An Experimental Investigation on Mechanical Behavior of Macro Synthetic Fiber Reinforced Concrete

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Abstract **- Concrete is an indisputable material for the construction of various types of structures in the modern advancement of civil infrastructures. Concrete is strong in compression but weak in tension and shear. To eliminate those problems, the introduction of fiber was brought in as an alternative to developing concrete in view of enhancing its tensile and shears strength as well as improving its ductile property. Hence, the purpose of this study was to investigate the mechanical behavior of concrete reinforced with macro (structural) synthetic fibers. To determine these properties experimental work was carried out. Four batches of concrete were cast: one with no fibers and the remaining three with three different volume fractions fibers of 0.33, 0.42 and 0.51%, respectively. Concrete specimens (cubes, prisms and beams) were cast to determine the mechanical behavior such as compressive, tensile, shear strength and stress-strain relationships. Test results showed that macro synthetic fiber enhanced the compressive strength insignificantly. However, macro synthetic fibers at 0.33, 0.42 and 0.51% volume fractions improved the tensile strength by at least 10, 15 and 14%, respectively, compared to the control specimen. Similarly the ultimate shear strength was increased significantly by at least 15, 45 and 65% for macro synthetic fibers of 0.33, 0.42 and 0.51% volume fractions, respectively, compared to the control beams. The failure of plain concrete specimens was sudden (brittle) for both the tensile and shear strength tests. However, the concrete reinforced with macro synthetic fibers showed more ductile behavior compared to the plain concrete. Macro synthetic fibers improved the ultimate strain value by at least 50, 60 and 60% for macro fibers of 0.33, 0.42 and 0.51% volume fractions, respectively.**

Key words **- Fiber reinforced concrete, macro (structural) synthetic fiber, fiber volume fractions, mechanical behavior.**

I. INTRODUCTION

CONCRETE and cement based materials have been implemented in structural members since prehistoric times. Day by day the significance of concrete has developed and the limitations of concrete have been slowly but surely eliminated which increases the durability of concrete allowing a higher performance value to be achieved. However, concrete is strong in compression but weak in tension. To overcome this weakness in concrete, steel reinforcement is utilized to carry the tensile forces and prevent any cracking or by pre-stressing the concrete so that it remains largely in compression under load [1].

The introduction of steel fibers was brought in as an alternative to developing concrete in view of enhancing its flexural and tensile strengths. Although the basic governing principles between conventional reinforcement and fiber systems are identical, there are several characteristic variations; such as - fibers are generally short, closely spaced and dispersed throughout a given cross section [2]. However reinforcing bars or wires are placed only where required. Moreover steel fibers helps to reduce the problems associated with congestion of shear reinforcement such as interference with concrete compaction [3]. These may attributed to the honeycombing and poor quality of concrete, particularly at critical sections such as beam-column junctions.

With the development of synthetic fiber, synthetic macro-fiber (fiber's diameter is larger than 0.1mm is defined as macro-fiber [4]) has been used widely in civil engineering. Due to some limitations of steel fiber, macro synthetic fiber could be a better solution for enhanced performance, such as- facilitate light weight concrete structure, high corrosion resistance; better residual (post-cracking) flexural strength, smaller crack width and improved performance in impact, abrasion along with more of a leveled surface than traditional steel fiber reinforced concrete. Synthetic macro fiber, such as Strux90/40 is a new type reinforcement material in concrete.

In this study, mechanical behavior of concrete reinforced with four different percentages of macro synthetic fibers (Strux90/40) where plain concrete as a control specimen was investigated. In pursuit of this investigation, several laboratory works were performed

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– for instance, casting and testing of – (i) cubes for compression and tension. (ii) beams for shear and (iii) prisms for the determination of stress-strain relationships and finally (iv) making comparison and discussion on the test results.

II. EXPERIMENTAL PROGRAM

1) Materials

The main component of the polymeric fiber used in this study was polypropylene as shown in Figure 1. This synthetic macro fiber's nominal length was 40 mm and had an aspect ratio of 90 and a specific gravity of approximately 0.92. The fiber had a rectangular cross-section with average width of 1.4 mm and average thickness of 0.11 mm. The average tensile strength of the fiber was 620 MPa with a modulus of elasticity of 9500 MPa.

