

Experimental and Theoretical Analysis Using FEA of Fiber-Reinforced Concrete Beam Flexural Performance

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An experimental and theoretical program was conducted to enhance comprehension with regard to how variations in fibre ratio affect the structural performance of concrete beams. In this research a concrete mix with Three fibre volume fractions of 0.5%, 1.0%, and 1.5% were tested to evaluate the fibre effect on concrete strength. The results showed that the fibre increased the tensile strength by a maximum of 86% (1.05MPa Vs 1.95MPa) and the compressive strength by 8%. The research also included testing four beams under four-point loading tests to evaluate the flexural strength. The tests showed that adding fibre increased the flexural strength of the beam by 17%, the initial stiffness by 77%, and flexural toughness by 20%. A three-dimensional finite element model was created using ABAQUS to simulate the beam behaviour, the model was calibrated using the experimental data and good agreement was obtained from the model. It was concluded that increasing the fibre content generally enhanced the material up to the point where the concrete workability of the concrete was adversely affected by increasing fibre content.

Keywords: polyolefin fibre; Flexural Performance; FEA; ABAQUS

I. INTRODUCTION

The tensile capacity of the concrete in a reinforced concrete beam (RC Beam) is usually neglected by engineers for flexure design, that is because the contribution of the concrete in the tensile zone is mostly addressed as a stress transferee media to the reinforcement in the tensile zone of the section (ACI Committee 318, 2014).

However, the contribution of that part of concrete to the stiffness of the beam is partially neglected as per the cracked section analysis that shall consider that all concrete under the neutral axis of the section have a stress level of zero due to cracking (McCormac & Brown, 2015). This type of analysis, although conservative to a point, yet it is true for only the area with maximum moment, this area in a commonly loaded beams is usually less than 10% of the beam span.

In a normal low high building that might not be of a significant importance, however, for high rise building or buildings with large spans weight saving is of great important to accommodate the soil capacity or to reduce the required

height of a beam required for a certain span (Coull & Smith 1991).

There currently several methods used to work around this issue, the obvious one is increasing the depth of the beam thus providing more stiffness in the cracked section stage, increasing the compressive strength of the concrete and as the tensile strength is related to compression strength value the increment shall provide more stiffness by lowering the neutral axis and permeating the addition of more tensile steel, these solution despite being adequate to solve the lack of stiffens of the beam adds more weight to the structure or make the concrete more expensive (El Bakzawy *et al.*, 2024).

In this research, a polyolefin fibre is utilised to increase the tensile strength of the concrete by adding several percentages of it to already tested mix and comparing the concrete tensile and compressive strength and the overall beam behaviour.

The addition of fibre to concrete enhances its ability to resist cracking by increasing the tensile strength of concrete, furthermore the fibre bridges the cracks thus improving the

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beam toughness and flexural strength (Sedaghatdoost & Amini, 2017; Wu *et al.*, 2022).

Recent studies have increasingly focused on the integration of synthetic macro-fibres, particularly polyolefin fibres, to improve the structural performance and crack resistance of concrete elements. For instance, (Yuvashri *et al.*, 2021) evaluated the flexural behaviour of high-performance concrete beams reinforced with polyolefin micro and macro fibres, demonstrating that the inclusion of these fibres noticeably enhances both the first-crack load and the ultimate load-carrying capacity while improving ductility.

Similarly, (Alberti *et al.*, 2020) highlighted that polyolefin-based macro-synthetic fibres offer excellent chemical

stability and corrosion resistance, providing reliable residual tensile strengths and effective crack-bridging behaviour in structural fibre-reinforced concrete

Furthermore, investigations by (Sobhan *et al.*, 2021) on structural beams containing polyolefin fibres confirmed substantial enhancements in post-cracking performance and residual flexural capacity compared to unreinforced mixes. Despite these developments, further experimental data on specific configurations remain valuable for validating analytical models and expanding their application in structural design.

Table 1. Concrete Mix Design content per $1m^3$

ID	w/c	Water (kg/m ³)	Cement (kg/m ³)	Sand (kg/m ³)	Normal coarse aggregate (kg/m ³)	Polyolefin (kg)	Polyolefin %	SP (kg)
P.O.0.0%	0.49	181.3	370	740	1110	0.00	0.0	2
P.O.0.5%	0.49	181.3	370	740	1110	4.55	0.5	2
P.O.1.0%	0.49	181.3	370	740	1110	9.10	1.0	2
P.O.1.5%	0.49	181.3	370	740	1110	13.65	1.5	2

II. EXPERIMENTAL WORK

The experimental work consists of casting four beams using four mix designs which differ only in their Polyolefin content, the percentage includes 0% as the control mix, 0.5%, 1.0%, and 1.5% of polyolefin fibre. The concrete where design according to ACI Methode (without fibre) as the base mix-design to get a grade C35 concrete then the volume fracture of fibre was added. Table 1 and 3 depicts the content of the concrete mix and the results of the concrete test for the above-mentioned mix designs.

