DYNAMIC AND MECHANICAL PROPERTIES OF FIBER REINFORCED ROLLER COMPACTED CONCRETE

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Abstract

Roller Compacted Concrete (RCC) is a new development in concrete technology; it is based on zero slump mix with very low water content in order to facilitate compaction. The reduction in construction and shortening of construction period can be achieved when this type of concrete is used.

The use of fibers in RCC is appropriate because fibers mixing and distribution in the zero slump concrete are greatly facilitated. The main aim of this investigation is to study the effect of steel and polypropylene fibers (type, volume fraction and aspect ratio) on dynamic and mechanical properties of fiber RCC (FR-RCC)

The experimental program included using four types of fiber namely: straight fibers, hooked end steel fibers, flat steel fibers and polypropylene fibers. The fiber content was 0.5%, 0.75% and 1% by volume. For hooked steel fibers two aspect ratios (60 and 100) were examined. The dynamic properties of FR-RCC (impact strength, dynamic modulus, ultrasonic pulse velocity, damping expressed in terms of Q-value and Poisson's ratio) and mechanical properties (compressive strength, splitting tensile strength, flexural strength and elastic modulus) were studied.

The test results show that addition of fibers substantially enhance the impact strength over those of plain RCC. The results also indicate that the type of fibers have a direct influence on the properties of FR-RCC. Steel fibers shape and aspect ratio have a marked effect on most properties of FR-RCC

Keywords: Roller Compacted Concrete, steel fibers, Polypropylene fibers, impact, dynamic, strength tests

1. Introduction

Roller Compacted Concrete (RCC) is a stiff zero-slump concrete consisting of dense graded aggregate, cementitious materials and water. Because it contains less water content,

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it cannot be placed by the same method used for conventional (slump) concrete. It is densified by compacting with vibrating roller. Compaction of concrete is attractive because strength properties are attainable at cement content much lower than that of conventional concrete and also because handling and placing are simpler and faster. RCC uses no forms, requires no conventional finishing, and needs no dowels or reinforcing steel [(1,2)]. The RCC technique achieves significant time and cost saving in the construction concrete [(3,4)]. So RCC is used when strength and economy are primary needs: military facilities, parking storage and low speed roads [(5)].The use of fiber reinforcement in compacted concrete is appropriate for the reasons that conventional steel bar reinforcement is not practically feasible and secondly because fiber mixing and distribution in the zero-slump matrix are greatly facilitated. The function of the fibers as in the conventional matrix is to provide a crack arrest mechanism.

In the field of the effect of using steel fiber reinforcement in RCC and its mechanical properties was carried out by several investigators [(6,7)]. They concluded that the fiber length and geometry has significant effect on flexural behavior of RCC.

The use of waste plastic reinforcement in RCC improves the toughness characteristics significantly and moderately in flexural strength.

There are very few studies on dynamic properties of plain RCC [(3)] and no investigation was found on the dynamic properties of RCC reinforced with fiber.

The main aim of this study was to experimentally investigate the effect of using different types and amount of fibers on dynamic and mechanical properties of fiber reinforced RCC.

2. Experimental Program

2.1 Materials

Ordinary Portland cement (Type I) was used for all concrete mixtures. Two types of aggregate were used, combined aggregate of grading satisfying the Iraqi standard specifications for roads class (A) and natural sand of maximum size 4.76mm with grading conforming to BS 882:1992. These two types of aggregate are combined together in order to satisfy the requirements of the combined grading of ACI-325-10R-95.

Four types of fibers were used namely: straight steel fibers with length, L=24mm and diameter, d=0.4mm, hooked steel fibers with L=60mm and diameter d=0.5, flat steel fibers with length L=30mm and cross section (0.25 x 3) mm and polypropylene.

2.1-1 Water:

Potable water was used throughout this investigation for mixing and curing.

2.1-2 Fibers:

Four types of fibers were used namely: straight steel fibers, hooked end steel fibers, flat steel fibers and polypropylene fibers. For hooked steel fibers, two aspect ratios were examined. The geometrical characteristics of fibers used throughout the experimental work are illustrated in Tab. (1)

2.2 Mixes:

In order to select the mixture proportion for RCC, the design method recommended by ACI committee 207 was used. Many trial mixes were carried out to select suitable mix, the final mix had the following constituents: cement: 150 kg/m^3, water: 120 kg/m^3, fine aggregate: 630 kg/m^3, coarse aggregate: 1550 kg/m^3

2.3 Mixing:

A rotary mixer of 0.1 m^3 capacity was used. The raw materials of the reference mix of the RCC were added, they were dry-mixed in the mixer for about of one minute before the required water was added to the mixture. Then the constituents were mixed wet for about three minutes until homogeneous concrete was obtained (generally mixing time for RCC was initially set at 4 minutes because of the good homogeneity of mixture).

When fibers were used, for each type of fiber, three different contents 0.5, 0.75 and 1% by volume were used. The main point to be considered in preparing a fiber RCC mix is the uniform dispersion of fibers. The matrix materials were mixed first and then fibers were progressively added into the mix by hand, ensuring that fibers entered the concrete matrix individually, and mixing was continued for one minute after the last fiber had reached the mix.