Fig. 1: Macro synthetic fiber

Ordinary Portland Cement (OPC) was used as a binding material. The fine aggregate with a maximum size of approximately 2 mm was used in the experimental work. The coarse aggregate used in this concrete mixture was gravel with a nominal maximum size of 10 mm. Concrete was cast with a water-cement ratio (w/c) of 0.42 throughout the work.

2) Mixing proportions

The concrete mix ratio was 1:2:3:0.42 (cement: fine aggregate: coarse aggregate: w/c ratio). Table1 shows the detail of mixes which were used in concrete casting.

Table 1: Details of concrete mixes

Macro Synthetic Fiber	Fiber volume fractions	Cement	Fine Aggregate	Coarse Aggregate	Water
(kg/m^3)	(%)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
None	V_f = 0%	376	752	1128	131
3	V_f =0.33%	376	752	1128	131
3.8	V_f =0.42%	376	752	1128	131
4.6	V_f =0.51%	376	752	1128	131

Three types of moulds were used to cast the specimens. The moulds with dimensions of 100 mm × 100 mm × 500 mm were used for beams, the moulds with dimensions of 100 mm × 100 mm × 300 mm were used for prisms and the moulds with the dimensions of 100 mm × 100 mm × 100 mm were used for cubes. Where, cubes were cast to determine the compressive and tensile strength, beams were cast to determine the shear strength and prisms were cast to determine the stress-strain relationships of the macro synthetic fiber reinforced concrete. Among the four batches, six cubes, three beams and three prisms were cast in each batch.

A total of 0.10 m^3 concrete mixes involving four batches were cast with four different quantities of macro synthetic fibers such as 0, 3, 3.8 and 4.6 kg/m^3 which corresponds to 0, 0.33, 0.42 and 0.51% of volume fractions of macro synthetic fibers respectively. Plain concrete specimen was used as a reference to compare with all other specimens. Mechanical behavior of concrete, for instance, compressive, tensile and shear strength and stress-strain relationships were determined after a curing period of 28 days.

3) Mixing sequences

A mixer machine was used to get the standard quality of concrete. In the mixer machine, firstly, the coarse aggregate was added followed by the macro fibers. These dry ingredients were mixed for about two minutes so that the fibers were evenly distributed throughout the mix. Special care was taken so as to ensure no fiber balls were formed which would effect the concrete's consistency (e.g. slump or flow). Then fine aggregate and cement were added into the mixture machine. These dry ingredients were mixed for about one minute and then mixed with water. Concrete was placed in the moulds in two layers and a vibrator was used to compact properly. After finishing the vibrating of the top surface a trowel was used to make the top surface smooth. The specimens were stored for 24 hrs under a temperature of 15^0C to 27^0C to set the concrete. After 24 hrs the specimens were demoulded and kept in the water tank for 28 days of curing and then the specimens were prepared for testing.

4) Instrumentation and testing

Two types of universal testing machines were used. Compressive strength test procedure was carried out in accordance to BSI [5]. The prepared cubes were instrumented in Avery Denison testing machine manufactured in the United Kingdom and a maximum crushing load was measured. Compressive strength was then calculated by the equation, $f_{cu} = \frac{P}{ab}$; where, f_{cu} was the compressive strength (MPa), P was the maximum crushing load resisted by the specimen before failure (N), a and b were the sides of the cube (mm).

An indirect tensile test procedure was carried out in accordance to BSI [6]. The prepared cubes were instrumented and a failure load (P) was measured. The indirect tensile strength of concrete was calculated using the following equation, $f_{ct} = \frac{2P\ x\ 1000}{\pi cb}$;where, f_{ct} was the maximum tensile splitting strength (MPa), c and b were the sides of the cubes (mm).

Fig. 2: Instrumentation of beam specimen for direct shear test

To determine the material properties in shear, beams 100 × 100 × 500 mm were tested in accordance with the Japan Society of Civil Engineers standard test procedure JSCE [7], with some modifications. Figure 2 shows the experimental setup of beam specimen for direct shear test. The shear load was applied by a loading block 100 mm apart. The specimen was supported on two rigid blocks 300 mm apart. Since the specimen in direct shear contained two shear failure planes, the ultimate shear strength of the specimen was calculated using the following equation, $\tau_{max} = \frac{P_{max}}{2A_{eff}}$; where, τ_{max} was the ultimate shear strength, P_{max} was the average peak load supported by the specimen and A_{eff} was the effective area of shear plane on either side.