The fibre employed in this study, straight Polyolefin fibre with a rough surface. Table 2 lists the primary Polyolefin fibre from the Sika Fibre® Force-60 data sheet.

Table 2. Polyolefin fibre characteristics.

Properties	Value
Tensile Strength (MPa)	765
Elastic Modulus (GPa)	7.5
Valent Diameter (mm)	0.84
Length (mm)	60
Density (kg/L)	0.91

A. Concrete Test Results

From the result in Table 3 adding more Polyolefin fibre increased the tensile strength of concrete, however the additional volume of fibre more than 1% decreased the workability of concrete leading to decrease in concrete compressive strength. The concrete test results include the following tests:

- Compressive Strength (f_{cu}) and Concrete Strength (f'_c):** As previously noted, there is a slight decrease in compressive strength with increasing polyolefin content. This suggests that while polyolefin fibres enhance other mechanical properties, they may slightly reduce the concrete's capacity to resist compressive forces. The highest compressive strength is seen in the mix with polyolefin (P.O.1.0%). As can be seen in Figures (1 and 2). The tests were carried in accordance with BS En 12390-3(Standard 2009) for the cube test and ASTM C39/C39M(ASTM International 2004) for cylinders.
- Splitting Tensile Strength (f_{ct}):** the value for f_{ct} increases with the addition of polyolefin fibres. The tensile strength increases from 2.50MPa in P.O.0.0% to 3.75MPa in P.O.1.0%. Polyolefin, fibres help the concrete

resist cracking, improving its behaviour under tension. Consistent with the compressive test behaviour the value of f_{ct} showed that the optimum value at 1.0% of fibre. Beyond this point the 1.5% dosage led to slight decrease in the tensile strength value from 3.75MPa to 3.63MPa. The results are shown in Figure 3.

3. **Direct Tensile Strength (f_t):** the f_t value also increases with polyolefin content, from 1.05 MPa in P.O.0.0% to 1.95 MPa in P.O.1.5%. This shows that polyolefin fibres provide better resistance to direct tension and improve the material's capacity to withstand forces that pull apart the concrete. The test specimen is shown in Figure (4).

From the direct tensile test, the 1.5% fibre dosage also increased the tensile strength unlike the results obtained from the compressive strength and splitting test. That difference can be due to the type of stress applied from the tests, where the compressive and splitting tests depends on the concrete matrix, thus the air void have greater impact on the test result (Smirnova *et al.*, 2019). The direct tensile strength on the other hand is more fibre controlled, where the fibre is more directly loaded (Wu *et al.*, 2022).

4. **Modulus of Rupture (f_r):** The modulus of rupture increases as polyolefin content rises, showing that the concrete can better resist failure under bending or flexural stresses. It increases from 4.03MPa in P.O.0.0% to 6.80MPa in P.O.1.5%, indicating that the addition of polyolefin fibres improves the concrete's bending resistance. The same argument regarding the fibre effect on this test result can be made, where the fibre contribution did not decrease for fibre content larger than 1%.

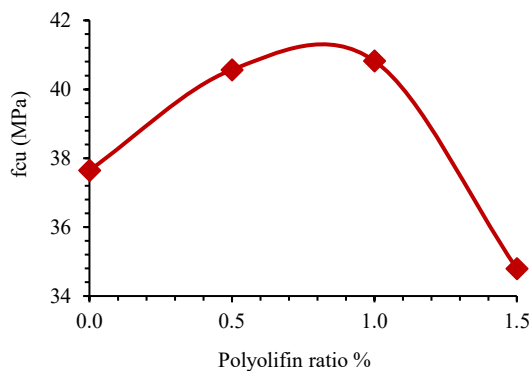


Figure 1. Compressive Strength (f_{cu})

