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Enhancement of Hybrid Beam Capacity with Glass Fiber Reinforced Polymer (GFRP): The Experimental Investigation into Metakaolin Substitution Effects

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Abstract

The improvement of beam capacity is achievable through various alternatives, such as using high-strength concrete. However, enhancing concrete strength in beam without increasing the tensile reinforcement capacity can result in a smaller depth of concrete compression block. Reinforcing beams with high tensile strength materials such as Fiber Reinforced Polymer (FRP) can significantly increase flexural capacity. Previous investigations have established that concrete in the compression zone can fail before FRP reaches the yield point. This phenomenon shows the need for a combination of using flexural reinforcement with high tensile strength and substituting a portion of cement with metakaolin to produce higher-strength concrete. Therefore, this study aimed to investigate the effect of 10% metakaolin substitution on the flexural behavior of hybrid beams reinforced with Glass Fiber Reinforced Polymer (GFRP). The metakaolin substitution was used to enhance the compressive strength of concrete while minimizing the environmental impact of cement consumption. Although GFRP offered high tensile strength and corrosion resistance, previous investigations reported limitations in modulus of elasticity for improving the initial capacity of concrete. In this study, beams with variations of normal concrete and metakaolin-modified concrete were tested using a four-point bending configuration. The results showed a 20.7% increase in cube strength, a 57.83% rise in ultimate flexural load, a 39.74% reduction in beam deflection, and a decrease in strain in concrete compression zone compared to control beam. Ductility was observed to be high as compressive strength increased, while high reinforcement ratio resulted in a significant decrease.

1. Introduction

Several alternatives are available for consideration to enhance beam capacity including increasing the area of tensile reinforcement, enlarging the dimensions of beam, and using high-strength concrete (HSC). Among these alternatives, the use of HSC has become very popular due to the high compressive strength, durability, and high resistance to various environmental conditions. HSC also possesses high elastic modulus, low permeability, and resistance to various forms of damage. Generally, increasing concrete strength directly correlates with higher cement usage, which has significant environmental implications. This phenomenon has led to the substitution of a portion of the cement with metakaolin to achieve HSC.

Metakaolin is a mineral additive that is incorporated into concrete mixes to reduce porosity by filling microscopic pores and enhancing the pozzolanic reaction to improve density, strength, and durability [1][2]. Research by Manisha Verma and Parves Alam [3] stated that replacing 20% of cement with metakaolin and 1% nano Alumina in strength 30 Mpa concrete resulted in a 23% improvement in strength concrete, offering several advantages such as high compressive strength and reduced water absorption [4] .

Manar Ahmed and Ehab Lotfy [5] used metakaolin as a substitute for cement at a rate of 10% to enhance concrete strength and performance, particularly in reinforced concrete beams. Based on the analysis, seven beams were constructed, with varying concrete grades from 27 MPa to 39 MPa, as well as ratios of flexural and shear reinforcement. The results showed that the use of 10% metakaolin could improve concrete strength, enhancing overall early cracking load, ultimate load, deflection, and maximum toughness. Additionally, increasing concrete grade by 27% only enhanced beam capacity by 9%, causing a significant shift from flexural-shear to shear failure.

According to Abiraami R, et al [6], a 22.6% improvement in the strength concrete 30 Mpa due to the application of metakaolin, steel fibers, and M-Sand increased capacity of reinforced concrete beams by 13%. This shows that the application of high-strength concrete, alongside flexural reinforcement with high tensile strength can also be an alternative to enhance capacity of reinforced concrete beams. An alternative material with high tensile strength is Fiber-Reinforced Polymer (FRP), offering several advantages, such as being lightweight, high strength, corrosion resistance, and non-magnetic properties. However, the limitations of FRP include low modulus of elasticity and the absence of a yielding phase in FRP bars, leading to the development of wide cracks, significant deformations, and poor ductility in Fiber-Reinforced Polymer Reinforced Concrete (FRP-RC) structures. These limitations have restricted the use of FRP-RC in civil engineering applications, as reported by [7] and [8]. Consequently, recent research has started combining FRP with traditional reinforced concrete (RC) to develop Hybrid-RC beams.

Hybrid-RC beams combine the high tensile strength of FRP bars, alongside the excellent ductility and high stiffness of steel bars, with distinct characteristics from FRP-RC and Steel-RC beams. Research conducted by Maria Antonietta Aiello and Luciano Ombres [9] found that integrating steel bars into AFRP-RC beams can improve overall performance, increase beam stiffness, and reduce deflection under load. Yoon Young-Soo, et.al [10] showed that the use of hybrid combination of steel and FRP bars enhanced properties such as stiffness reduced significant deflection, mitigated wide cracks, and improved ductility in pure FRP-RC beams after cracking. According to Rendy Thamrin, et.al [11], the area ratio (A_f/A_s) between FRP and steel bars significantly affects the flexural behavior of Hybrid-RC beams. As the A_f/A_s ratio increases, beams' flexural bearing capacity gradually improves, but ductility decreases. Ahmed El Refai, et.al [12] found that the flexural capacity of Hybrid-RC beams increases as the effective reinforcement ratio improves. Furthermore, Enas M. Mahmood, et.al [13] stated that incorporating shear connectors and web reinforcement in GFRP I-Beam beams enhanced the maximum load and ductility of beams.

The use of FRP in normal-grade concrete beams has the potential to enhance capacity and ductility, but the compressive concrete region tends to fail before the FRP reaches the yield point. However, improving concrete strength in beams without adding tensile reinforcement can lead to a decrease in the depth of concrete compression block (a) or the neutral axis depth (c), resulting in difficulty in achieving an increase in beam capacity. This shows the need to investigate GFRP-reinforced Hybrid beam, alongside the partial substitution of cement with metakaolin to elevate concrete strength from normal-grade to high-strength. Therefore, this research aimed to investigate the impact of improving concrete strength through the use of metakaolin on the flexural behavior of GFRP-reinforced hybrid beam. The investigation was carried out to analyze the flexural capacity, deformation, strain in each constituent material, the failure modes, and ductility of beams.