If polypropylene fiber was used, the final mixing of matrix was done by hand because the blades of the conventional mixer cause shredding of the fiber, thus reducing their effectiveness.

Tab. (1) Characteristics of fibers

Type of fiber		Length (mm)	Diameter or cross-section (mm)	Aspect ratio
Steel	Straight	24	0.4	60
	Hooked end	50	0.5	100
	Hooked end	30	0.5	60
	Flat	30	0.25 x 0.3	35
Polypropylene*		22	1 x 0.05	

***** (density 910 kg/m^3)

2.4 Preparation of Specimens:

The size of the specimens was made as large as possible, within the standard requirement. The factors to be considered in selecting the moulds were, the maximum size of aggregate and the maximum length of fibers because the orientation of fibers is governed by the dimensions of the mould.

The specimens of RCC were prepared by using cylinder steel moulds of size (150 x 300) mm for most testing which was carried out throughout this work, except for the flexural strength testing in which prisms (100 x 100 x 400) mm were used. The specimens used in the impact strength test were 150 mm in diameter and 63.5 mm thick.

Soil compaction equipment was used automatically to compact the specimens for Proctor and C.B.R tests, the concrete was placed in three equal layers if cylinder moulds were used and in two layers for prisms and one layer for moulds of impact test.

An automatic blow pattern ensures optimum compaction for each layer of concrete. The rammer of 4.5 kg weight itself travelled across the mould and the table rotated the mould in equal steps on a base that is extremely stable, each layer received 56 blows according to ASTM D-1557 (modified Proctor) test method.

2.5 Curing:

After demoulding, all RCC specimens were cured by the same method which consisted of covering the specimens with burlap and spraying them with water four times daily, the specimens were cured until the beginning of the tests at 28-days age.

2.6 Experimental Test:

- A test that measures the impact strength of fiber RCC has been developed by ACI Committee (9) was used to determine the impact strength of RCC with fiber reinforcement. The number of blows required for the first visible crack to form at the top surface and for ultimate failure was then recorded. The average reading of five specimens was recorded.
- Dynamic modulus of elasticity was measured in accordance to BS 1881-209:1990 and ASTM C215-02 for testing concrete specimens by resonant frequency method. The resonant frequency was recorded to calculate the dynamic modulus of elasticity.
- It was calculated using the following equation:

$$Ed = (4\, n^2\, L^2 \boldsymbol{\rho})\, 10^{-15} \qquad \ldots\ldots\ldots\ldots (1)$$

where:
Ed: Dynamic modulus of elasticity, (GPa)
L: Length of specimen, (mm)
n: Frequency of the fundamental mode of longitudinal vibration, Hz

ρ: Density of concrete, kg/m3

- The determinat`ion of the damping coefficient in resonance experiment was carried out from a measurement of the band width of the resonance curve. In this method frequencies F1, and F2, are determined on either side of the resonant frequency Fo, such that the corresponding amplitudes are 0.707 times the amplitude at resonance. The damping (expressed in terms of Q-value) is given by:

$$Q = \frac{Fo}{F2 - F1} \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

- The pulse velocity of RCC specimens was measured by using velocity tester type (PUNDIT) according to ASTM C-597. The test was performed on the same cylinder after being tested for dynamic modulus.

- The compressive strength was determined from cylinder specimens and tested according to ASTM C-39. Sulfur capped cylinders specimens were tested under compression.
- The splitting tensile strength was carried out according to ASTM C-496 standard
- Flexural strength conducted on prisms using testing machine of 300kN capacity according to ASTM C-78
- The elastic modulus was obtained from uniaxial compression tests and was carried out according to the ASTM C-469.

3. Results and Discussion

3.1 Dynamic Properties of Fiber Reinforced Roller Compacted Concrete

3.1.1 Impact Strength:

The effect of' volume fraction of fibers on the impact strength of RCC specimen at 28 days in terms of the number of blows is shown in Tab. (2). Generally it can be seen that there is a considerable improvement in impact strength of RCC specimen at first cracks and ultimate failure because of additions of fibers (steel and polypropylene), this improvement ranges from high for hooked and straight steel fibers to low for flat steel and polypropylene fiber. This behavior in improvement of impact strength increases both at first crack and ultimate failure by the increase in the volume fraction of fibers.

The data in Tab. (2) shows also that both the steel fiber geometry and its aspect ratio have a significant effect through the fiber-matrix bond strength on the impact strength of RCC specimen reinforced with fiber. The flat steel fiber appears to possess the least impact strength this is probably because of its brittle nature and

Tab. (2) Effect of Fiber Rinforcement on the Impact Strength of Roller Compacted Concrete at 28 days

Mix.	Type of Fiber	% of fiber by volume	Average number of blows causing first crack	% increase* in first crack blows of FRRCC	Average number of blows causing ulimate failure	% increase** in ulimate failure blows of FRRCC
A	Non	0	10	----	19	---
B_S	Straigth steel	0.5	36	260	115	505
C_S		0.75	46	360	177	833
D_S		1.0	62	520	235	1137
B_{H1}	Hooked steel (H_1) (L=50mm)	0.5	95	850	173	810
C_{H1}		0.75	116	1060	223	1073
D_{H1}		1.0	145	1350	294	1447
B_{H2}	Hooked	0.5	81	710	145	663

