\pi LD} \quad (2)$$

where ft' is the splitting tensile strength of concrete in N/mm^2 or MPa, P is the maximum applied load indicated by the testing machine at failure in N, L is the length of the specimen in mm, and D is the diameter of the specimen in mm.

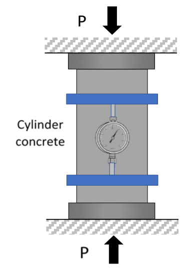
The static modulus elasticity test of concrete was determined based on ASTM C469/C469M "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression" [40]. For the measurement of axial strain, an extensometer with a minimum gauge length of three times the maximum aggregate size (and typically two-thirds of the specimen's length) was securely attached to the mid-height of each cylinder. The extensometer used in this study was capable of measuring deformation to an accuracy of at least 5 millionths of strain (5 microstrains). The specimens were then placed in a Compression Testing Machine (CTM). The load was then continuously applied at a rate of 241 ± 34 kPa/s (0.241 ± 0.034 MPa/s) until the stress reached 40% of the concrete's previously determined ultimate compressive strength (fc'). During this loading, simultaneous readings of load and corresponding axial strain were recorded at regular intervals (20 kN). The static modulus elasticity value of concrete can be obtained based on equation (3) as follows:

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005} \quad (3)$$

where E_c is the static modulus of elasticity in MPa, S_2 is the stress corresponding to a longitudinal strain of 0.000050 (50 microstrains) in MPa, S_1 is the stress corresponding to 40% of the ultimate compressive strength (fc') in MPa, and ε_2 is the longitudinal strain produced by stress S_2. This method provides the chord modulus of elasticity, which is a key parameter for structural design, reflecting the concrete's stiffness under service loads. Each mechanical test have quite complex data, therefore identification of the possibility of outlier data using ASTM E178 [41] with the Grubbs Test (10% significance level) approach is carried out. Illustrations of (a) compressive strength, (b) splitting tensile strength, and (c) modulus of elasticity testing can be seen ini Figure 3



(a) (b)



(c)

Figure 3 Specimen testing (a) Compressive strength (b) Splitting tensile strength (c) Modulus of elasticity

2.3 Data Analysis

Data analysis for this research was performed to evaluate the mechanical performance of the five concrete variations (V1 to V5) based on the test results for compressive strength, splitting tensile strength, and modulus of elasticity. The analysis focused on two primary objectives: first, to quantify the strength and stiffness of each mix, and second, to investigate the synergistic effects of the hybrid fiber combination and the optimal ramie fiber proportion.

First, the average values and standard deviation for each mechanical property were calculated from the three specimen results per variation. These values were then used to plot the performance curves shown in the results section, allowing for a clear visual comparison between the control (V1), single-fiber (V2), and hybrid-fiber (V3, V4, V5) mixes. The percentage increase or decrease in each property was calculated relative to the control mix (V1) to quantify the impact of fiber addition.

Second, a qualitative analysis was conducted by observing the failure patterns and cracking behavior of the specimens under load. This visual data was correlated with the quantitative results to understand how the fibers altered the concrete's failure mechanism from brittle to ductile. For example, the presence of controlled spalling and multiple hairline cracks in hybrid mixes was directly linked to the enhanced post-cracking performance indicated by higher splitting tensile strength and modulus of elasticity. The entire data analysis process is summarized in the flowchart below (Figure 4).