This study advances the state of the art by combining metakaolin-modified high-strength concrete with GFRP reinforcement in hybrid beams, providing new insights into the flexural behavior and sustainability of these structures. While previous studies, such as those by Qiu Li, et.al [14] and related works, have highlighted the benefits of pozzolanic materials like fly ash and silica fume for sustainability in construction, this research critically evaluates the unique contributions of metakaolin. Metakaolin not only enhances the mechanical and durability properties of hybrid reinforced concrete beams, as shown in studies on microstructural improvement [15], but also supports environmental sustainability by reducing the carbon footprint associated with cement use [16]. Furthermore, by integrating insights into material sustainability, economic feasibility [17], and advanced structural optimization, the experimental results contribute to the development of hybrid beam designs with superior performance and reduced environmental impact, addressing critical gaps in the current literature.

2. Experimental Program

The research flowchart, which outlines the methodology and sequence of steps undertaken in this study, is presented in Fig. 1. This diagram provides a clear and systematic representation of the experimental process, including the preparation of materials, testing procedures, and data analysis stages. By referring to Fig. 1, readers can easily understand the comprehensive approach employed to evaluate the effects of metakaolin and GFRP on the flexural behavior and durability of hybrid reinforced concrete beams.

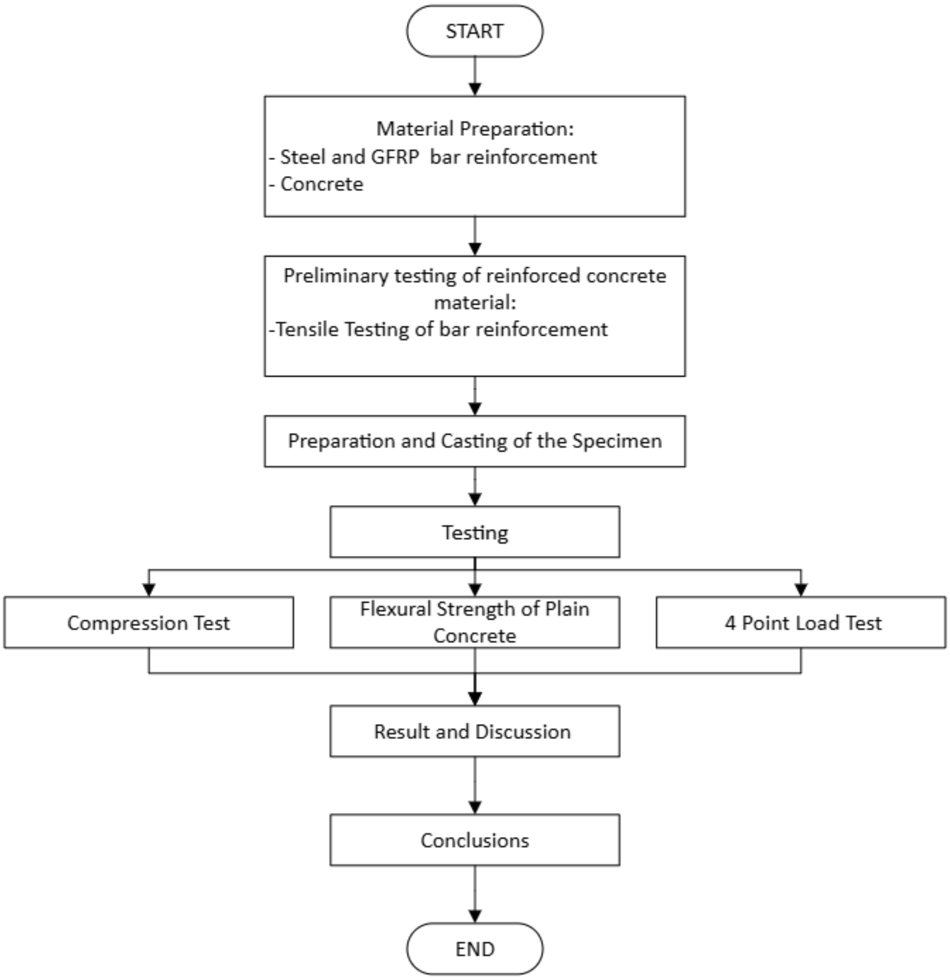


Fig. 1 *Flowchart of the research*

2.1 Materials

2.1.1 GFRP and steel bars

GFRP used in this research was covered with sand along the cross-section [18], characterized by strong bond with concrete. The mechanical properties of GFRP and reinforcing steel are shown in Table 1, while Fig. 2 illustrates the cross-section of GFRP. Subsequently, tensile testing for both steel and GFRP refers to [19] and [20], respectively.

Table 1 *Mechanical properties of GFRP and reinforcing bar*

Types	Diameter (Mm)	Elastic Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)
GFRP	16	44.1		804.7
Plain Bar	6	200	476.7	514.8
Deform Bar	12	200	584.2	707.3

Fig. 2 *Type of GFRP*

2.1.2 Concrete

Table 2 shows the composition of concrete mix for 1 m^3 used in this research, which was obtained from Beton Mix Sdn Bhd in Batu Pahat, Malaysia. The coarse aggregate size was 20 mm, while the fine aggregate was in Zone 1, with a water-to-cement ratio of 0.32. For every 1 kg of cement, 4 ml of Real Set (RS) 233 and 15 ml of Real Flow (RF) 610 were used as additives. RS233 is as a mixture of water reducer and setting retarder for concrete, containing modified lignosulfonate formulated to provide optimal performance in reducing water and delaying concrete setting to facilitate placement and finishing. RF610 is a mixture of water reducer and high-strength accelerator for concrete. In this research, two types of concrete were made, consisting of Grade 40 MPa, and Grade 40 MPa concrete with a partial substitution of cement with 10% metakaolin.

Table 2 *Mix design concrete*

Types Concrete	Cement (Kg)	Water (Kg)	Fine Sand (Kg)	Coarse (Kg)	RS233 (ml)	RF610 (ml)	Metakaolin (Kg)
Grade 40 MPa	500	160	783	957	1980	2640	
Grade 40 MPa + 10%MK	450	160	783	957	1980	2640	50

Metakaolin used in this research was sourced from Kaolin Malaysia Sdn. As shown in Fig. 3, metakaolin was used at a 10% substitution relative to the weight of cement according to previous research by Ismail et. al [4], with Physical properties in Table 3 and chemical compounds presented in Table 4.