C_{H2}	steel (H_2) (L=30mm)	0.75	98	880	201	958
D_{H2}		1.0	121	1110	267	1305
B_F	Flat steel	0.5	26	160	88	363
C_F		0.75	34	240	105	453
D_F		1.0	47	370	136	616
B_P	Polyprop-ylene	0.5	21	110	102	437
C_P		0.75	29	190	156	721
D_P		1.0	35	250	226	1089

* percentage increase in number of blows required to cause first crack of FRRCC over the corresponding plain RCC
** percentage increase in number of blows required to cause ultimate failure of FRRCC over the corresponding plain RCC

small aspect ratio (35). The straight fiber comes next. Both the hooked fibers (H1) and (H2) have excellent mechanical anchorage at their ends, this together with good fiber length and high aspect ratio leads to high fiber-matrix bond strength. These characteristics are reflected in their high impact strength both at first crack and failure.

The relationship between impact index (impact strength of reinforced specimen over that of unreinforced specimen) of RCC at 28 days to cause first crack and ultimate failure for steel and polypropylene fiber and volume fraction of fibers is shown in Figs (1) and (2). In general it can be seen from these figures that there is an essentially linear relationship between impact index and volume fraction of fiber at both first crack and ultimate failure. Fig (1) shows also that there is a considerable increase in impact index at first crack as the volume fraction of fiber increases for hooked steel fiber over other types. On other hand Fig (2) shows a significant increase in impact index at ultimate failure as the volume fraction for all fiber types (steel and polypropylene).

Modes of Failure under Impact:

Fig (3) shows the modes of failure of fiber reinforced RCC specimens and plain RCC subjected to the falling weight test used in this investigation, also it can be seen from Fig (3-A) a complete separation of the failed parts, and most failures occurred by breaking into three pieces and the failure in all specimens was brittle. No significant differences were noticed in the mode of failure in unreinforced specimens. these specimens on the other hand showed that the fracture tended to become more clean with little debris, thus emphasizing the tensile nature of the actual failure process.

The RCC specimens reinforced with fiber displayed different modes of failure depending on the type, shape, length and aspect ratio of fibers. Fig (3-B) Bp, Cp, Dp shows the modes of failure of RCC specimens reinforced with polypropylene of 0.5%, 0.75% and 1% by volume of fiber respectively. It is noticed that specimens B, C and D do not show completely separated failed parts but they have remained attached.

Fig (3-C) shows the mode of failure of the typical RCC specimens B, C and D reinforced with different steel fibers of (0.5, 0.75 and 1) % by volume respectively. Specimens show no separation of failed pieces occurring and these specimens remained attached.

In general, it can be seen from Figs (3-B) and (3-C) that in most specimens reinforced with 1% by volume of steel and polypropylene fibers, the mode under repeated impact loads involves multiple cracking, multiple planes, excessive crushing, spalling and shearing not only in the region of impact but also along the failure plane.

3.1.2 Dynamic Modulus:

Fig (4) shows the development of the dynamic modulus of RCC specimens reinforced with different steel fibers and polypropylene between 3 to 28 days of age. The results for each type of fiber have been plotted against age separately. Generally it can be seen that the rate of increase in dynamic modulus is high at an early age up to 7 and 14 days, thereafter it is slow up to 28 day age. The figure shows also that there is a little increase in dynamic modulus because of the additions of hooked fiber (H_1) and (H_2) of 0.5% by volume. Further increase in fraction of fibers seems to have a very slight increase in the dynamic modulus.

Fig (4) also indicates also that there is a slight reduction in dynamic modulus because

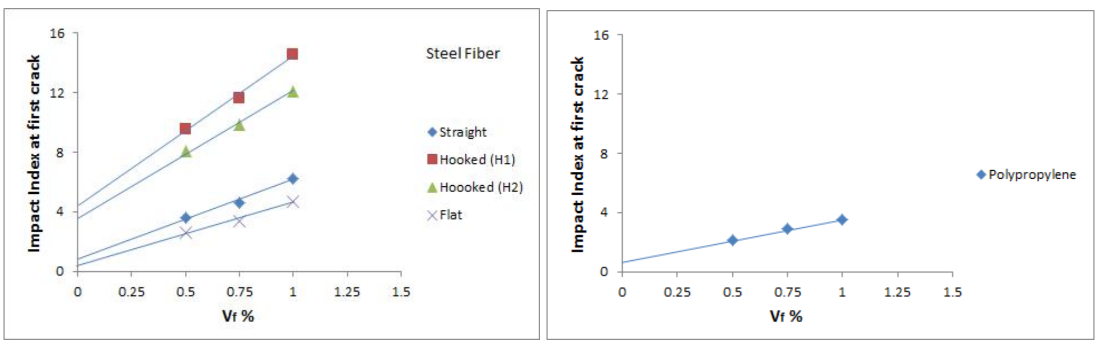

Fig. 1: Relationship between Volume Fraction of Fiber and Impact Index of RCC at First Crack