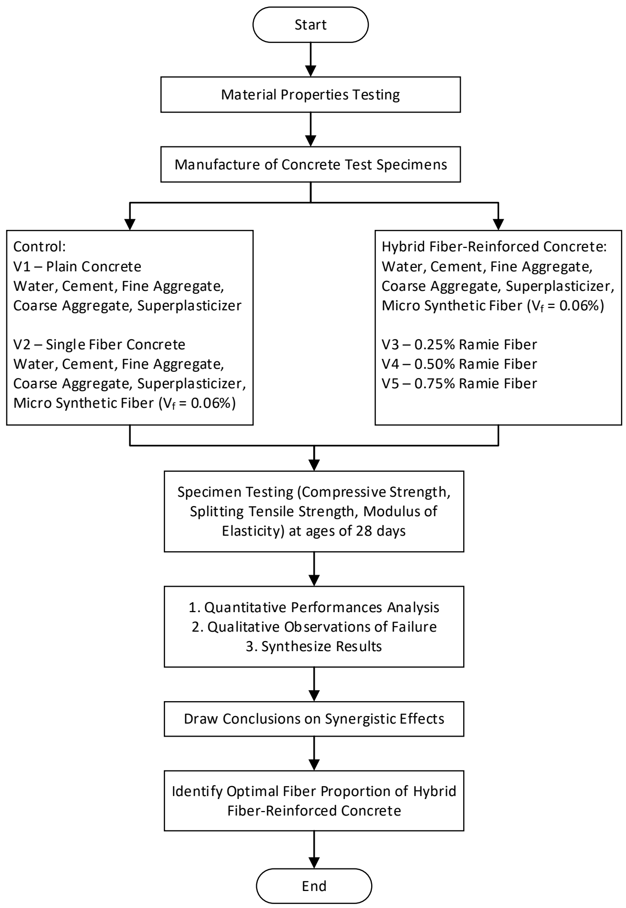


Figure 4 Data analysis flowchart

3.0 RESULTS AND DISCUSSION

3.1 Compressive Strength Test

This section will present the results of the compressive strength tests of 5 variations of hybrid fiber-reinforced concrete that were conducted at 28 days of age, each consisting of 3 specimens. The maximum load recorded when the specimens were crushed was used to calculate the compressive strength of the concrete. The compressive strength results of each specimen along with the average value for each variation can be seen in Table 5. As previously mentioned, identification of the possibility of outlier data using ASTM E178 [41] with the Grubbs Test (10% significance level) approach is carried out, and also shown in Table 5, considering a high COV value in certain variations. To improve visual representation, the results of compressive strength test are also graphically portrayed in Figure 5 and Figure 6 as follows.

In this research, concrete without fiber addition (V1 - 0% micro synthetic fiber and 0% ramie fiber) was used as control 1, and concrete with micro synthetic fiber addition without ramie fiber addition (V2 - 0.06% micro synthetic fiber and 0% ramie fiber) was used as control 2. Meanwhile, the synergistic effect of hybrid fiber addition (micro synthetic fiber and ramie fiber) was evaluated in the next 3 variations (V3 - 0.06% micro synthetic fiber and 0.25% ramie fiber; V4- 0.06% micro synthetic fiber and 0.50% ramie fiber; and V5 - 0.06% micro synthetic fiber and 0.75% ramie fiber). The results of the research on compressive strength testing showed that the highest compressive strength value was obtained in the concrete variation without the addition of fiber (V1 - control 1) with a value of 32.44 MPa, higher than the target compressive strength of 28-day concrete which is 30 MPa. Meanwhile, the concrete with the lowest compressive value was obtained in the concrete variation with the addition of one type of fiber, i.e. micro synthetic fiber (V2 - control 2) with a value of 22.07 MPa. The concrete variations with the addition of hybrid fibers i.e. V3, V4, and V5 resulted in compressive strength values of 26.60 MPa; 25.46 MPa; and 23.48 MPa, respectively. These results are higher than concrete with the addition of 1 type of fiber but still lower than concrete with the addition of fiber. The optimum value in the hybrid fiber concrete variation was obtained in V3 (0.06% micro synthetic fiber and 0.25% ramie fiber), with detailed deviations from control 1 and control 2 in Table 5.

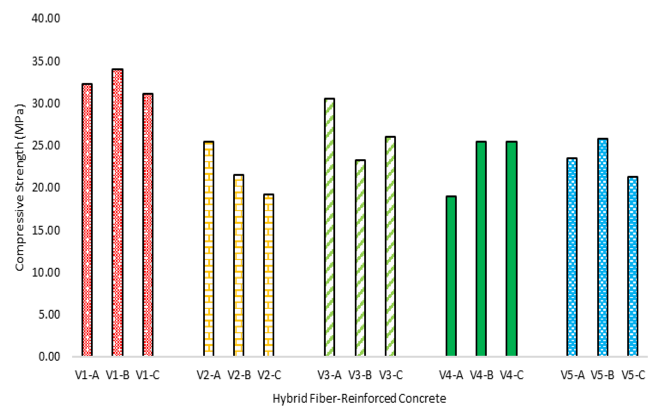


Figure 5 Compressive strength of hybrid fiber-reinforced concrete (HFRC) at ages of 28 days for each specimen

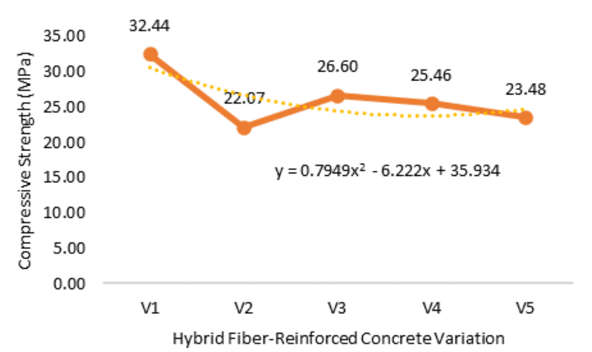


Figure 6 Average compressive strength of hybrid fiber-reinforced concrete (HFRC) at ages of 28 days for varied hybrid fiber addition