The stress-strain relationships of macro synthetic fiber concrete mixes were obtained by testing 100 mm × 100 mm × 300 mm prisms in uniaxial compression, utilizing a Dertec Servo-Hydraulic testing machine which is shown in Figure 3.

Fig. 3: Load vs. deformation test set up

This machine can plot automatically a graph, Load vs. Deformation, which made it possible to plot stress-strain graph of a specific sample. The loading capacity of this machine was 500 kN. The experiment was done using this machine with a compressive loading rate of 0.00015 mm/s. Two linear variable displacement transducers (LVDT) were used in measuring the strain and these were protected by a stiff metal sleeve, so that when the transducers came to the end of their travel the anchorage blocks would be dislodged without causing damage to the transducers.

The loads vs. deformation data were recorded from the test and the stress-strain relationships were calculated using the following equation, $\sigma = \frac{F}{A}$; where, σ was the stress (MPa), F was the applied load (N) and A was the cross sectional area of prism specimen (mm^2) and $\varepsilon = \frac{\Delta l}{l}$; where, ε was the strain (mm/mm), Δl was the change in length (mm) and l was the gage length (mm)

III. Results and Discussion

A. *Compressive strength test results*

A total of 12 cubes of size 100×100×100 mm with four different percentages of macro synthetic fiber volume fractions, such as 0, 0.33, 0.42 and 0.51% were tested. Table 2 shows the compressive strength test results and the changes in the compressive strength for each type of specimen.

Table 2: Compressive strength test results

Specimen ID.	Cube Types	Compressive Strength (MPa)	Average Strength (MPa)	Strength Increase (%)
C1	Control Cubes	38.74	38.91	-
		39.12		
		38.86		
C2	0.33% Macro Synthetic Fiber	40.23	40.54	4.19
		40.76		
		40.62		
C3	0.42% Macro Synthetic Fiber	41.34	41.43	6.48
		40.85		
		42.10		
C4	0.51% Macro Synthetic Fiber	41.87	41.59	6.89
		41.35		
		41.56		

Figure 4 shows the changes in average compressive strength relative to the cube types. Test results reveal that addition of macro synthetic fiber in concrete enhanced the compressive strength of the specimens. It was improved by at least 4% for the specimen C2 and gradual improvement was found by at least 6.48 and 6.89% for the specimen C3 and C4, respectively with respect to the control cube specimens. Hence, it is a matter of further research to identify the optimum percentage of macro synthetic fiber which will yield the maximum compressive strength of concrete.

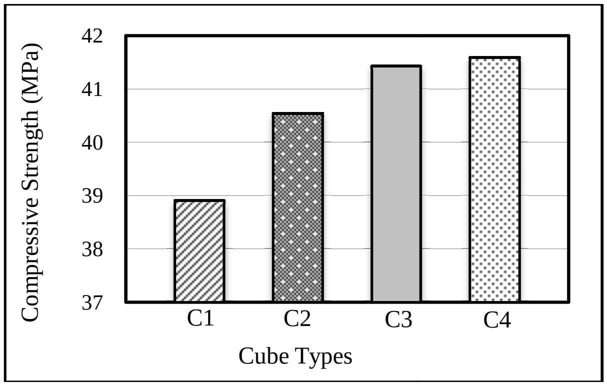

Fig. 4: Variation of Compressive Strength

B. *Tensile strength test results*

Table 3 below shows the average indirect tensile strength recorded during the test and the percentage changes in tensile strength for all mix batches relative to the control batch.

Table 3: Tensile strength test results

Specimen ID.	Cube Types	Tensile Strength (MPa)	Average Strength (MPa)	Strength Increase (%)
T1	Control Cubes	3.52	3.55	-
		3.76		
		3.38		
T2	0.33% Macro Synthetic Fiber	4.07	3.91	10.14
		3.85		
		3.82		
T3	0.42% Macro Synthetic Fiber	4.24	4.10	15.49
		4.12		
		3.93		
T4	0.51% Macro Synthetic Fiber	3.97	4.07	14.65
		4.16		
		4.08		

Figure 5 below shows a graphical representation of the average indirect tensile strength for concrete containing no fibers and concrete containing different volume fractions of fibers.