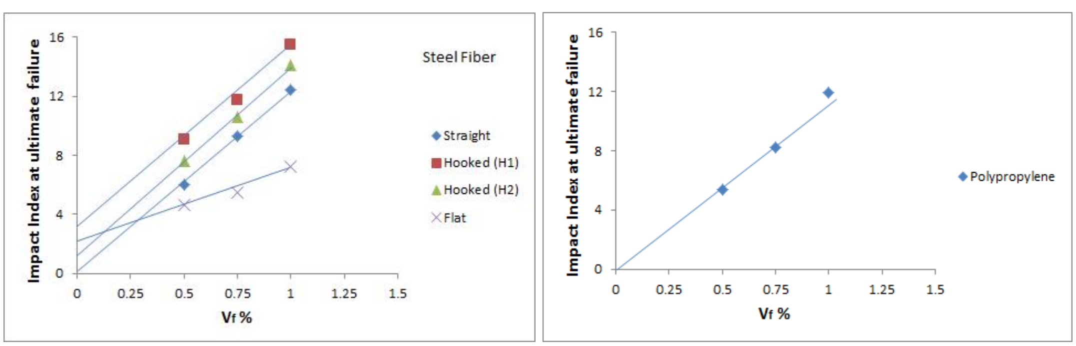

Fig. 2: Relationship between Volume Fraction of Fiber and Impact Index of RCC at Ultimate Failure

Fig. 3-A: Typical Mode of Failure in Plain RCC Specimens under Impact Load

Fig. 3-B: Failure of RCC Specimens Reinforced with Polypropylene Fiber

Fig. 3-C: Failure of RCC Specimens Reinforced with Different Types of Steel Fibers

of the addition of polypropylene fiber. This may be attributed to the fact that the polypropylene fiber has a low modulus of elasticity when compared with the matrix, which affects directly the dynamic modulus of the specimen reinforced with polypropylene fiber. Further increase in volume fraction of fiber has no effect on the dynamic modulus.

Fig (5) shows the effect of volume fraction of fiber on the dynamic modulus at 28 days. The figure shows that the dynamic modulus of the RCC with steel fiber increaseslinearly with volume fraction of fiber and the hooked fiber appears to have higher dynamic modulus than the other types, the average increase was 4%. Also it can be noticed that in the case of polypropylene fiber the dynamic modulus decreases linearly with a very slight value i.e. 1%.