Table 5 The 28-day hybrid fiber-reinforced concrete (HFRC) compressive strength

No	ID	Ultimate Load P (N)	Concrete Compressive Strength f_c (MPa)	Average Concrete Compressive Strength f_c' (MPa)	Coefficient of Variation COV (%)	Grubbs Statistic G_i	Critical Value $G_{critical}$	Description	Average Concrete Compressive Strength (Considering Outliers) f_c' (MPa)	Deviation to V1 (%)	Deviation to V2 (%)
1	V1-A	570,000	32.26			0.13245		-			
2	V1-B	600,000	33.95	32.44	4.39	1.05963	1.15312	-	32.44	-	47.01
3	V1-C	550,000	31.12			0.92717		-			
4	V2-A	450,000	25.46			1.07763		-			
5	V2-B	380,000	21.50	22.07	14.28	0.17961	1.15312	-	22.07	-31.98	-
6	V2-C	340,000	19.24			0.89803		-			
7	V3-A	540,000	30.56			1.06749		-			
8	V3-B	410,000	23.20	26.60	13.95	0.91499	1.15312	-	26.60	-18.02	20.51
9	V3-C	460,000	26.03			0.15250		-			
10	V4-A	335,000	18.96			1.15470		Outlier			
11	V4-B	450,000	25.46	23.30	16.13	0.57735	1.15312	-	25.46	-21.51	15.38
12	V4-C	450,000	25.46			0.57735		-			
13	V5-A	415,000	23.48			0.00000		-			
14	V5-B	455,000	25.75	23.48	9.64	1.00000	1.15312	-	23.48	-27.62	6.41
15	V5-C	375,000	21.22			1.00000		-			

Based on the results calculated with equation (1), V1 (plain concrete) exhibited the highest compressive strength due to its integral cement-aggregate matrix and optimal density, as it lacks fibers that could introduce voids or reduce workability. Fiber, although it has a positive influence on concrete if it is not well dispersed it can reduce the workability of the mix and cause voids that can reduce the compressive strength. Conversely, V2 (0.06% micro synthetic fiber) showed the lowest strength, likely due to reduced workability, poor fiber dispersion causing voids, and potential interference with cement hydration. Micro synthetic fibers even in very small volume fractions tend to absorb the free water required for workability so that the mix becomes more difficult to compact which sub-optimal compaction will lead to an increase in voids in the concrete matrix. Hybrid fiber-reinforced concrete (V3, V4, V5), combining 0.06% micro synthetic fibers with varying ramie fiber content, yielded higher compressive strengths than V2 but remained lower than V1. This improvement is attributed to the synergistic effect of the hybrid fibers, where ramie fibers (with their rougher surface and longer length) enhance mechanical bonding and provide more effective crack bridging at various scales. Longer ramie fibers with a rougher surface will bridge larger cracks while micro synthetic fibers control very fine micro cracks. However, the hybrid fiber proportions were not optimal to surpass V1's performance. Specifically, V3 (0.25% ramie) showed significant improvement over V2, while higher ramie contents in V4 (0.50%) and V5 (0.75%) led to a slight decrease or stabilization, suggesting an optimal ramie content had been exceeded. This aligns with findings by Mahendra & Risdianto (2019) [22], indicating that excessive ramie fiber can negatively impact concrete properties by absorbing water needed for hydration and disrupting bonding.

The crack exhibited by each variation was also observed to provide additional qualitative data on the concrete's behavior under compression testing. The results of visual observations of cracks and failures of test specimens after compressive strength testing at the age of 28 days show variations in the pattern of cracks and the level of failure which can be seen in Figure 7. Based on Figure 7, V1 (concrete without fiber) clearly shows diagonally spreading cracks and some significant longitudinal cracks, leading to cone failure or brittle failure. This is a common failure pattern in concrete without fibers as concrete is brittle, and failure is sudden and explosive with considerable fragmentation where the stored energy is released rapidly. In V2, there is a dominant splitting failure that splits the cylinder into several large fragments. The fragmentation was less explosive than in V1, but the vertical cracking was quite prominent. In line with the compressive strength test results which gave the lowest values, likely, the fibers were not optimally dispersed to fully alter the brittle failure pattern. The prominent longitudinal cracks indicate that lateral tensile stresses are still very dominant, the micro synthetic fibers may have only slightly delayed crack propagation without preventing their formation. The micro synthetic fibers are better at resisting micro cracks and delaying crack propagation from crushing like V1, but less able to effectively resist cracking at the macro scale. V3, V4, and V5 showed a transition towards slightly more ductile behavior, characterized by the possibility of more controlled fragmentation and scattered cracks. Although the compressive strength did not surpass that of V1, the ability of the hybrid fibers to bridge cracks and delay explosive complete failure became apparent. The gradual increase in ramie fiber fraction at V3, V4, and V5, although not necessarily increasing the compressive strength, tends to improve the post-cracking behavior and change the failure mode to be more ductile. This is possible as the synergy between the micro synthetic fibers in resisting micro-crack propagation and the longer ramie fibers with rougher surfaces results in better interfacial bond strength that prevents macro-scale crack propagation. This is consistent with the role of fibers in concrete to improve ductility and crack resistance, even if the peak compressive strength is slightly reduced.