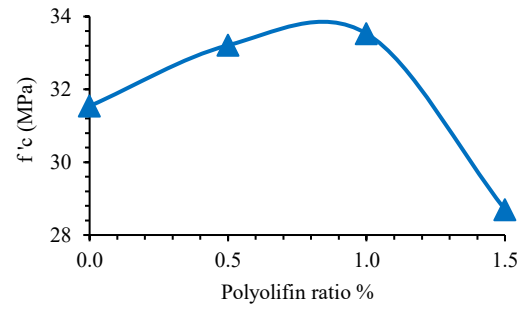


Figure 2. Concrete Strength (f'_c)

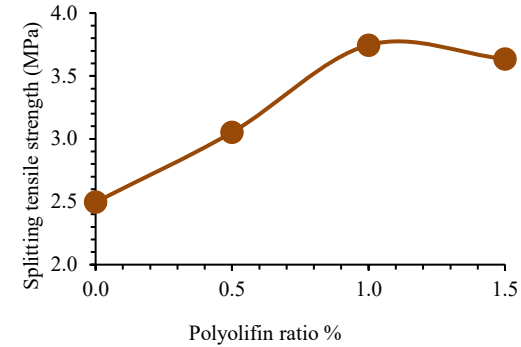


Figure 3. Splitting Tensile Strength (f_{ct})

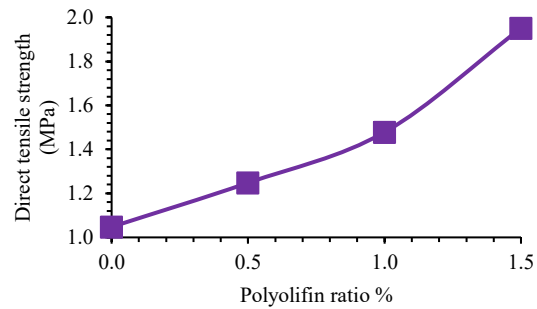


Figure 4. Direct Tensile Strength (f_t)



Figure 5. Direct tensile strength test.

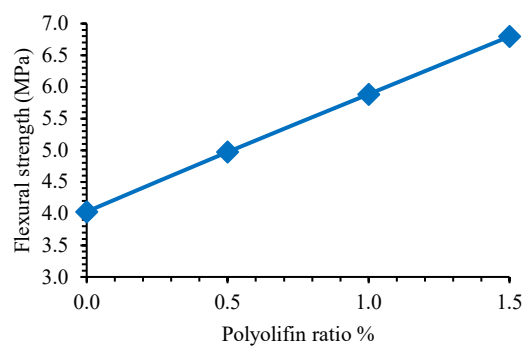


Figure 6. Modulus of Rupture (f_r)

Table 3. Concrete Mix Design Test Results

ID	fcu (MPa)	f'c (MPa)	fct (MPa)	ft (MPa)	fr (MPa)	fct/fcu	fct/fr	√fcu (Mpa)
P.O.0.0%	37.65	31.54	2.50	1.05	4.03	7%	62%	6.14
P.O.0.5%	40.57	33.21	3.05	1.25	4.97	8%	61%	6.37
P.O.1.0%	40.83	33.53	3.75	1.48	5.88	9%	64%	6.39
P.O.1.5%	34.80	28.70	3.63	1.95	6.80	10%	53%	5.90

Where:

f_{cu} : Cube compressive strength (a 150×150×150mm Cube)

f'_c : Cylinder compressive strength (a 150mm×300mm Cylinder)

f_{ct} : Splitting Tensile Strength.

f_t : Direct Tensile Strength.

f_r : Modulus of Rupture.

B. Ratios

The f_{ct}/f_{cu} ratio (splitting tensile to compressive strength) and f_{ct}/f_r ratio (splitting tensile to modulus of rupture) both increase with polyolefin fiber content. This suggests that polyolefin fibers in the range of 0.5 to 1.0% improve the tensile and flexural resistance of the concrete relative to its compressive strength, enhancing the material's overall durability and ductility.

However, increasing the fibre content from 1.0% to 1.5% has decreased the splitting strength of the concrete from 3.75MPa at 1.0% to 3.63MPa at 1.5% fibre. This is consistent with the compression strength results as the higher fibre content reduced the workability of concrete leading to less compaction of concrete and higher air void in the matrix which can affect the concrete ability resist not only the compression stress but its ability to transform the tensile stress to the fibre (Sedaghatdoost & Amini, 2017).

In a low workability concrete, it is also important to refer to the poor distribution of fibre in the matrix which also affects fibre efficiency in improving the tensile strength of the concrete.

C. Modulus of Elasticity (E)

The Modulus of Elasticity (also known as Young's Modulus) represents the stiffness of a material. In the context of concrete, it measures how much the concrete deforms under an applied stress within the elastic range (before it starts to fail).