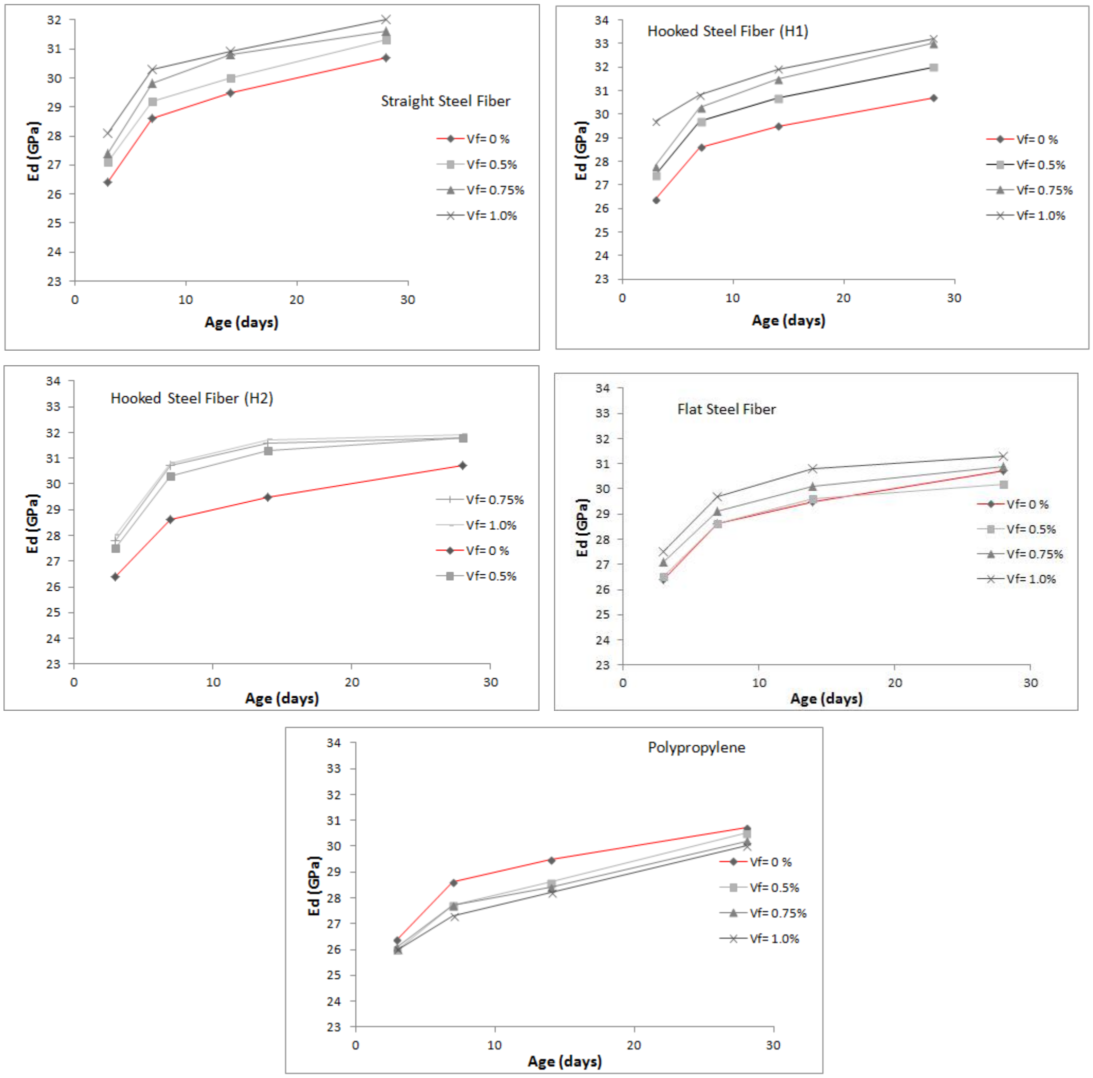

Fig. 4: Dynamic Modulus of RCC Reinfoced with Fiber

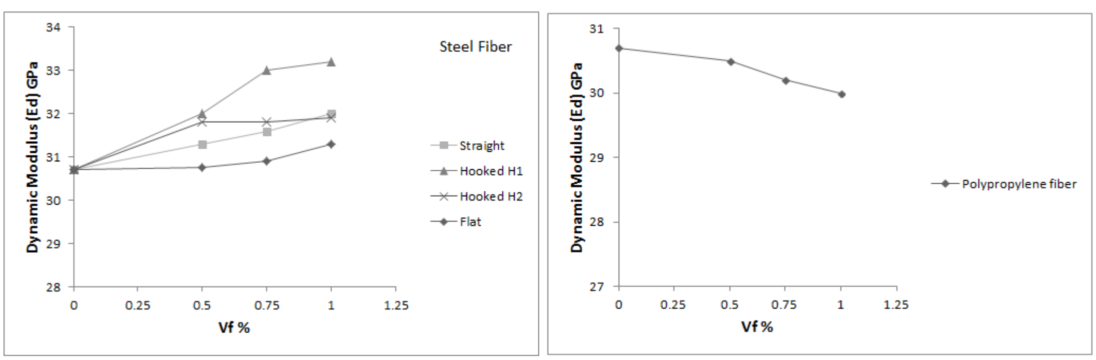

Fig. 5: Effect of Volume Fraction of Fiber on the Dynamic Modulus of RCC Reinfoced with Various Types of Fibers at 28 Days

3.1.3 Pulse Velocity:

Fig (6) shows that the pulse velocity of the RCC with hooked and straight steel fibers increases linearly with the increase in volume fraction of fiber, the increase in pulse velocity is slight and the average value is 1.5%. It is also noticed that flat steel fiber appears to have no effect on the pulse velocity.

The figure shows also that the pulse velocity of the specimen reinforced with polypropylene decreases linearly but very slightly with increase of volume fraction of fiber.

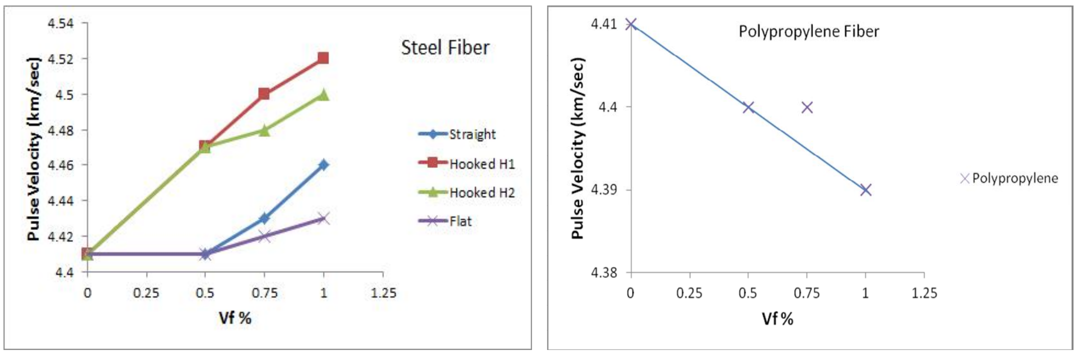

Fig. 6: Effect of Volume of Fraction of Fiber on the Ultrasonic Pulse Velocity of RCC Reinforced by Fiber at 28 Days

3.1.4 Damping:

Fig (7) shows the effect of volume fraction of fiber steel and polypropylene RCC at 28 days. It can be seen also that there is a little increase in Q-value because of the addition of steel fibers (straight/hooked), the average increase in value is 9% over that of the unreinforced specimen, while the flat fiber appears to have no effect on Q-value. The figure shows also that in the case of polypropylene fiber there is a little decrease in the Q-value as the volume fraction of fiber increases, the average decrease in Q-value is about 7% from that of unreinforced specimen.