Although it provides good effects on crack resistance and ductility, HFRC, which still does not exceed the compressive performance of plain concrete (V1), shows that challenges in maintaining the density and homogeneity of concrete mixes with fibers remain. Further research on fiber dispersion, mix workability, and fiber-matrix interaction will provide a deeper understanding of these phenomena.

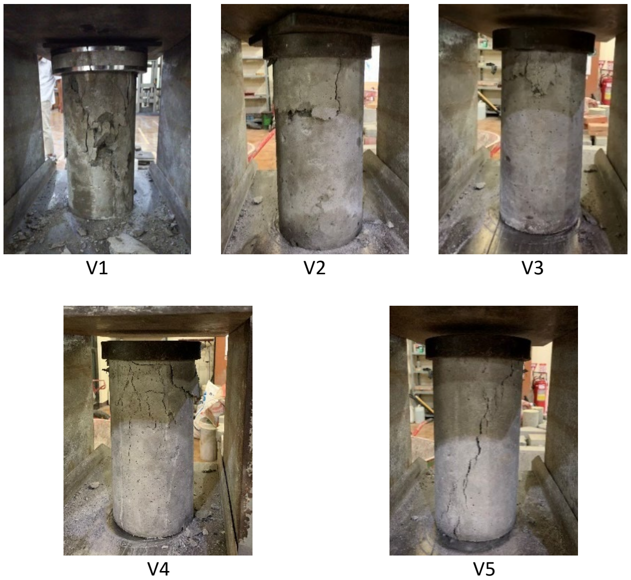


Figure 7 Crack and failure hybrid fiber-reinforced concrete (HFRC) at ages of 28 days for varied hybrid fiber addition under compression testing

3.2 Splitting Tensile Strength Test

The splitting tensile strength test results of hybrid fiber reinforced concrete, calculated with equation (2), can be seen in Table 6 and will be graphically portrayed in Figure 8 and 9. The failure modes are also shown in Figure 10.

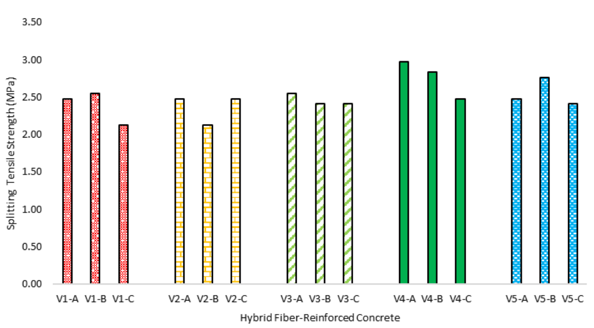


Figure 8 Splitting tensile strength of hybrid fiber-reinforced concrete (HFRC) at ages of 28 days for each specimen

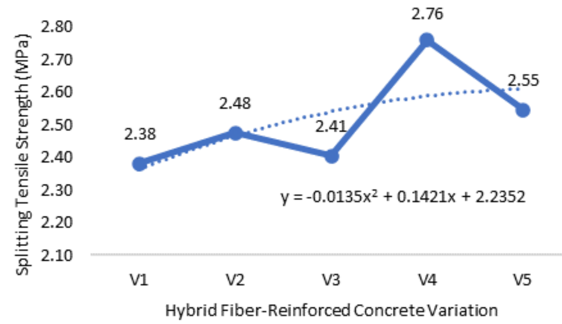


Figure 9 Average splitting tensile strength of hybrid fiber-reinforced concrete (HFRC) at ages of 28 days for varied hybrid fiber addition

Based on Table 6, considering the outlier data using ASTM E178 [41] with the Grubbs Test (10% significance level), Figures 8, 9, and 10 show that V1 has a good initial splitting tensile strength of 2.38 MPa for non-fiber concrete. The addition of a single micro synthetic fiber (V2) showed a marginal increase in splitting tensile strength (with a value of 2.48 MPa) compared to the control concrete (V1). Micro synthetic fiber, despite its short length, is effective in controlling micro-cracks in the concrete matrix before reaching peak load. This increase, although small, indicates that micro synthetic fibers are beginning to contribute to an increase in crack energy. The most interesting phenomenon is in V3, which recorded the lowest tensile strength among fiber addition variations with 2.41 MPa, even though it is higher than the plain concrete (V1). This indicates the presence of initial synergy disruption or negative effects when ramie fibers are added at low concentrations (0.25%). There are two possible main causes: 1) Workability degradation: ramie fibers, as long natural fibers (19 mm) that are highly water-absorbent (hydrophilic), likely interfere with the workability and uniformity of the mixture (dispersion); 2) Weak Interfacial Transition Zone (ITZ): At low doses, there are not enough ramie fibers to effectively bridge macro cracks. However, their presence is sufficient to create a large weak area around the fibers due to poor ITZ bonding, causing tensile failure to occur more quickly. V4 and V5 gave a significant increase in the splitting tensile strength to 2.76 MPa and 2.55 MPa, respectively, which is a positive indication of the use of hybrid fibers, which improved 15.84% and 6.93% respectively, from the concrete without fibers (V1) and 11.43% and 2.86% from the concrete with only micro synthetic fibers (V2). The tensile strength reaches its peak at V4 (0.50% ramie fiber). This substantial increase proves that the critical point of dispersion and effectiveness of ramie fibers has been reached. At this concentration, longer ramie fibers provide effective crack bridging, while micro synthetic fibers continue to control micro-cracks. This combination allows concrete to withstand higher tensile stresses, resulting in the best tensile performance. Further addition of ramie fiber up to 0.75% (V5) causes a decrease in splitting tensile strength from the peak value of V4. This indicates that the saturated point has been reached. Excessive fiber dosage may cause ball-up and increase porosity.