It is calculated as the slope of the linear region of the stress-strain curve, typically before the concrete starts to yield or exhibit plastic deformation by the secant method used in ASTM C469/C469M(American Standard Testing and Material 2014) as shown in Figure (8). The modulus is

essential for understanding the ability of concrete to resist deformation under load. The stress strain curves for the tested specimens are shown in Figure (9). From the test the value of modules of elasticity (E) for concrete are listed in table 4.

The value of E can also be calculated for normal light weight concrete using the ACI (ACI Committee 318 2014)equation as

$$E_c = 4700\sqrt{f'_c}$$

Applying the above equation to the concrete compression strength gives a value that is conservative within a ±5% from the value taken from the test, these results are consistence with those reported in another research (Katman *et al.* 2022).

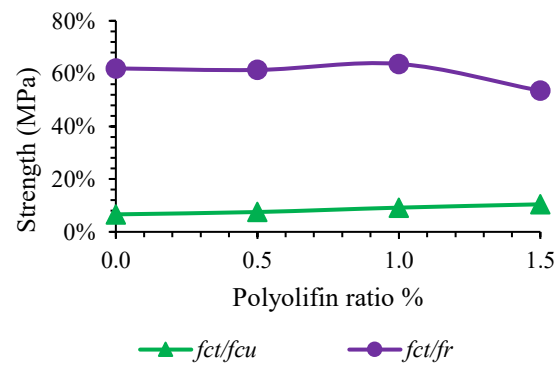


Figure 7. splitting tensile to compressive strength f_{ct}/f_{cu} & splitting tensile to modules of rupture f_{ct}/f_r



Figure 8. stress strain test setup

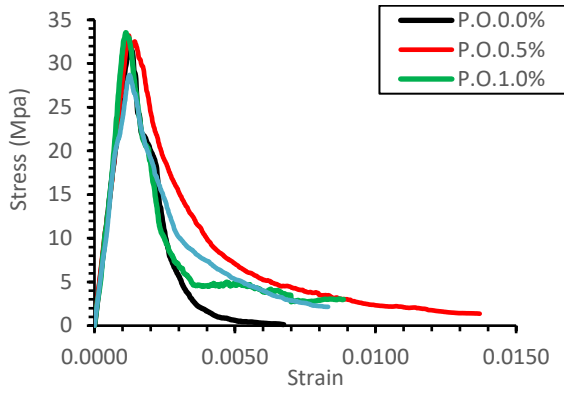


Figure 9. stress strain curve for the four tested samples

Table 4. Modules of elasticity value (E)

ID	Stress strain curve MPa	ACI Equation MPa	Test/ACI
P.O.0.0%	27,300	26,395	103%
P.O.0.5%	28,562	27,085	105%
P.O.1.0%	27,720	27,215	102%
P.O.1.5%	23,942	25,179	95%

D. Concrete Test Result Conclusion:

Polyolefin fibres significantly improve the tensile and bending properties of concrete, particularly splitting tensile strength, direct tensile strength, and modulus of rupture. This makes concrete more resistant to cracking and breaking under tension and bending forces.

While the *compressive strength* slightly decreases with increasing polyolefin fibre content, the improvements in tensile and bending strength suggest that polyolefin fibres could be particularly useful in applications where cracking, bending, and tensile stresses are a concern (such as in pavements, thin slabs, or other structures prone to cracking).

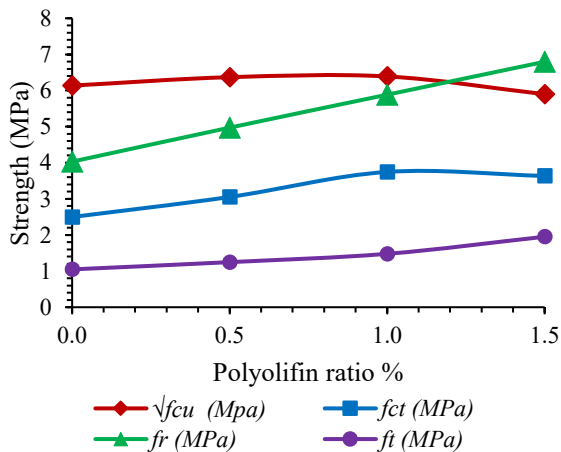


Figure 10. Variation of Concrete Strength Parameters with Polyolefin Ratio (Line Representation)