It can be seen that there is scattering in the results. This might be attributed to the imperfection of the specimen, which increases as the volume of fraction of fiber increases and also this may be due to the increase of the size of the specimen (the specimen used in this investigation was cylindrical having (150 x 300) mm dimensions such specimens would have patterns of distribution of voids and cracks, these are the main causes for energy dissipation in concrete, this dissipation is affected by the distribution of these voids and cracks, which is not identical in all specimens.

3.1.5 Poisson's Ratio:

The value of dynamic Poisson's ratio (μ) can be calculated from equation (3)[10]

$$\left(\frac{V}{2nL}\right)^2 = \frac{(1-\mu)}{(1+\mu)(1-2\mu)} \qquad \text{.................... (3)}$$

where:

V: pulse velocity (mm/sec)

n: resonant frequency (Hz)

L: length of specimen (mm)

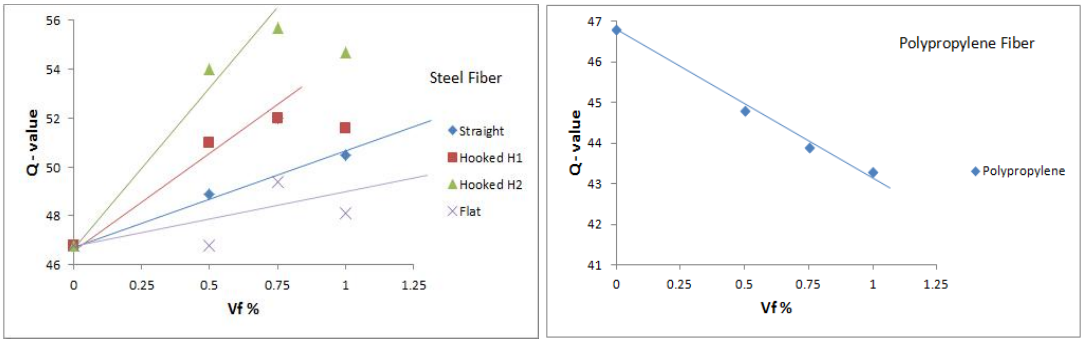

Fig. 7: Effect of Volume of Fraction of Fiber on the Q-Valueof RCC at 28 Days

Tab. (3) indicates the effect of different types of steel and polypropylene fiber on Poisson's ratio of RCC at age of 7 and 28 days. Generally the results show that there is a tendency of for Poisson's ratio to decrease very little with the progress of age from 7 to 28 days.

It can be seen also that addition of fibers appears to have little effect on the Poisson's ratio, this is because of small difference between Poisson's ratio of fibers and matrix. The value of μ at 28 days ranges from 0.22 to 0.24 for RCC with steel fibers and 0.24 to 0.25 for RCC with polypropylene fiber.

3.2 Mechanical Properties:

3.2.1 Compressive Strength:

The variation of the compressive strength of RCC specimens at 28 days with fiber volume fraction for different types of fibers (steel and polypropylene) is shown in Fig

Tab. (3) Dynamic Poisson's Ratio of Fiber Reinforcement RCC

Mix.	Type of Fiber	% of fiber by volume	Age Days	Poisson's Ratio
A	Non	0	7	0.26
			28	0.25
B_S	Straigth steel	0.5	7	0.24
			28	0.23
C_S		0.75	7	0.23
			28	0.22
D_S		1.0	7	0.23
			28	0.22
B_{H1}	Hooked steel (H_1) (L=50mm)	0.5	7	0.24
			28	0.23
C_{H1}		0.75	7	0.24

			28	0.23
D_{H1}		1.0	7	0.24
			28	0.23
B_{H2}	Hooked steel (H_1) (L=50mm)	0.5	7	0.26
			28	0.23
C_{H2}		0.75	7	0.25
			28	0.23
D_{H2}		1.0	7	0.23
			28	0.22
B_F	Flat steel	0.5	7	0.26
			28	0.24
C_F		0.75	7	0.25
			28	0.24
D_F		1.0	7	0.25
			28	0.23
B_P	Polypropylene	0.5	7	0.26
			28	0.24
C_P		0.75	7	0.26
			28	0.24
D_P		1.0	7	0.26
			28	0.25

(8-a). It can be seen that the compressive strength of the specimens reinforced with steel fibers increases with increased fiber volume fraction, the average increase for the three steel fiber types used [straight, hooked (H_1) (aspect ratio 100), hooked (H_2) (aspect ratio (60)] was 13% over that of plain specimen. This is due to the fact that the presence of steel fibers increases strainability in compressive failure [(11)] and hence the compressive strength increases. It can be also noted that the specimen reinforced with hooked fiber (H_1) of aspect ratio 100 has a compressive strength lower by about 3% than that reinforced with same type (H_2) but of aspect ratio (60). This is because the long fiber may be bent during the process of compacting the specimen [(12, 13)].

The effect of using polypropylene fiber on compressive strength is shown in Fig (8-b), which shows that the compressive strength tends to decrease with increase in the volume of fraction of fibers, the average decrease was 6%. This may be due to fact that the polypropylene is a compressible material causing debonding and microcracking, then the failure occurs at lower strength compared with the reference specimen, or this is probably due to fact that the polypropylene leads to increase the porosity of mix [(14)].