The failure mode experienced by the concrete is also in line with its splitting tensile strength value. In V1, mode A failure occurred, i.e. the specimen split into two large fragments with a single clear crack (brittle failure). In V2 one specimen experienced mode A failure and most specimens experienced mode B failure i.e. the specimen did not split into two, leaving a bridge of material, or only a major vertical crack without complete fragmentation (more ductile/ductile failure). This indicates the ability of the fibers to bridge the crack and hold the integrity of the specimen after the initial crack. At V3, V4, and V5 all specimens experienced mode B failure with the smallest cracks occurring at V4. The mode B failures that occurred in V3, V4, and V5 show strong evidence of the effectiveness of hybrid fibers in improving the ductility and crack resistance of concrete under tensile stress. The ability of the fibers to prevent the specimen from splitting into 2 separate fragments suddenly is very clear. This indicates that the fibers successfully bridged the formed cracks, distributed the stress, and allowed the specimen to withstand greater deformation after the initial crack appeared. The smallest crack pattern in V4 is also in line with its highest split tensile strength.

Table 6 The 28-day hybrid fiber-reinforced concrete (HFRC) splitting tensile strength

No	ID	Ultimate Load	Concrete Tensile Splitting Strength	Average Concrete Tensile Splitting Strength	COV	Grubbs Statistic	Critical Value	Description	Average Concrete Tensile Splitting Strength (Considering Outliers)	Failure Mode
		P (N)	f_t (MPa)	f_t' (MPa)	(%)	G_i	$G_{critical}$		f_t' (MPa)	
1	V1-A	175,000.00	2.48	2.38	9.55	0.41478	1.15312	-	2.38	A
2	V1-B	180,000.00	2.55			0.72587		-		A
3	V1-C	150,000.00	2.12			1.14065		-		A
4	V2-A	175,000.00	2.48	2.36	8.66	0.57735	1.15312	-	2.48	B
5	V2-B	150,000.00	2.12			1.15470		Outlier		B
6	V2-C	175,000.00	2.48			0.57735		-		A
7	V3-A	180,000.00	2.55	2.45	3.33	1.15470	1.15312	Outlier	2.41	B
8	V3-B	170,000.00	2.41			0.57735		-		B
9	V3-C	170,000.00	2.41			0.57735		-		B
10	V4-A	210,000.00	2.97	2.76	9.25	0.83205	1.15312	-	2.76	B
11	V4-B	200,000.00	2.83			0.27735		-		B
12	V4-C	175,000.00	2.48			1.10940		-		B
13	V5-A	175,000.00	2.48	2.55	7.35	0.37796	1.15312	-	2.55	B
14	V5-B	195,000.00	2.76			1.13389		-		B
15	V5-C	170,000.00	2.41			0.75593		-		B

(a) (b)

Figure 10 Failure mode of tensile splitting strength test (a) Mode A and (b) Mode B

3.3 Modulus of Elasticity Test

The results of the elastic modulus tests on 28-day hybrid fiber-reinforced concrete, calculated with equation (3) are presented in Table 7 and illustrated in graphical form in Figure 11. The failure modes are also shown in Figure 12. As previously mentioned that elastic modulus testing produces quite complex data, identification of the possibility of outlier data using ASTM E178 [41] with the Grubbs Test (10% significance level) approach is carried out and showed in Table 7. The test results show that the increase in the elastic modulus of concrete is strongly influenced by the addition of fibers, especially in the hybrid configuration. V1 (concrete without fibers) showed the lowest elastic modulus of 8,729.35 MPa and classic brittle failure with long vertical cracks (mode A). This relatively low value indicates that V1 is the least rigid material or most prone to elastic deformation under load. The addition of micro synthetic fibers to V2 gave a slight increase in elastic modulus with a failure mode of large spalling (mode B) indicating the fiber's attempt to arrest the main crack but not yet optimal. This small increase in the modulus of elasticity value indicates that the micro synthetic fibers, although in a small volume fraction and previously exhibiting low compressive and split tensile strengths, are beginning to make a minor contribution to the stiffness of the concrete. These fibers may help slightly in resisting internal deformation, but the effect is not yet significant. The hybrid fiber concrete variations (V3, V4, and V5) significantly increased the modulus of elasticity with V5 (0.75% ramie fiber) reaching the highest value of 26,018.11 MPa, indicating a progressive increase in stiffness with the addition of ramie fiber. The failure pattern observed in the hybrid fiber concrete variation of small spalling (mode C) confirmed the increased ductility and ability of the fibers to control cracks.