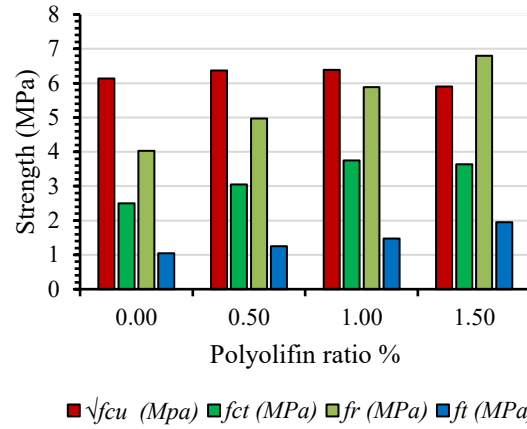


Figure 11. Comparison of Concrete Strength Parameters at Different Polyolefin Ratios (Bar Representation)

E. Beam Test Results

For this research a total of four beams has been tested using the prementioned concrete mix design with 0%, 0.5%, 1.0%, and 1.5% of fibres, the beam details are as shown in Figure (12). The beams were reinforced with 2Ø12mm main rebar and a Ø10mm stirrups at 80mm spacing. The test is carried out by load increment measuring the mid span deflection at each increment, the recorded values for load deflection are shown in Figure (13).

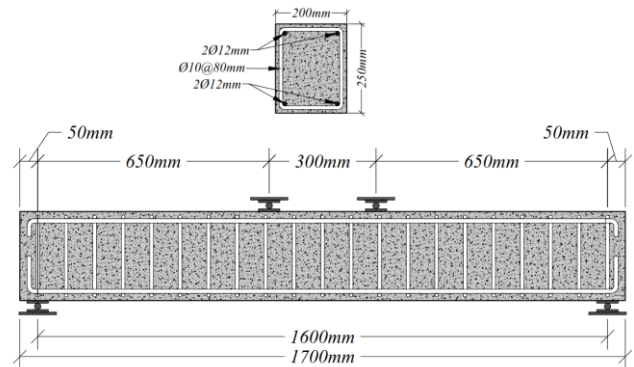


Figure 12 Tested beam details.

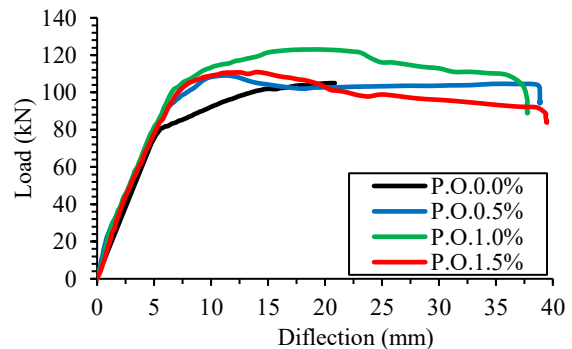


Figure 13. Load deflection Curves for the four beams.

To evaluate the fibre effect on the beam behaviour several factors have been calculated using the experimental results such as the maximum load, initial stiffness and ductility.

The ductility is defined as the ability of the beam to withstand load after yielding, from the load deflection behaviour of the beams the yield load can be calculated graphically by intersecting a horizontal line tangent to the curve at ultimate load with the initial stiffness line as shown in Figure (14). Then the ductility can be calculated as:

$$Ductility = \frac{\Delta_{Ultimate}}{\Delta_{yield}}$$

The yield load of the four beams is shown in Table (5). From the results of Table (5) the displacement ductility was calculated and as shown in Table (6).

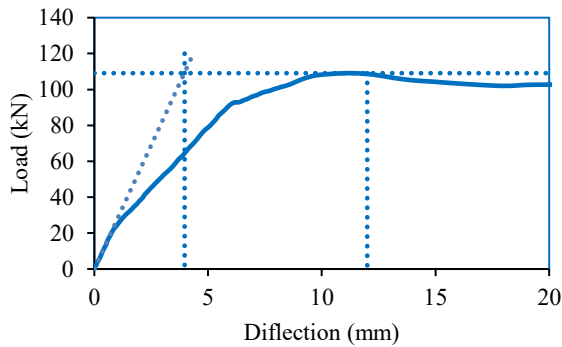


Figure 14. Beam P.O.0.5% load deflection curve and yield load calculations.