Fig. (9) shows the relationship between the compressive strength and pulse velocity of RCC reinforced with steel fiber at age 28days. The equation of regression between compressive strength and the ultrasonic pulse velocity is expressed as:

$$\sigma = 14.6 + 0.68v - 0.09v^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Correlation coefficient = 0.9

where,

σ: Compressive strength (N/mm^2)

v:Ultrasonic pulse velocity (km/sec)

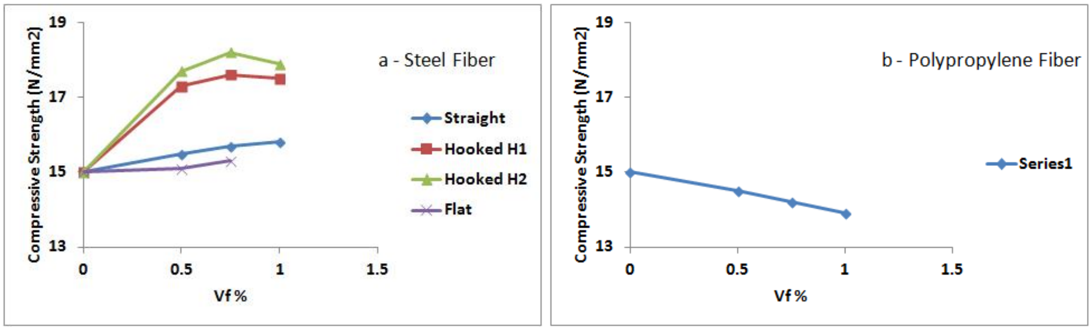

Fig. 8: Relationship between Compressive Strength of RCC and Volume Fraction of Fiber at 28 Days

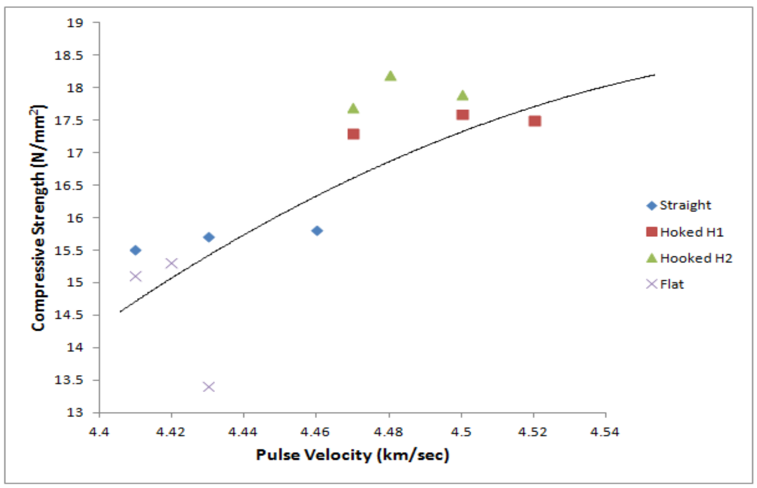

Fig. 9: Relationship between Pulse Velocity and Compression Strength of RCC Reinforced with Steel Fiber at 28 Days

3.2.2 Splitting Tensile Strength:

Fig (10-a) shows the effect of volume fraction of fiber on the splitting tensile strength of RCC specimen at 28 days. In general it can be seen that the splitting tensile strength improves by the addition of steel fibers, the average increase in splitting tensile strength of the four steel fiber specimens used by additions 1.0% by volume was 59% over that of plain specien.

The effect of polypropylene fiber on the splitting tensile strength is shown in Fig (10-b). The Figure shows also that there is a little increase in splitting tensile strength, the average increase is 11%.

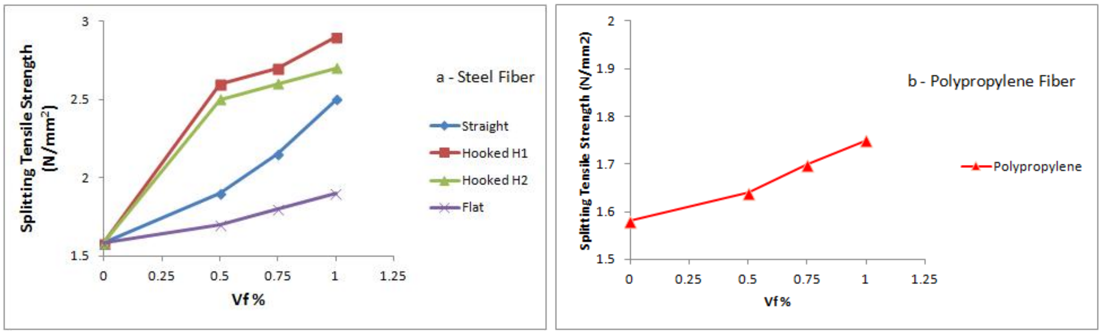

Fig. 10: Relationship between Splitting Tensile Strength of RCC and Volume Fraction of Fiber at 28 Days

3.2.3 Modulus of Rupture:

Fig (11-a) shows also that there is an essentially linear relationship between modulus of rupture and volume fraction of fiber, because the modulus of rupture of all steel fiber types increases as the volume of fraction increases. It can be seen that hooked steel fibers (H1) and (H2) appear to have much greater influence on improving the modulus of rupture than other steel fiber types, the average increase at 1% by volume was 90%. This is because the modulus of rupture is influenced by the geometry of the fiber and these fibers have excellent mechanical anchorage at their ends [(15)]. This leads to high fiber matrix bond strength compared with that reinforced by straight and flat steel fibers.