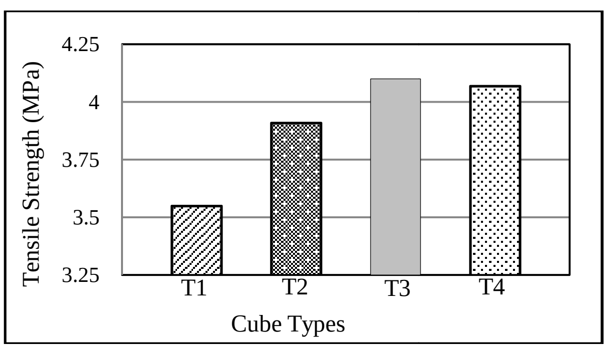

Fig. 5: Variation of tensile strength

Table 3 and Figure 5 show that the indirect tensile strength was increased with the addition of macro synthetic fibers. The tensile strength of the concrete for the cube specimens T2 and T3 was increased by at least 10 and 15%, respectively, relative to the sample T1. The maximum tensile strength was recorded as 4.10 MPa for the cube with a macro synthetic fiber volume fraction of 0.42%. This increase in tensile strength was due to the fibre bridging properties in the concrete. The reinforced concrete was split apart in the tensile strength test and as a result the load was transferred into the fibres as pullout behaviour when the concrete matrix began to crack where it exceeded the pre-crack state. The control batch specimens containing no fibres failed suddenly once the concrete cracked (Figure 6), while the macro fibre reinforced concrete specimens exhibited cracks but did not fully separate (Figure 7). This shows that the macro fibre reinforced concrete has the ability to absorb energy in the post-cracking state.

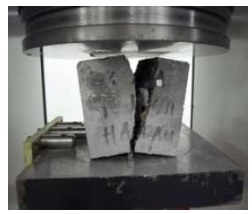

Fig. 6: Plain concrete after tensile test

Fig. 7: Macro Fibre concrete after test

However, the tensile strength of the cube specimen was decreased for the sample T4 by 0.35 MPa compared to the cube specimen T1. The reason for this downward trend in the T4 cube (0.51% macro fibre volume cube) may be due to the inadequate concrete's workability (fibres are known to decrease workability) for higher dosages as well as full compaction not being achieved. It can be improved by a slight increase of fine aggregate, as this would provide a sufficient paste volume for coating the fibres and the addition of super plasticizer to offset the possible reduction in the slump, particularly for the mixtures with high fibre content.

C. *Shear strength test results*

Table 4 shows the average shear strength of two identical samples of the beams and percent increase in shear strength with three different percentages of macro synthetic fiber volume fractions, compared to the reference beams.

Table 4: Shear strength test results

Specimen ID.	Beam Types	Shear Strength (MPa)	Average Strength (MPa)	Strength Increase (%)
S1	Control Beams	3.86	3.74	-
		3.64		
		3.73		
S2	0.33% Macro Synthetic Fiber	4.45	4.32	15.32
		4.14		
		4.36		
S3	0.42% Macro Synthetic Fiber	5.25	5.43	44.97
		5.57		
		5.46		
S4	0.51% Macro Synthetic Fiber	5.92	6.18	65.10
		6.43		
		6.19		

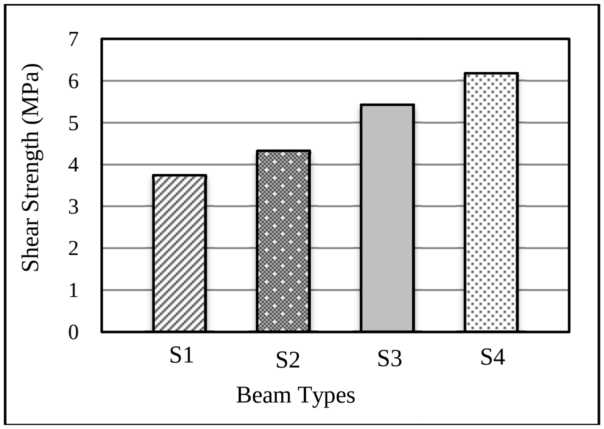

Fig. 8: Variation of shear strength

Figure 8 represents the average shear strength for a plain concrete beams without fibers and the concrete beams with three different percentages of macro fiber volume fractions**.**

The results of the shear strength test shows that the concrete's shear strength increased gradually with the increase of macro fiber dosages. Shear strength was increased by about 15% for the beam specimen S2. However, this was increased significantly by about 45% for the beam sample S3. Finally, the shear strength was increased to a maximum value of about 65% for the beam specimen S4.