Table 5. Beam Ultimate Load and Displacement

Name	Ultimate load	Yield load displacement	Ultimate load displacement
P.O.0.0%	105.0	6.60	18.00
P.O.0.5%	109.1	3.97	12.00
P.O.1.0%	123.0	5.27	20.00
P.O.1.5%	110.9	5.94	14.20

Table 6. Tested Beams Displacement Ductility and Compression with The Control Beam

Name	Ductility	Relative to Control Beam
P.O.0.0%	2.73	0%
P.O.0.5%	3.02	11%
P.O.1.0%	3.80	39%
P.O.1.5%	2.39	-12%

The increase in ductility for the 0.5% and 1.0% Fiber content is consistent with the values seen in the concrete test for the compressive and tensile strength, the curves showed a smoother post peak load decay in beam strength. The presence of fibre also redistributed the cracks along the tensile zone of

the beam as can be seen in Figures (15-18). These results are consistent with previous results(Said *et al.* 2020; Yang *et al.* 2021).



Figure 15. Beam P.O.0.0% Failure

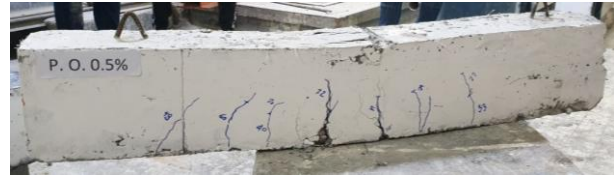


Figure 16. Beam P.O.0.5% Failure



Figure 17. Beam P.O.1.0% Failure



Figure 18. Beam P.O.1.5% Failure

Table 7 presents the initial stiffness values for the tested beams. The data clearly indicates that the inclusion of fibres markedly enhances the linear elastic response, particularly at a fibre volume fraction of 0.5 %. At this dosage the stiffness is approximately 77 % greater than that of the plain-concrete control specimen (0 % fibre). The fibres improve the concrete's tensile capacity, which postpones the formation of the first crack during loading. Consequently, the beam retains its full-section stiffness over a larger load range compared with a fibre-free beam. These observations lead to the conclusion that incorporating a modest amount of fibres into the concrete matrix can substantially increase the beam's linear-elastic stiffness.

Table 7. Tested Beams Initial Stiffness and Compression with The Control Beam

Name	Initial Stiffness kN/mm	Diff. Compared to Control Beam %
P.O.0.0%	15.56	0%
P.O.0.5%	27.59	77%
P.O.1.0%	23.33	50%
P.O.1.5%	18.67	20%

For the Flexural toughness of the beams the values were calculated up to L/150 (10.6mm) of deformation for all beams (ASTM International 1997). As it is a measure of the post cracking ductility of the beam the fibre effect on the toughness value of the beams is like that of ductility. The highest value of Flexural toughness for beam with a fibre content of 1.0% were 807.04N.m which is 20% more than the control beam.

Table 8. Tested Beams Flexural Toughness and Compression with The Control Beam

Name	Flexural toughness N m	Diff. Compared to Control Beam %
P.O.0.0%	670.68	0%
P.O.0.5%	765.93	14%
P.O.1.0%	807.04	20%
P.O.1.5%	769.12	15%

III. FINITE ELEMENT ANALYSIS (ABAQUS)

For this research, the results of the four beams were simulated using the finite element analysis program ABAQUS (Simulia (Dassault Systèmes) 2014). For concrete a concrete damaged plasticity model CDPM were used to simulate the inelastic behaviour of the concrete. The CDPM was developed by (Jeheo & L, 1998). The concrete under low confining pressure behaves as brittle material, the CDPM simulate the concrete failure mechanism as crashing in compression and cracking in tension. Based upon the applied stress ABAQUS calculates the stress-strain curve based on the stress inelastic strain (Kakooei *et al.* 2012).

In parallel with continuum damage models, another evolving numerical framework gaining traction in concrete mechanics is the cohesive-based finite element approach. This method utilises traction-separation relationships to

explicitly model crack initiation and propagation, governed primarily by key parameters such as the maximum cohesive stress and fracture energy (Ahmad *et al.* 2021; Omar *et al.* 2023). While traditional damage plasticity approaches remain standard for capturing overall structural response, incorporating cohesive behaviour offers a detailed alternative for tracking localised damage and softening mechanisms in fibre-reinforced cementitious composites.

A. Modelling and Support Conditions

The beams were modelled as simply supported beam with a clear span of 1600mm and total length of 1700mm, the cross-section dimension and reinforcement were as shown in Figure (12). Figure 19 and 20 shows the model and selected mesh size for the beams.

The beam was calibrated for geometric and material parameters such as mesh size, eccentricity, dilation angle, viscosity, the ratio of uniaxial stress to biaxial stress and different element types of steel and concrete, the sensitivity study conducted were as mentioned in the work of (Maulana *et al.* 2023). The material parameters for the CDPM are shown in Table (9).