This indicates that hybrid fibers not only make the concrete stiffer but also more ductile, preventing sudden failure and allowing more controlled loading even after the initial cracks appear. Where micro synthetic fibers make a minor contribution to micro-cracking, ramie fibers create a network that resists macro-crack propagation, so that energy is released through scattered micro-cracks and controlled small spalling. Thus, while fibers may not necessarily increase peak compressive strength, their role in increasing stiffness and changing failure modes to be more ductile is crucial for better structural performance of concrete.

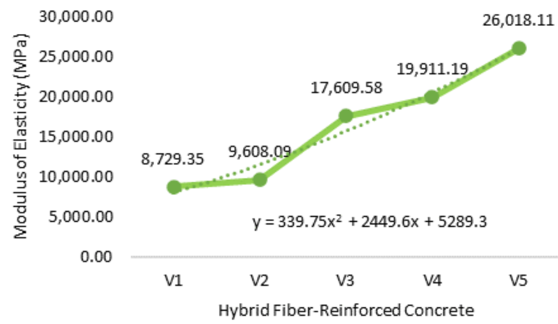
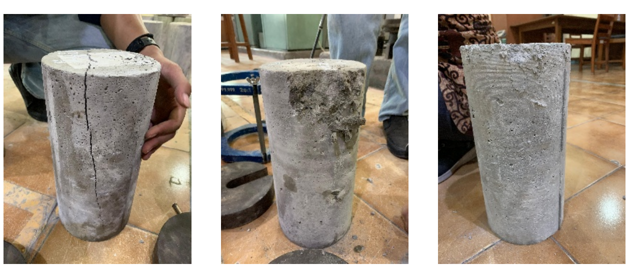


Figure 11 Modulus of elasticity of hybrid fiber-reinforced concrete (HFRC) at ages of 28 days for varied hybrid fiber addition

Table 7 The 28-day hybrid fiber-reinforced concrete (HFRC) modulus of elasticity

No	ID	Concrete Modulus of Elasticity	Average Concrete Modulus of Elasticity	Grubbs Statistic	Critical Value	Description	Average Concrete Modulus of Elasticity (Considering Outliers)	Failure Mode
		E (MPa)	E' (MPa)	G_i	$G_{critical}$		E' (MPa)	
1	V1-A	10,270.94		1.01210		-		A
2	V1-B	8,691.80	8,729.35	0.02465	1.15312	-	8,729.35	A
3	V1-C	7,225.31		0.98745		-		A
4	V2-A	10,891.74		0.37064		-		B
5	V2-B	5,686.17	9,608.09	1.13240	1.15312	-	9,608.09	B
6	V2-C	12,246.37		0.76177		-		B
7	V3-A	6,916.72		0.63193		-		C
8	V3-B	8,793.78	17,609.58	0.52100	1.15312	-	17,609.58	C
9	V3-C	37,118.24		1.15292		-		C
10	V4-A	20,802.93		0.10974		-		C
11	V4-B	11,376.19	19,911.19	1.05034	1.15312	-	19,911.19	C
12	V4-C	27,554.44		0.94060		-		C
13	V5-A	25,410.11		0.62856		-		C
14	V5-B	26,626.11	32,761.31	0.52458	1.15312	-	26,018.11	C
15	V5-C	46,247.70		1.15314		Outlier		C



(a) (b) (c)

Figure 12 Failure mode of modulus of elasticity test (a) Mode A, (b) Mode B, and (c) Mode C

A striking observation demanding further discussion is the unusually large increase in the static modulus of elasticity, escalating from 8,729.35 MPa for V1 to 26,018.11 MPa for V5, representing an increase of nearly 198%. This finding contrasts with typical micro-polymer FRC studies, where the modulus of elasticity often changes only slightly, as polymer fibers are usually less stiff than the cement matrix. However, the use of a hybrid system incorporating natural ramie fiber provides the key justification. Ramie fiber itself possesses a significantly high modulus of elasticity, approximately 61.5 GPa (Mahendra & Risdianto (2019) [22], which is much higher than that of the cement paste. At higher ramie loading percentages (V5), these stiff ramie fibers become the dominant structural contributor to the composite stiffness. Furthermore, the combination of micro synthetic fibers (controlling micro-cracks and potentially acting as a filler) and ramie fibers (acting as internal, high-stiffness reinforcement) likely facilitated a much denser packing of the concrete matrix and reduced internal micro-porosity. This combined effect of the ramie fiber's intrinsic high stiffness and the improved material density is hypothesized to be the cause of this non-conventional and highly desirable enhancement in the elastic modulus.