Table 3 *Physical properties of metakaolin*

	Standard	Result
Moisture	Below 0.3%	0.15
Brightness	92.0 - 97.0 %	93.1
pH (30% Solid)	5.5 - 7.5	5.6
325 Mesh Residue	Below 0.01%	0.008
Average Particle Size	0.5 - 0.8 μ	0.8

The use of 10% metakaolin (MK) as a partial replacement for cement consistently provided significant improvements in the mechanical properties of concrete, such as compressive, splitting tensile, and flexural strength. According to Manisha Verma and Parves Alam [3], metakaolin enhanced workability, compressive (10% to 23%), bending, and splitting tensile strength. As reported in [1], the highest compressive strength was achieved at 10% MK. Mohd Hanif Ismail, et.al [4] found that using 10% MK produced optimal outcomes but with a 61.7% reduction in workability. Based on the report by Oluwatobi O. Akin et .al [21], replacing cement with approximately 10% metakaolin significantly improved concrete compressive strength. Nasir Shafiq, et.al [22] observed that a mix of 10% MK + 1% NS (Nanosilica) as part of cement replacement showed the highest mechanical properties and durability characteristics of concrete. Similarly Salim Barbhuiya, et.al [23] found that replacing 10% of cement with metakaolin improves concrete strength, particularly at an optimal water-to-binder ratio of 0.5.

Table 4 *Chemical composition of metakaolin*

	Chemical Composition (%)
Silicon dioxide (SiO2)	55.04
Aluminum oxide (Al2O3)	37.44
Iron oxide (Fe2O3)	0.75
Calcium oxide (CaO)	0.02
Magnesium oxide (MgO)	0.81
Potassium oxide (K2O)	2.31
Loss of ignition (LOI)	2.5
SiO2+Al2O3+Fe2O3	93.23

(a) **(b)**

Fig. 3 *Metakaolin used (a) in 25 kg packaging; (b) visually observed*

2.2 Details of the Tested Specimens

A total of 10 cube samples with dimensions of 10x10x10 cm were prepared to determine the actual concrete strength, followed by testing at the age of 28 days according to the BS EN 12390 standard [24] . To determine the flexural strength of plain concrete, beam samples with dimensions of 10x10x40 cm were tested at the age of 28 days following the standard [25]. Subsequently, four beams with simple supports were tested to investigate the static flexural behavior of normal concrete and metakaolin GFRP hybrid beam. The testing matrix for the experimental program conducted is listed in Table 5.

The same reinforcement as hybrid beam with normal concrete was used to determine the flexural behavior of metakaolin. The experiment was carried out using two 6 mm compression reinforcements, two bar deform of 12 mm diameter were applied as tension reinforcement, and one 16 mm GFRP was added at the mid-span between the tension reinforcements. Meanwhile, 6 mm diameter reinforcements with a spacing of 150 mm were used for stirrup reinforcement, and concrete cover of 40 mm was applied, as shown in Fig. 4. All hybrid beam was designed with ductile failure based on [26]. The ratio of reinforcement installed on hybrid beam is shown in Table 6. Where ρ_f is ratio of GFRP reinforcement and ρ_s is ratio of steel reinforcement.

Table 5 *Detail of hybrid beam*

Sample	Size (mm)			Reinforcement			Concrete strength (MPa)
	Length	depth	width	Compression	Tensile	Stirrup	
Hybrid Beam Normal Concrete (HB-N)	3000	250	200	2R6mm	2 Y 12 mm	R6 -150 mm	48.56
Hybrid Beam Normal Concrete and GFRP (HB-N- G)					2 Y 12 mm and GFRP Dia 16 mm	R6-150 mm	
Hybrid Beam Metakaolin Concrete (HB-M)					2 Y 12 mm	R6-150 mm	58.63
Hybrid Beam Metakaolin Concrete and GFRP (HB-M- G)					2 Y 12 mm and GFRP Dia 16 mm	R6-150 mm	

Table 6 *Ratio of reinforcement*

Beam	GFRP Reinforcement area, A_f (mm²)	Bar Reinforcement area, A_s (mm²)	ρ_f	ρ_s
HB-N		226.19		0.0054
HB-NG	201.06	226.19	0.0048	0.0054
HB-M-N		226.19		0.0054
HB-M-NG	201.06	226.19	0.0048	0.0054

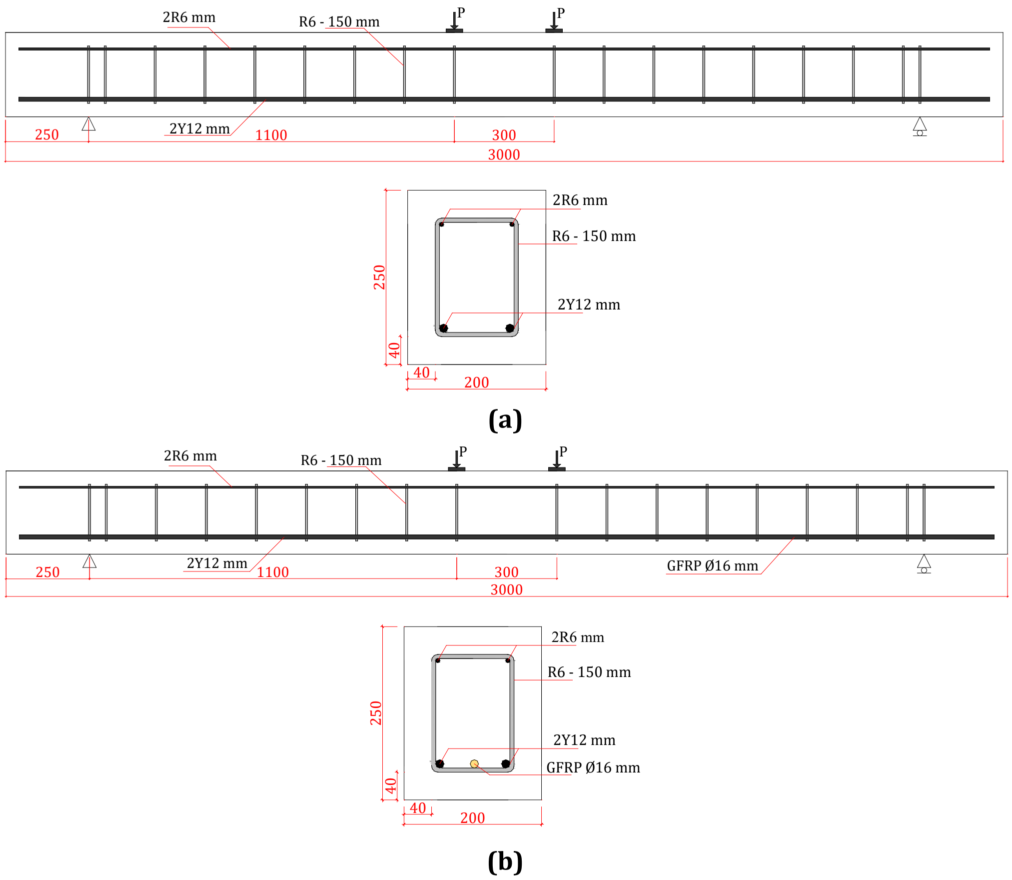


Fig. 4 *Dimension and detail of specimens (a) Reinforcement of beams HB-N and HB-M; (b) Reinforcement of beams HB-N-G and HB-M-G*