For the beam to be analysed accurately with a reasonable run time for the model a refining process was conducted to capture the accurate beam behaviours, the aim was to select a mesh size so that at least 8 element in the cross section depth are selected which lead to starting with a mesh size of 31mm (in all three dimensions depth width and length), the size was refined until a balance between the computation time and the accurate capturing of the local stress gradient yield zones and flexural crack spacing. The selected size for the mesh was 10mm. it is worth mentioning that when analysing beams with nonlinear behaviour it is more sensitive to the mesh size thus the study was conducted.

The concrete was modelled using 8-node brick element with reduced integration (C3D8R), as for the reinforcement a 2-node linear three-dimensional truss element were used (T3D2).

For the dilation angle the study starts with a low value of 31 for normal concrete up to 46 and the selected value for the normal concrete was 36 as mentioned in Table 8. As for the beams with fibre concrete the value selected for the dilation angle ranged from 42 to 45.

The boundary conditions for the model were set for the loading and support plate, for the support plate the line at the mid of the plate were confined in U1, U2, and U3 directions and released in the rotation around the three axis to represent a hinge, as for the other support plate the line were confined in U1, and U3 direction and released in the rotation in all axes to represent a roller. The reinforcement was modelled as embedded item in concrete, and the loading and supporting plates contact to concrete surface were modelled as fully bonded surface.

When the model was validated for the first beam it was implemented for the other beams. The results of the finite element load deflection behaviour to the experimental behaviour were as shown in Figures 22 to 25.

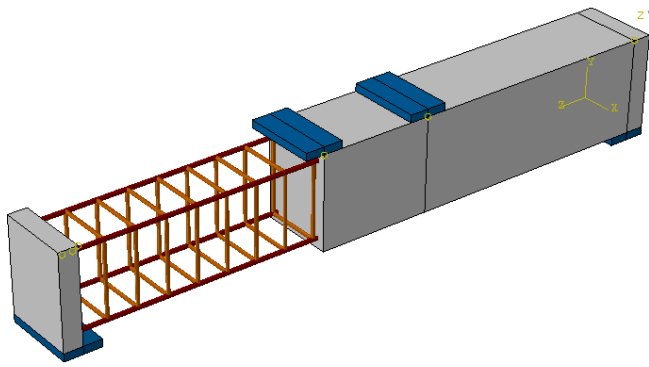


Figure 19. F.E Model showing a part of the reinforcement imbedded in concrete.

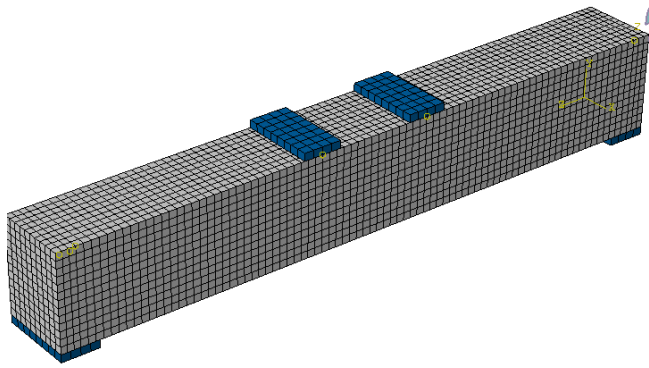


Figure 20. F.E Model mesh size.

Table 9. Celebrated parameters for compound stress in CDP model

Parameter	Value
Dilation angle	42-45 (NC 36)
Eccentricity	0.100
f_{bo}/f_{co}	1.160
k_c	0.667
Viscosity	0.002

The CDP requires two more values to be input compressive Behaviour and Tensile Behaviour, the value for tensile are shown in Figure 21, as for the compression behaviour the values are extracted from the stress strain curved from the tested specimens in Figure 9.