Furthermore, the concrete specimens containing no fibers cracked and failed in a brittle condition when it had reached the ultimate strain in the concrete. On the other hand, fiber reinforced concrete also cracked at the ultimate strain but it was capable of carrying the load well after the crack developed on the concrete which is shown in Figure 9. This indicates that the fiber reinforced concrete has the ability (ductility) to hold the beam from falling apart at the position of the crack.

Fig. 9: Illustration of fibrous beam after direct shear test

D. Stress-strain relationship analysis

Figure 10 shows the comparison on the average stress-strain curves for four different types of prisms reinforced with four different percentages of macro synthetic fiber volume fractions such as 0, 0.33, 0.42 and 0.51%, respectively.

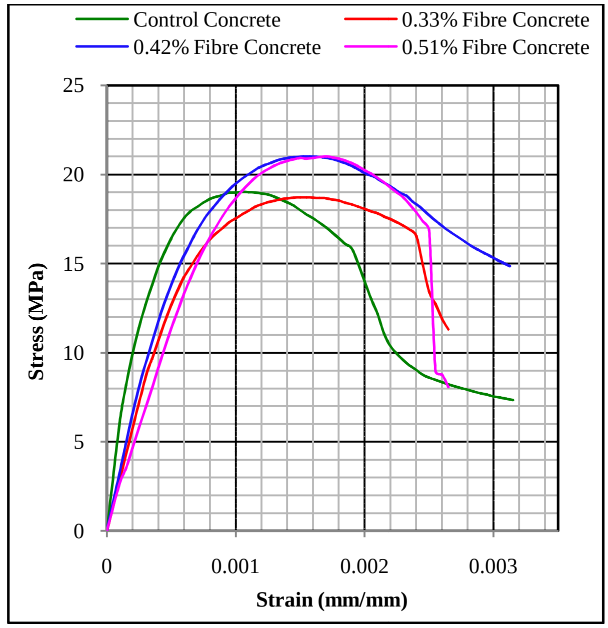

Fig. 10: Average stress-strain curves for prisms with 0, 0.33, 0.42 and 0.51% macro synthetic fiber

Fiber reinforced concrete did not enhance the ultimate stress. However, it had improved the peak strain value by at least 50, 60 and 60% corresponding to the prisms reinforced with macro synthetic fiber volume fractions of 0.33, 0.42 and 0.51%, respectively. This was attributed to the fibers' ability (ductility) to distribute stresses and slow down the crack propagation process.

IV. Conclusion

This paper has been concerned with the investigation of some mechanical behavior of concrete reinforced with macro synthetic fibers. The experimental studies were done on compressive, tensile and shear strength of the FRC. Beside this, stress-strain behavior of FRC was also investigated. Hence the conclusions can be summarized as:

i) From this study, it was found that with the addition of fibers the compressive strength was increased even if, it was insignificant.

ii) The addition of macro synthetic fibers to concrete also improved the tensile strength compared to plain concrete. Moreover, the control batch specimens containing no fibers failed suddenly once the concrete cracked, while the macro synthetic fiber reinforced concrete specimens were still remain as a unique cubes. This shows that the macro synthetic fiber reinforced concrete has the ability to absorb energy in the post-cracking state.

iii) The addition of fibers improved the shear strength of concrete significantly. Shear failure in plain concrete beams containing no fibers was brittle. In each of the plain concrete beams once the peak load occurred, the beams failed and a post peak load capacity was non existent as opposed to those with the macro synthetic fiber reinforced beams. This indicates that the fiber reinforced concrete has the ability to hold on the crack of the concrete and resist the concrete beams from falling apart.

iv) In this study, macro synthetic fibers did not improve significantly, the ultimate stress of the specimens. However, the ultimate strain values were improved which suggest increased ductility or perhaps increased creep occurring in the macro synthetic fiber reinforced concrete.

Hence, from this study it can be concluded that the addition of macro (Structural) synthetic fibers improved the compressive, tensile and shear strength as well as the ductility of concrete. As the concrete is a fundamental material in the field of construction engineering, the improvement of its mechanical properties by the addition of this fiber will certainly increase the use of this composite material which will offer more strong and durable structures in the future and will open a new era in the field of construction materials.

V. References

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