2.3 Experimental Setup and Instrumentation

The specimens were subjected to testing as supported simply beams, with the application of two concentrated loads at the mid-span using a hydraulic jack with a capacity of 1000 kN. The deflection observed at the mid-span was measured using a linear variable differential transformer (LVDT), as shown in Fig. 5. To capture the strain developed during loading, several strain gauges were positioned on various components. Strain gauges 5 mm were affixed at the mid-span of beam on the tensile reinforcement, GFRP, and compressive concrete (60 mm) at the top of beam. Subsequently, strain gauges 3 mm were installed for shear reinforcement near the support, as shown in Fig. 6. Crack patterns were documented to identify the type of failure that occurred.

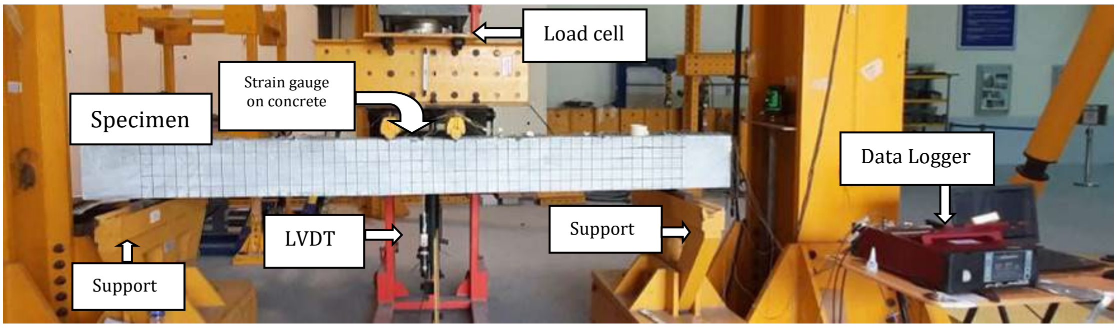


Fig. 5 *Static loading setup*

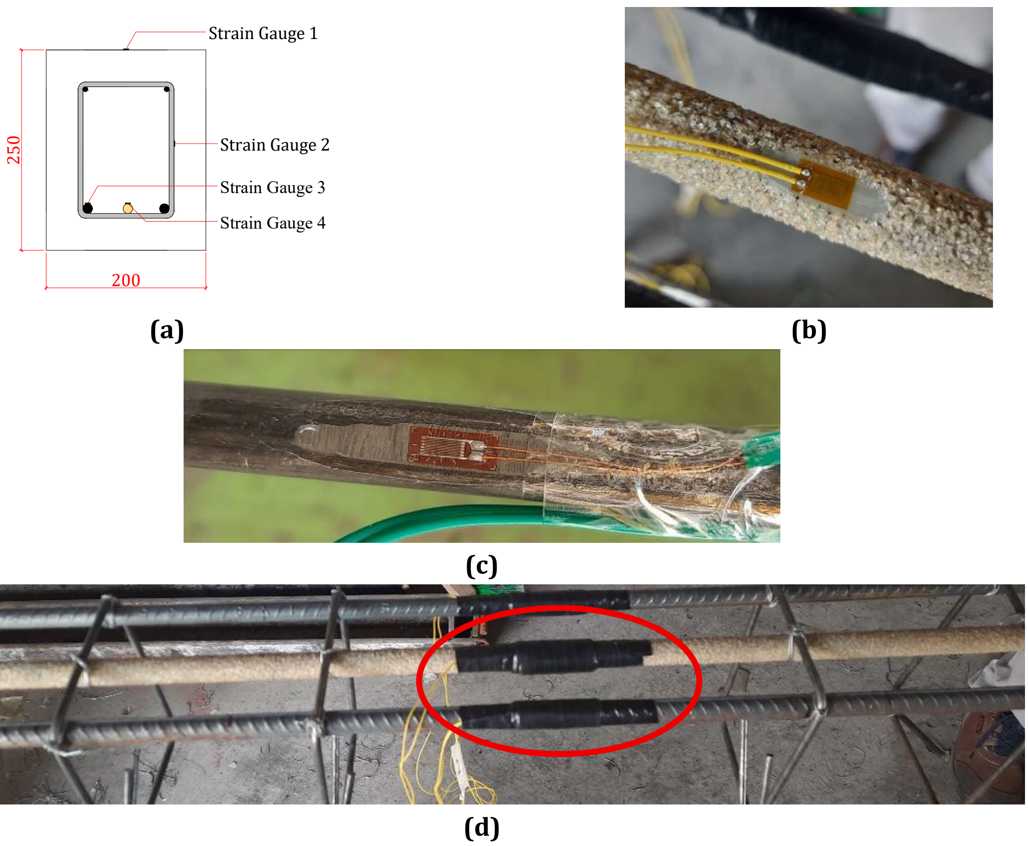


Fig. 6 *Strain gauge on the beam (a) detail strain gauge on concrete; (b) strain gauge on GFRP; (c) strain gauge on the stirrup; (d) strain gauge installed at tensile reinforcement*

To mitigate challenges encountered during sample preparation, such as ensuring the homogeneity of metakaolin in the mix, the addition was performed gradually with the use of a superplasticizer to maintain workability. The compaction was carefully controlled using mechanical vibrators, and samples were cured under standard conditions to achieve uniform hydration. These measures were implemented to ensure consistency and reliability in experimental results.

This study focused on experimental laboratory testing to evaluate the effects of metakaolin substitution and GFRP reinforcement on the flexural behavior of hybrid beams. All presented data and analyses, including initial cracking load, ultimate load, and displacement, were obtained directly from physical testing using the four-point bending method. This experimental method was selected to ensure that the results accurately showed the performance of materials and structures under real-world conditions, without reliance on assumptions or numerical modeling often used in simulations.