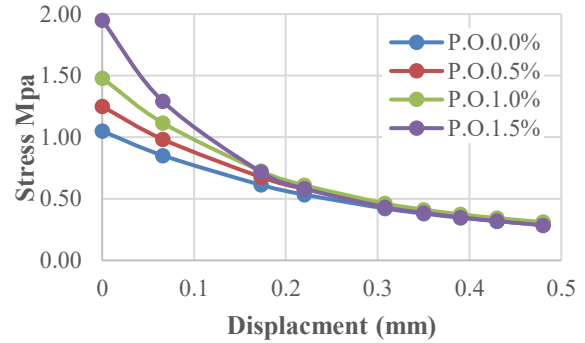


Figure 21 Stress Displacement in tension for the CDP model

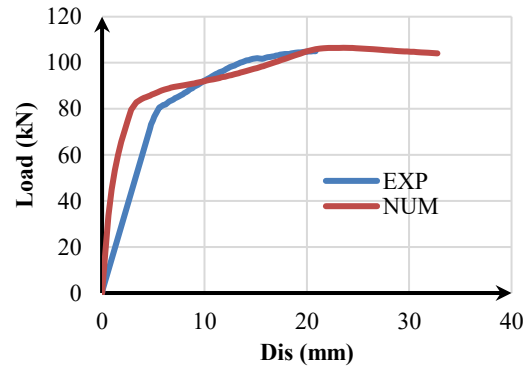


Figure 22 Beam P.O.0.0% Experimental and Numerical Load deflection behaviour.

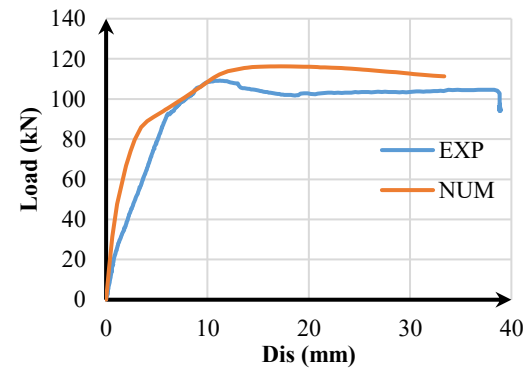


Figure 23. Beam P.O.0.5% Experimental and Numerical Load deflection behaviour.

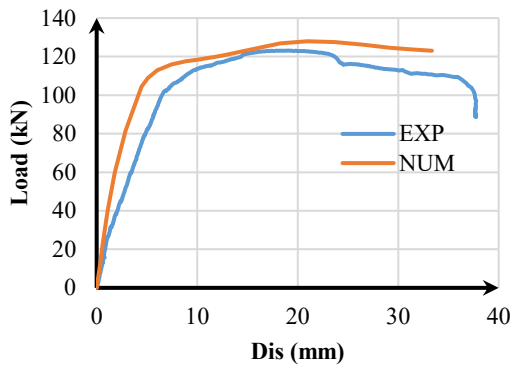


Figure 24. Beam P.O.1.0% Experimental and Numerical Load deflection behaviour.

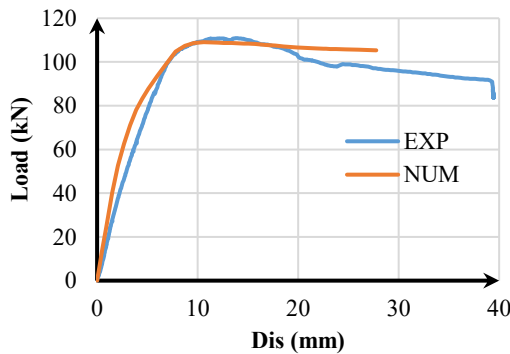


Figure 25. Beam P.O.1.0% Experimental and Numerical Load deflection behaviour.

From the numerical results of the model, it can be stated that the model can represent the experimental beam with acceptable accuracy.

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IV. DISCUSSION OF RESULTS

For the concrete mix adding the fibre increased the tensile strength with average (taking the average of the three tensile strength tests) of 22%, 46%, and 67% for fibre content of 0.5%, 1.0%, and 1.5%, respectively.

However, the compressive strength value was increased only up to fibre content of 1.0% as the 1.5% reduced the concrete workability resulting in less compacted concrete with relatively higher air void ratio.

As the beams were loaded, cracks start appearing at the mid span bottom part of the beam (the maximum tension zone) for the control beam without fibre the cracks were localised and enlarged progressively as the load increase up to a failure point. For beams with fibre content the cracks were distributed along longer portion of the mid span due to the fibre contribution in resisting the tensile stress.

The fibre also improved the beam displacement ductility by 39% for beam with 1.0% fibre, and the flexural toughness at L/150 by 20% for the same beam.

The initial stiffness for the beams was also increased by adding fibres; however, the increment was at maximum value for beam with 0.5% fibre where the value was 77% more than that of the control beam.

Thus, as a conclusion, adding Polyolefin fibres enhanced the overall properties of the concrete and the beam behaviour and strength providing that the added fibre dose not impact the concrete workability drastically.

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