Fig (11-b) shows the effect of volume fraction of polypropylene fiber on the modulus of rupture of RCC specimen at 28 days. It can be noted that there is a little increase in modulus of rupture, the average increase at 1% by volume is 7%.

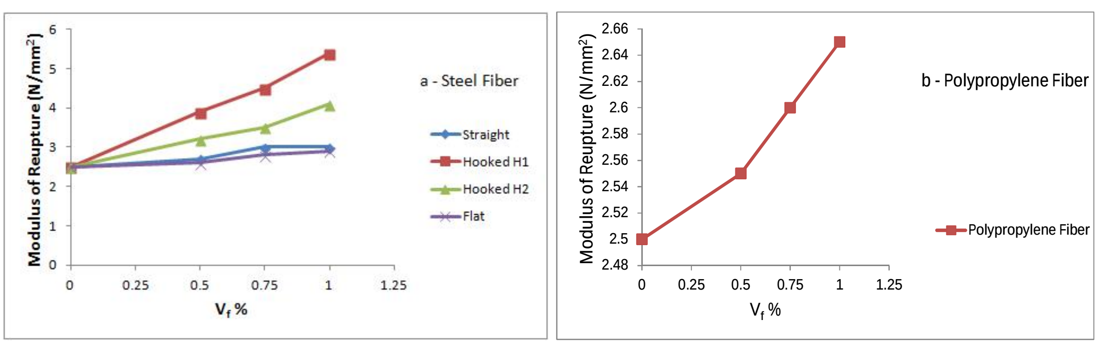

Fig. 11: Relationship between Modulus of Rupture of RCC and Volume Fraction of Fiber at 28 Days

3.2.4 Static Modulus of Elasticity:

Fig (12) shows the effect of volume of fraction of fibers (steel and polypropylene on the static modulus of elasticity of RCC at 28days. It can be seen that there is a significant increase in the static modulus of elasticity with the increase in the volume of fraction of both types of hooked steel fibers up to 0.5%, thereafter the rate of increase is slower beyond the 0.5% by volume, while the relationship in the case of straight and flat fibers, the static modulus increases linearly with variation of volume fraction of fiber. The average increase for four steel fibers is 8%. The figures show also that there is a slight reduction in the static modulus as the volume of fraction of polypropylene fiber increases, the value of reduction with addition of 1% by volume is 4%.

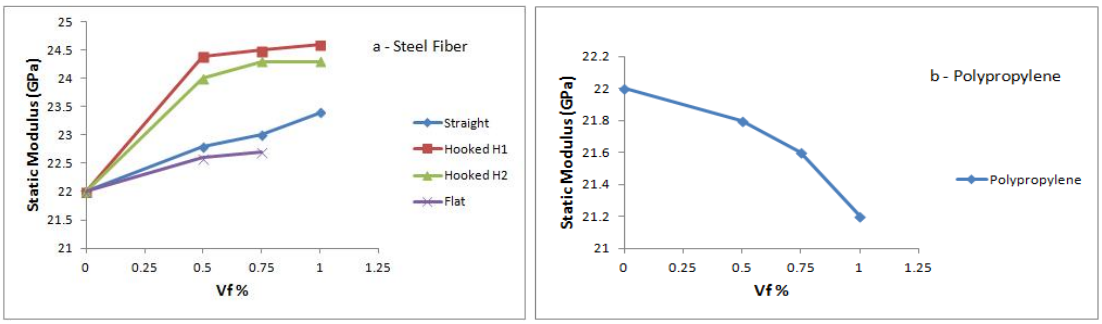

Fig. 12: Effect of Volume of fraction of Fiber on the Static Modulus of RCC

4. Conclusions

From the results of this investigation, the following conclusions can be drawn;

1. Steel fibers shape and aspect ratio have a marked effect on the impact strength, the fiber reinforced specimen cracks remained intact under impact load.
2. The results show that the impact strength increases as the volume fraction of fiber increases (Vf = (0.5-1) %) and with volume fraction of 1% fibers there is a substantial increase in impact strength compared with that of plain RCC.
3. The failure mode under repeated impact loads involves multiple cracking, concrete crushing and spalling compared with that of unreinforced RCC which showed that it has clear cracks with little debris.
4. The addition of fibers (steel and polypropylene) appears to have little effect on the dynamic modulus, pulse velocity, damping and Poisson's ratio of the fiber reinforced RCC.
5. The addition of polypropylene fibers (Vf = (0.5-1) %) to RCC mixes has a little effect on the mechanical properties of fiber reinforced RCC, except the impact strength which was found to increase as the fiber volume fraction increases.
6. The ultimate flexural strength increases linearly with volume fraction of steel fibers (Vf = (0.5-1) %).
7. Good correlation was obtained between the compressive strength and the pulse velocity at 28days of fiber reinforced RCC.

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