Although simulations using software such as ANSYS or Abaqus could provide additional validation or expand the analysis, this study prioritized experimental results as the foundation for evaluation. The primary focus was to understand the material response and the interaction between metakaolin concrete, steel reinforcement, and GFRP under actual conditions, including unforeseen variables such as mix homogeneity, curing conditions, and reinforcement adhesion.

This study offered a significant contribution in the form of empirical data, serving as a basis for future research that could integrate numerical simulation methods. Future investigations should use simulation software to validate the results, test additional loading scenarios, or explore a broader range of parameters without extensive physical testing. However, the reliability of laboratory experimental data remained the main reference for gaining an in-depth understanding of hybrid structural performance.

3. Experimental Results and Discussion

3.1 Mechanical Properties of Concrete

The cube compressive strength test results for normal concrete were 48.56 MPa and 58.63 MPa for concrete with metakaolin substitution, showing a 20.7% increase. Similarly, as highlighted in [27] the partial substitution of cement with metakaolin could enhance the compressive strength of concrete.

The flexural strength of plain concrete increased by 28.1% due to the addition of 10% metakaolin. The data on compressive strength and flexural plain concrete results are shown in Table 7.

Table 7 *Mechanical properties of concrete*

Type Concrete	Cube strength (MPa)	Flexural strength, f_{cf} (Mpa)
Normal Concrete	48.56	4.16
Metakaolin Concrete	58.63	5.33

3.2 Load-Deflection Curves

A relationship of load-deflection curves is essential to show the beneficial impact of reinforcement scheme, requiring the installation of LVDT at the mid-span. Fig. 7 shows the measured load-deflection response of all beams, where that of the control beams (HB-N and HB-M) is observed to be tri-linear with different load values. The first part shows a linear increase in load until the initial crack, while the second part has a similar progression to the yielding of the steel bars, with reduced stiffness. In the third part, the load-deflection curves are still linear with a small increase in load but beams experienced a significant increase in deflection, specifically in HB-N.

For beams reinforced with GFRP (HB-N-G and HB-M-G), the transition from the first crack to the yielding of the steel reinforcement is not clearly visible, as shown in Fig. 7. This is because the curve is only a straight linear line with almost the same slope. Both reinforced specimens show higher post-yield stiffness compared to the control specimens due to the support provided by GFRP layer. Effects of improved concrete strength due to metakaolin substitution result in an increased load in metakaolin beams (HB-M and HB-M-G), as shown by a steeper load-deflection curve. This phenomenon showed that the improvement in concrete strength in beams could enhance the load-carrying ability.

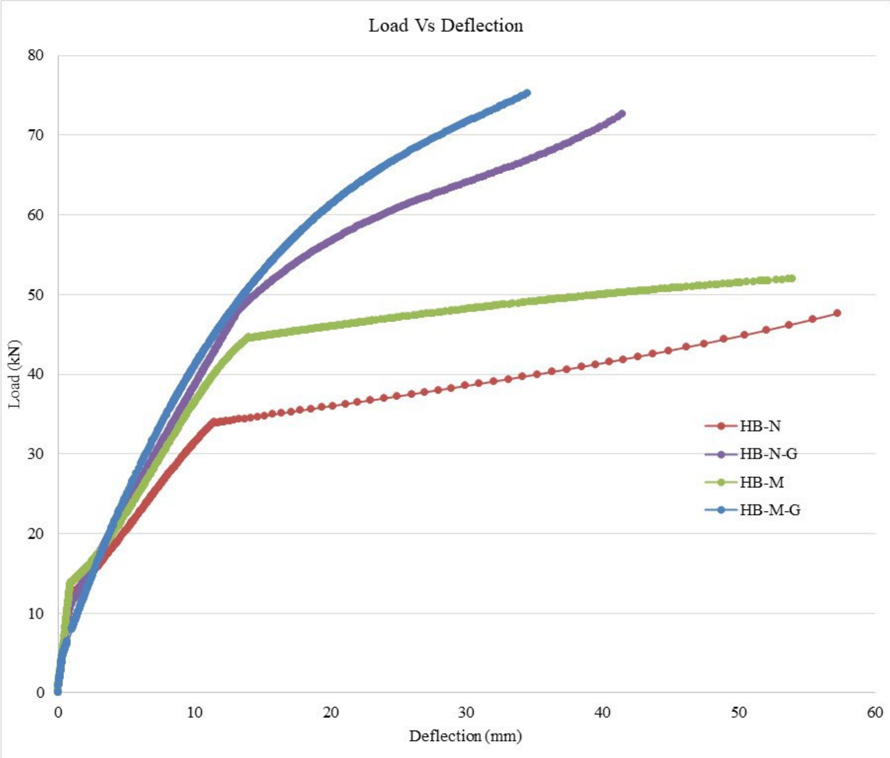


Fig. 7 *Load vs deflection response*

Theoretically, the initial cracking load is influenced by the concrete strength. This suggests that higher strength correlates with greater initial cracking load, as shown in HB-M, where the load increases to 13.9 kN (14.12%) higher than HB-N (12.18 kN). According to Ehab M. Lotfy and Manar Abdelshakor [5], concrete with metakaolin substitution experienced an increase in initial cracking load due to microstructure enhancement from the pozzolanic reaction between metakaolin and calcium hydroxide ($Ca(OH)_2$). This reaction produced more calcium silicate hydrate (C-S-H) compounds, strengthening the cement paste.

In HB-N-G, the initial cracking load slightly decreased to 11.6 kN, which was 4.76% lower than HB-N. This reduction was due to the low elastic modulus of GFRP reinforcement, which was not sufficiently effective in controlling initial tensile stresses in the concrete. According to Ahmed El Refai, et.al [28], GFRP reinforcement has a lower modulus of elasticity than steel, causing the concrete to reach the tensile limit before the GFRP significantly influences initial cracking.

A more significant reduction occurred in HB-M-G, with the lowest initial cracking load of 8.99 kN, a decrease of 35.32% compared to HB-M. This suggested that the combination of metakaolin concrete and GFRP caused lower resistance to initial cracking. The phenomenon was due to the high stiffness of metakaolin concrete, thereby reducing the effectiveness of withstanding early tensile deformation and increasing initial cracking. However, this reduction did not significantly impact the beam's ultimate load capacity.