3.4 The Synergistic Effect of Ramie and Micro Synthetic Fibers on Mechanical Performance of Hybrid Fiber-Reinforced Concrete

The overall analysis of the compressive strength, splitting tensile strength, and modulus of elasticity test results shows a complex synergistic effect between ramie fiber and micro synthetic fiber on the mechanical performance of hybrid fiber-reinforced concrete. The control concrete (V1) exhibited the highest compressive strength of 32.44 MPa, which is consistent with its properties as an undisturbed concrete matrix. In contrast, the addition of micro synthetic fibers alone (V2) resulted in the lowest compressive strength of 22.07 MPa. This phenomenon indicates that at a volume fraction of 0.06%, micro synthetic fibers are not yet effective in overcoming potential workability degradation or dispersion problems that can adversely affect the compressive strength properties of concrete. However, the addition of micro synthetic fibers alone provides a slight increase in the splitting tensile strength and modulus of elasticity compared to V1, from 2.38 to 2.48 and 8,729.35 MPa to 9,608.09 MPa, respectively, as well as a failure pattern that shows susceptibility to large spalling.

When ramie fiber is added (V3, V4, V5), there is a significant shift in the behavior of the concrete, indicating a clear synergistic effect. Although the compressive strength of hybrid fiber concrete remains below that of V1, the splitting tensile strength and modulus of elasticity show substantial increases, with V4 providing the highest splitting tensile strength of 2.76 MPa and V5 achieving the highest modulus of elasticity of 26,018.11 MPa. This highlights the role of ramie fibers, with their distinct characteristics (length, surface, stiffness), in creating better interfacial bonding and more effective crack bridging effects, thereby enhancing the concrete's ability to withstand tensile stress and deformation. This is in line with the research of Noorvand et al. (2022) [27] where fiber length affects fiber performance, and ramie fiber can increase the tensile strength and ductility of concrete [22], [26]. This also confirms that the main role of hybrid fibers is not to increase peak compressive strength, but rather to increase crack resistance and stiffness. Visual observations of failure patterns support these findings, with V1 showing sudden brittle failure with large vertical cracks, while V2 experienced large spalling. In contrast, all hybrid fiber concrete variations (V3, V4, and V5) exhibited more ductile behavior, characterized by small, controlled spalling. Micro synthetic fibers may be effective in controlling initial micro-cracks, while longer ramie fibers function as “bridges” for macro cracks. This synergy overall enhances the concrete's ability to absorb energy and maintain post-cracking integrity, making it a more resilient and durable material.

Correlations between test types and concrete variations also highlighted the specific role of fibers. Compressive strength, which measures peak axial load capacity, appeared to be more sensitive to potential workability and density issues due to fiber addition, so V1 remained superior. However, in terms of resistance to cracking and stiffness (splitting tensile strength and modulus of elasticity), hybrid fibers showed superior performance. The failure pattern changed from brittle (sudden failure in V1, large spalling in V2) to more ductile and controlled (small spalling in V3, V4, V5), which directly correlated with the increase in split tensile strength and elastic modulus. Micro synthetic fibers may be effective in controlling early micro-cracks, while longer ramie fibers play a role in bridging macro cracks, creating a more resilient system. Although there is an optimal point for the addition of ramie fibers (e.g., 0.50% for split tensile and 0.75% for elastic modulus), the synergy between these two types of fibers overall improves the ability of concrete to absorb energy and maintain post-cracking integrity, suggesting that hybrid fiber concrete holds promise for improved structural ductility and durability.

Correlation analysis between mechanical properties shows that the addition of hybrid fibers does not linearly improve all properties simultaneously, but rather selectively improves performance in crucial areas, which are described in more detail as follows:

a. Correlation between compressive strength and splitting tensile strength: Figure 13 shows a negative correlation between compressive strength and splitting tensile strength. V1 has the highest compressive strength, but its splitting tensile strength value is average. Conversely, V4 provides the highest split tensile strength even though its compressive strength is lower than V1. This confirms that fibers are more dominant in improving concrete's ability to withstand tensile stress by bridging cracks, while compressive strength is more influenced by the overall integrity of the concrete matrix.
b. Correlation between compressive strength and modulus of elasticity: Figure 14 shows that there is negative correlation between compressive strength and modulus of elasticity. V1, which has the highest compressive strength, has the lowest stiffness, while V5, which is the most rigid, does not have the highest compressive strength. This indicates that although the correlation between the stiffness of conventional concrete and its strength exists, the addition of hybrid fibers to concrete creates a different strengthening mechanism, where the fibers significantly increase the stiffness of the material to resist deformation, even if the peak compressive load does not increase.
c. Correlation between splitting tensile strength and modulus of elasticity: Figure 15 shows the strongest and most positive correlation between tensile strength and modulus of elasticity. An increase in one property tends to be accompanied by an increase in the other property. This is the most logical correlation because both properties are strongly influenced by the ability of the fibers to withstand internal stress and maintain matrix integrity. The more effectively the fibers bridge cracks (increasing split tensile strength), the stiffer the material becomes (increasing modulus of elasticity).