Based on Table 7, the metakaolin substitution in HB-M-G beams increased the ultimate load to 75.19 kN, which was 57.83% higher than the control beam (HB-N) and 4.13% higher than HB-N-G (72.21 kN). This increase showed that metakaolin concrete significantly contributed to the hybrid beam maximum flexural capacity. Additionally, the combination of metakaolin concrete with GFRP reinforcement enhanced the flexural capacity through post-cracking stress redistribution. Bingyan Wei, et.al [29] observed an increase in flexural capacity of hybrid beams reinforced with a combination of steel and FRP. This increase was due to the synergistic interaction between the high tensile strength of FRP and the ductile properties of steel, enabling a more uniform stress redistribution. The results showed that increased flexural capacity of HB-M-G indicated the synergy between the high tensile strength of GFRP, the ductility of steel reinforcement, and the improved concrete strength from metakaolin substitution.

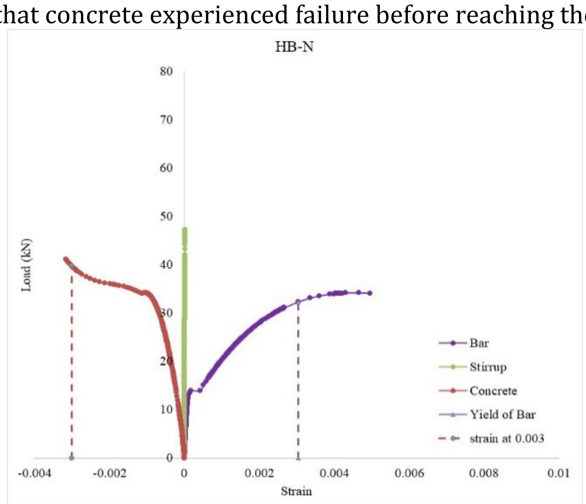
The displacement reduction ranged from 5.85% to 39.74%, showing an increase in stiffness for all three beams under ultimate load conditions. Meanwhile, the smaller displacement in HB-M-G showed that the combination of metakaolin concrete and GFRP reinforcement significantly enhanced the beam stiffness, leading to lower deformation under ultimate load. These results were in line with previous investigations by Abiraami R, et al [6] and Bingyan Wei, et.al [29], while Manisha Verma and Parves Alam [3] reported the limitations of the plastic deformation behavior of metakaolin concrete.

Table 8 *Detail of Initial crack load, ultimate load, and displacement on ultimate load*

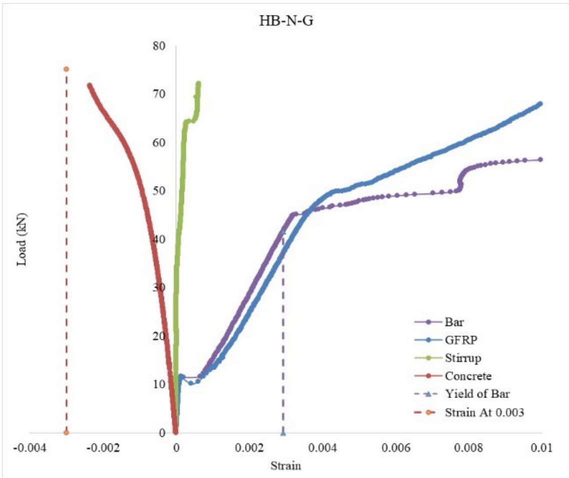
Condition	Type of Specimens			
	HB-N	HB-N-G	HB-M	HB-M-G
Initial crack Load (kN)	12.18	11.6	13.9	8.99
% Change to HB-N		- 4.76	+14.12	- 26.19
% Change to HB-M				-35.32
Ultimate Load (kN)	47.64	72.21	51.93	75.19
% Change to HB-N		+ 51.57	+ 9.01	+ 57.83
% Change to HB-M				+44.79
Displacement on ultimate Load (mm)	57.27	41.86	53.92	34.51
% Change to HB-N		- 26.91	- 5.85	- 39.74
% Change to HB-M				- 36.00

3.3 Load-Strain Relationship

Fig. 8 shows the strain that occurred during loading, with strain-load relationship curves for four beams presented on the same scale of load and strain. From the four images, all maximum compressive strain in concrete occurred after the yielding of the reinforcement steel. The largest compressive strain in concrete was found in beam HB-N, amounting to 0.00316, reaching the ultimate strain of concrete. This strain occurred at a load of 41.61 kN, showing that concrete experienced failure before reaching the maximum load.



(a)



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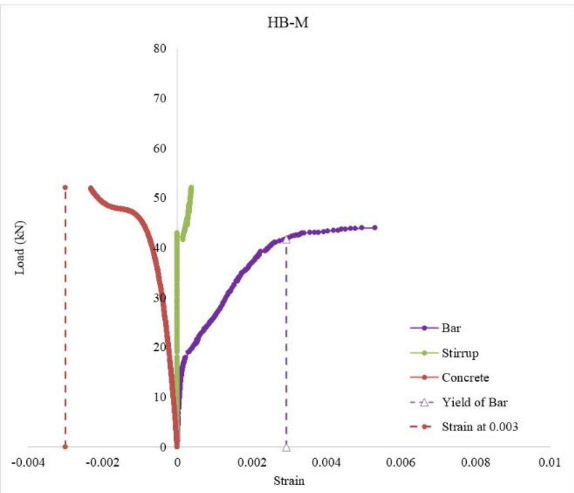

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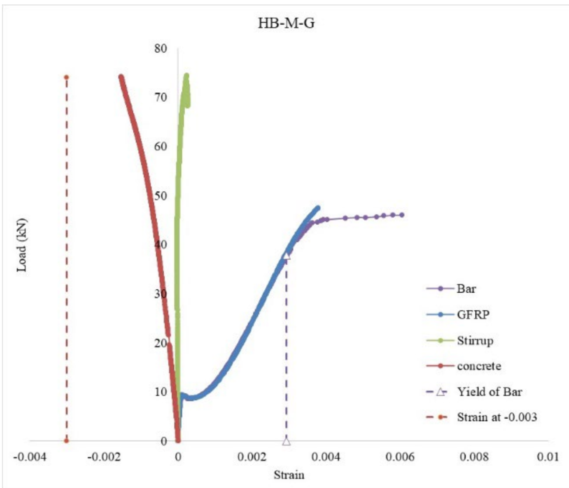

(d)

Fig. 8 *Load vs strain relationship (a)HB-N beam; (b)HB-N-G beam; (c) HB-M beam; (d)HB-M-G beam*

Strain in beam HB-M-G was the smallest, measuring 0.00153, followed by the other beams at 0.00232 and 0.00236, respectively. This implied that until the maximum load was reached, concrete had not experienced failure. In Fig. 8, the yield strain of steel (0.0029) for four beams occurred at different loads, with post-yield strain increasing inversely proportional. Effects of improving concrete strength due to substitution of metakaolin resulted in an increase in load required to reach the yield strain of steel in HB-M compared to beam HB-N. In contrast, for beam HB-N-G, a significant improvement in strain was observed in line with the increase in load, followed by a linear rise in GFRP until failure occurred. GFRP contributed significantly to providing higher strength to beams that were not reinforced.

3.4 Crack Patterns and Failure Modes

Based on the results obtained, the initial crack loads for each beam are shown in Table 7. Generally, cracking initiates when the tensile stress in the bottom side of the tested beam exceeds that of concrete, leading to stress transfer in steel reinforcement. The initial crack loads are closely spaced because the reinforcement and GFRP have not contributed to the first loading phase. However, as the load increases, additional cracks start to appear and develop, along with failure modes, as shown in Fig. 9.

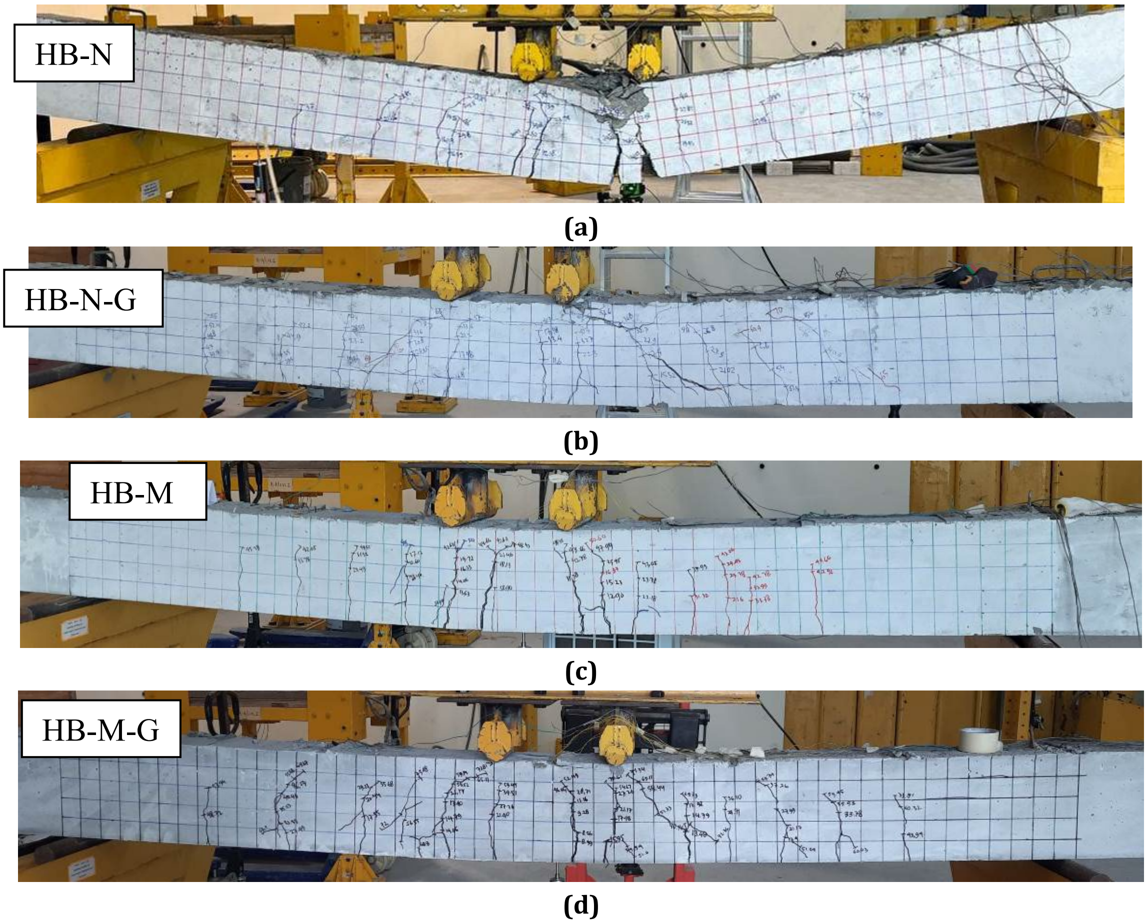

Fig. 9 *Failure modes of the tested beams (a) HB-N beam; (b) HB-N-G beam; (c) HB-M beam; (d) HB-M-G beam*

For beam HB-N, yielding of the steel reinforcement was initially observed, followed by the destruction of concrete in the compression zone. Subsequently, a fracture occurred in the bottom steel reinforcement, leading to the splitting into two separate parts, as shown in Fig. 9(a). In the case of beam HB-M, a greater number of cracks were formed compared to HB-N, but concrete in the compression zone presented in Fig. 9(c) did not fail. Generally, the cracks formed were straight, extending towards the top of beam, as pure flexural cracks. The failure mode of this beam was controlled by the behavior of the tensile reinforcement after the appearance of the first crack, as similarly reported by [30] and [31].

Regarding beams reinforced with GFRP, primary cracks developed at the mid-span and propagated towards the compression zone. As the applied load increased, more cracks developed, progressing with the depth of concrete cross-section. Based on the results, the number of cracks formed was higher compared to beams HB-N and HB-M. After reaching the yield load of the steel reinforcement, shear cracks (diagonal) started to form in the load direction. Flexural cracks were observed in beams HB-N-G and HB-M-G with a combination of shear, as reported by [32] and [33]. As observed in Fig. 9(c), improving concrete strength due to substitution of metakaolin prevented failure in the compression zone, where the cracks did not extend to the top of beam.

On average, there is smaller crack spacing in beams reinforced with additional reinforcement and metakaolin substitution in the tensile zone compared to HB-N. This indicates that improved concrete strength and reinforcement ratios can influence the cracking behavior of beam. The number of cracks observed is also higher, suggesting that metakaolin concrete is capable of distributing cracks more evenly, reducing the risk of large and critical cracks. According to Ehab M. Lotfy and Manar Abdelshakor [5], concrete with metakaolin substitution shows smaller crack spacing compared to conventional concrete. This shows more uniform crack distribution, which reduces stress concentration around the cracks.