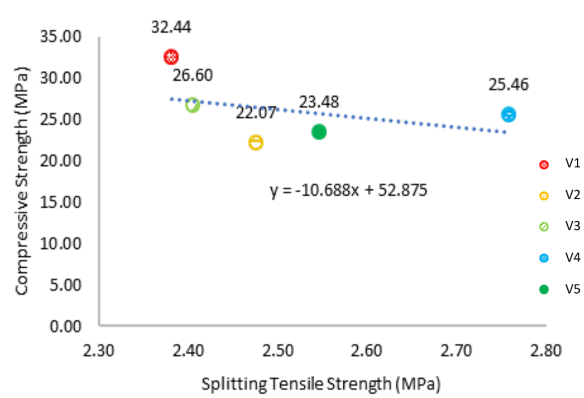


Figure 13 Compressive strength vs splitting tensile strength of hybrid fiber-reinforced concrete

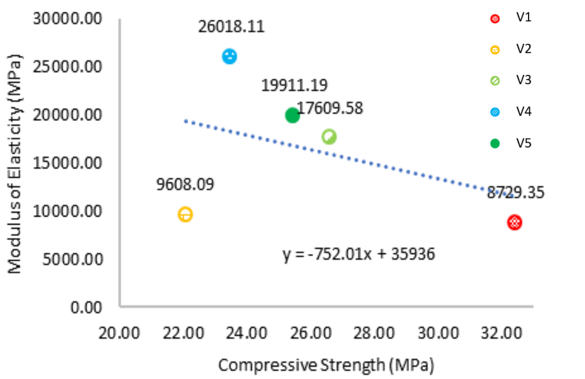


Figure 14 Compressive strength vs modulus of elasticity of hybrid fiber-reinforced concrete

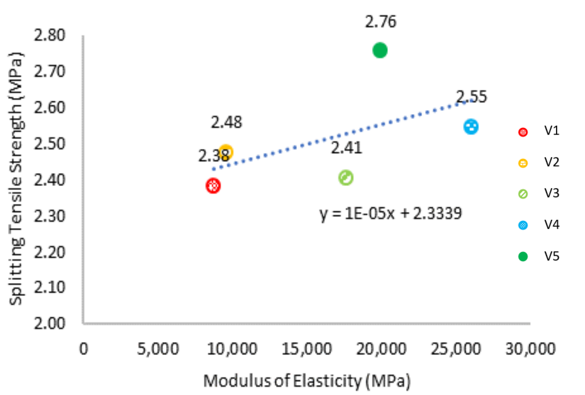


Figure 15 Splitting tensile strength vs modulus of elasticity of hybrid fiber-reinforced concrete

Based on a comprehensive analysis of the three mechanical properties and failure patterns, the V4 mixture (0.06% micro synthetic fiber and 0.50% ramie fiber) is the most optimal innovation in this research. Although V1 has the highest compressive strength, its brittle nature makes it less ideal for applications requiring ductility. V5 achieves the highest modulus of elasticity, but its splitting tensile strength is slightly lower than V4, indicating a saturation point. Conversely, V4 successfully achieved the best performance balance, in this case: 1) Highest splitting tensile strength, which is the main objective of fiber addition, and V4 excels in this regard; 2) Very high modulus of elasticity where the stiffness of V4 is almost equivalent to V5, making it an excellent material for resisting deformation; 3) The best failure mode, where the crack pattern in V4 is the most controlled with the smallest spalling, demonstrating exceptional ability to manage crack propagation. Therefore, the V4 mixture represents the most effective combination of strength, stiffness, and crack resistance, making it the ideal choice for structural applications requiring excellent ductile performance and durability.

4.0 CONCLUSION

Based on the results, it is concluded that the addition of fiber to concrete has a complex impact on its mechanical properties. Concrete without fibers (V1) showed the highest compressive strength but tended to be brittle with abrupt cracking patterns. The addition of micro synthetic fibers (V2) alone was ineffective, even slightly lowering the compressive strength, while providing only a slight increase in the splitting tensile strength modulus of elasticity. The use of hybrid fibers (a combination of micro synthetic fibers and ramie fibers in V3, V4, and V5) increased the splitting tensile strength and modulus of elasticity, reaching optimal values at a certain volume fraction of ramie fibers (0.5% ramie fibers for tensile splitting and 0.75% for elastic modulus), although the compressive strength remained below that of V1. Excessive fiber addition (beyond the optimum point) may cause a decrease in efficiency or even a slight decrease in certain properties due to dispersion or workability issues. Correlation between tests showed that the hybrid fibers successfully changed the failure mode of the concrete from brittle to more ductile, characterized by a more controlled crack pattern, exhibiting increased energy absorption capacity and better post-cracking integrity. The V4 (0.5% ramie fibers) mixture represents the most effective combination of strength, stiffness, and crack resistance, making it the ideal choice for structural applications requiring superior ductile performance and durability.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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