The increased number of cracks can be influenced by stress redistribution due to the combination of stiffer concrete and GFRP reinforcement with a low modulus of elasticity. Ahmed El Refai, et.al [12] reported that beams with a combination of high-strength concrete and GFRP often showed a greater number of cracks due to the difference in modulus of elasticity between the concrete and the reinforcement.

3.5 Ductility

Several definitions and ductility indices have been developed for traditional reinforced concrete (RC) structures that exclusively use steel rebars. In these elements, ductility is defined as the ratio of deflection at the point of ultimate load to yield load. FRP materials have a linear stress-strain relationship until failure, resulting in a linear release of energy in FRP beams, which differs from steel reinforcement. Consequently, in this research, ductility is determined following the energy theory, as stated by [34]. Ductility (μ_E) is computed using Equation (1), which depends on the load-deflection characteristics observed in the tested beams.

$$\mu_E = \frac{1}{2}(\frac{E_T}{E_{el}} + 1) \quad (1)$$

Where E_T (=E_{inel}+E_{el}) is the total energy, E_{inel} represents plastic energy, E_{el} denotes the elastic energy. E_{inel} and E_{el} can be obtained from the load-deflection curves of Hybrid-RC beams. According to Bingyan Wei, et.al [29], there are two methods to determine ductility when the shape of load-deflection curve occurs as shown in Fig. 10.

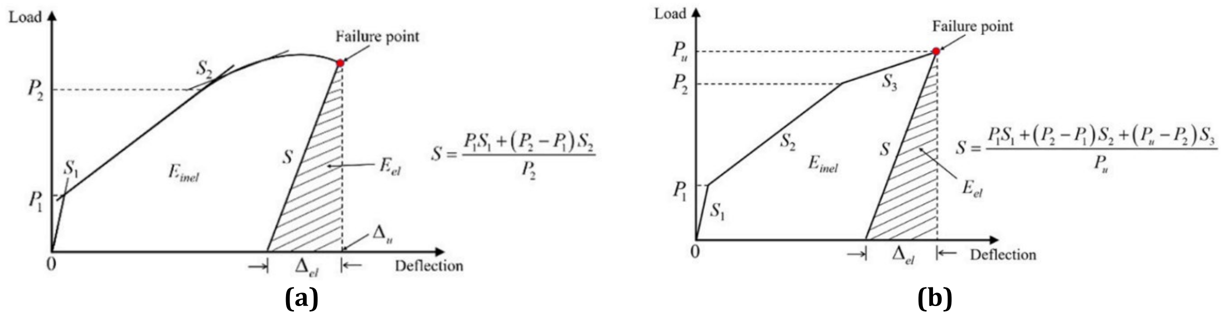

Fig. 10 *Determine E_{el} based on the curve shape (a) 2-slope curve shape; (b) 3-slope curve shape*

Table 9 shows that substitution of metakaolin increases strength concrete and enhances ductility of HB-M beams by 16.17% compared to HB-N. However, when using FRP (HB-N-G and HB-M-G) as reinforcement, substitution decreases ductility by 55.48% and 67.90% respectively [34] and [27]. This showed that an increase in reinforcement ratio (ρ_f) with a lower modulus of elasticity value could reduce beam ductility.

Table 9 *The ductility of the specimens*

Specimens	Slope S1	Slope S2	Slope S	ET	Eel	Ductility	% Change
HB-N	12.164	2.165	4.292	2084.55	264.49	4.44	
HB-N-G	13.028	3.017	3.688	2112.43	715.13	1.98	-55.48
HB-M	14.489	2.541	5.383	2334.38	250.55	5.16	+16.17
HB-M-G	13.664	3.967	2.974	1759.49	950.63	1.43	-67.9

The addition of metakaolin in HB-M-G beams can decrease ductility. The GFRP reinforcement in HB-N-G and HB-M-G beams has a much lower modulus of elasticity compared to steel. Consequently, GFRP shows a linear response until failure without providing a yielding phase similar to steel. The combination of GFRP with stiff metakaolin concrete increases ductility performance, without providing sufficient plastic deformation before failure. A study by Ahmed El Refai, et.al [12] showed that the use of GFRP reduced the ductility of structures, particularly when concrete showed high stiffness. According to Manar Ahmed and Ehab Lotfy [5], concrete with metakaolin substitution increased stiffness but reduced plastic deformation capacity due to the brittle nature of the material. Ahmed Hussein, et.al [7] stated that combining high-strength concrete with GFRP led to a significant reduction in ductility, despite an increase in flexural capacity.

The findings of this study provide valuable insights for optimizing hybrid beam design, combining high-strength concrete modified with metakaolin and GFRP reinforcement. By addressing sustainability challenges and improving structural performance, this approach offers a practical solution for modern infrastructure projects in aggressive environments. Future research could explore cost-benefit analyses and comparisons with alternative materials to further enhance its applicability.

4. Conclusion

This study showed that substituting metakaolin in concrete and adding GFRP reinforcement significantly enhanced the flexural capacity and stiffness of hybrid beams. Based on the test results, the HB-M-G beam, which combined metakaolin concrete, steel reinforcement, and GFRP, showed a 57.83% increase in ultimate load compared to the control beam (HB-N). A 39.74% reduction was also observed in displacement, showing improved beam stiffness. The metakaolin substitution improved the concrete's microstructure through pozzolanic reactions, causing higher compressive strength that contributed to the beam's maximum flexural performance. Initial cracking in the HB-M-G beam occurred at a lower load (8.99 kN), suggesting that the combination of metakaolin concrete and GFRP had limitations in resisting initial tensile stresses. These results showed that the metakaolin and GFRP combination was suitable for enhancing structural flexural capacity and stiffness. However, vulnerability to early cracking should be addressed for applications requiring significant initial deformation.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors' contributions to the paper are as follows: ***study conception and design:*** *Indriyani Puluhulawa, Mohd Hanif Bin Ismail, Norhafizah Salleh, Francis George Ambros;* ***data collection:*** *Indriyani Puluhulawa;* ***analysis and interpretation of results:*** *Indriyani Puluhulawa, Mohd Hanif Bin Ismail, Norhafizah Salleh, Francis George Ambros;* ***draft manuscript preparation:*** *Indriyani Puluhulawa, Mohd Hanif Bin Ismail, Norhafizah Salleh, Francis George Ambros. All authors critically reviewed the results and approved the final version of the manuscript.*

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