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Research Paper

Structural Behaviour of Steel Fiber Reinforced Concrete Composite under Blast Loading

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ABSTRACT

Fibre-reinforced concrete with its higher ductility and enhanced flexural behaviour shows better performance under blast and impact loading than conventional reinforced concrete. During impulsive loadings such as blast and impact, the structural response is to absorb large amounts of energy within a short period. This article proposes the structural responses of steel Fibre reinforced concrete composite under dynamic loading for varying percentages of steel fibres. The experimental results quantitatively indicate improvement in the performance of fiber impregnated concrete. A mathematical correlation based on empirical relations is presented as a basis function for evaluation of Fiber reinforced concrete subjected to blast/ dynamic loading. The experiments on a rectangular specimen of size 400 mm × 400 mm × 50 mm with 125gm ANFO which is equivalent to 100 gm TNT charge placed at different standoff distances, give insight of enhanced FRC behaviour. The article presents failure modes, and quantifies the elastic behaviour of FRC subjected to blast loading.

1 Introduction

Blast resistant structures call for tougher construction material. The steel as construction material raises material cost. Use of Timber is restricted due to deforestation policy, and also its strength is not comparable with steel structures when blast resistance is to be evaluated. Fiber reinforced material poses a midway solution in such case, especially in countries like India [1].

The concrete being good in compression as compared to tension. It is necessary to remodel concrete to achieve higher tensile strength. Incorporating steel fibers can improve tensile strength of concrete [2]. There are various types of steel fibres available with their advantages and disadvantages [1]. Among them, hooked end steel fibres perform better as fibre reinforced concrete because of its good tensile strength, shrinkage reduction, low surface permeability, resistance to the propagation of

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cracks, increased toughness against impact [3]. The addition of fibre in concrete leads to a reduction in brittle nature and increases the energy absorption capacity, ductility, tensile capacity, toughness [4-7].

The enhancement in the properties of concrete attracts the researchers to design the concrete for blast resistant structure. The incorporation of fibres in concrete delays the propagation of cracks [5]. The type of fibre, orientation, and dimension, play a vital role in the properties of concrete. Each type of fibres has different geometric properties such as the hooked fibres increases the pull-out strength and composite toughness [8]. The advantages of the use of the steel fibres in concrete attract the researchers to design it for blast resistant structure [9].

The performance of concrete against blast using steel fibres was studied by Foglar et al. [9]. The blast experiment was conducted on a concrete slab of 6 m $\times$ 1.5 m $\times$ 0.3 m with steel fibres 25 mm and polypropylene 54 mm long synthetic fibres were used with 0.5%, 1.0%, and 1.5% addition. From the tests, it was stated that the addition of fibre had less impact on the fracture energy value. Also, the results of the numerical simulation were in line with the experimental results.

Another study conducted by Luccioni et al. [5], reported the influence of types of fibres on the properties of high strength concrete under blast loading. The hooked carbon steel fibres of 60 mm length were used at 0.5% and 1% by volume of cement in high strength concrete. The addition of steel fibres showed a marginal reduction in compressive and flexural strengths as compared to that of reference concrete. The addition of steel fibres under static load showed an increase in residual loading capacity and toughness. The failure modes of concrete prepared with the addition of 0.5% and 1% have been drastically changed as compared to that of reference concrete. The increase in fibre content reduces the flexural crack due to increased toughness and flexural strength of concrete which was observed in static tests. Finally, they concluded that the use of long hooked carbon steel fibres shows a remarkable improvement in high strength concrete under static and blast loading.

The addition of steel fibres (0.5% and 1.0%) in high strength concrete (HSC) enhances the flexural and steel behavior reported by Omar et al. [6]. They stated that the addition of 1% fibres in HSC increases the shear capacity by 70% and prevents shear collapse as compared to that of reference concrete. Also, the residual deformation was reduced by 33% and 60% at 0.5% and 1% addition. Further, they stated that incorporation of 1% fibres in HSC enhances the stiffness, maximum load resisted ductility, and toughness by 38%, 11%, 219%, and 294% respectively as compared to that of reference concrete. Finally, they conclude that it is possible to design the blast-resistant structure by adding 1% fibres in high strength concrete.

Luccioni et al. [5], investigated the impact of fibre addition on the high strength concrete. The square slab of 550 mm with 50 mm thick was used with a 0.65 kg explosive at a minimum standoff distance of 15 m from the plate. They reported that the addition of hooked carbon steel fibres of 30 mm and 60 mm, length at 0.5%, and 1.0% shows significant improvements in static properties of concrete against blast. Also, the inclusion of fibre reduces the permanent deflection caused by the blast. They affirmed that; the expansion of cracks formed due to the explosion was controlled by the fibres present in the concrete. They also stated that the numerical simulation models will not predict accurate flexure failure, cratering, and spalling.

The blast performance of steel fibre reinforced concrete was also studied by Magnusson [10]. Three different concrete mixtures (35, 100, and 180 MPa compressive strength) and two different lengths of steel fibres (30 and 60 mm) were tested. The aspect ratio of the fibres was 80 and the strength was 2600 MPa. The fibre volume was chosen to be 1.0%. Plastic explosive charges 0.3–0.9 kg in weight was placed at a stand-off distance of 10 m. The specimens were beams with a span of 1.5 m. The test results showed that long fibres improve the blast performance more in concrete with low compressive strength, and short fibres improve the blast performance more in concrete with high compressive strength.

Li and Aoude [11], presented the effect of the addition of fibres in High-Strength Concrete (HSC) and High-Strength (HS) steel reinforcement under blast loading. The beam specimens (2.44 m $\times$ 0.125 m $\times$ 0.25 m) were used for the test with the addition of 0.75% and 1% steel fibres in concrete and tested under quasi-static and simulated blast loads using a shock-tube. They reported that the addition of steel fibres in concrete shows significant improvements in the properties of concrete beams under static and blast load.

The influence of the addition of 1% steel fibres of 30 mm length in High Strength Concrete beams subjected to blast load was studied by Li and Aoude [12]. The beam specimens (2440 mm $\times$ 125 mm $\times$ 250 mm) were used and tested under quasi-static and simulated blast loads using a shock-tube. The results of the study showed that the addition of steel fibres in HSC beams enhance the load-carrying capacity, stiffness, and ductility as compared to that of normal concrete, whereas the normal concrete without fibres fails suddenly. They finely summed up that, the inclusion of fibres in HSC improves the resistance against blast and reduced the displacements.

This paper deals with the influence of fibre content on the performance of concrete under static and blast load.



Fig. 1 – Experimental set up for Blast Test

2 Materials

For the preparation of control concrete and fibre reinforced concrete, the ordinary Portland cement (OPC) 53 grade is used for this study which satisfies the requirement of BIS: 1489-part 1-1991 [13]. The initial and final setting time of cement was 30 minute and 580 minutes whereas the compressive strength of cement at 28 days was 58.6 MPa.

The fine aggregate used in the study confirms to grading zone II as per BIS: 383-1960 [14]. Locally available coarse aggregate of maximum nominal size of 10 mm is used which satisfies the requirement of BIS: 383-1960 [14]. The properties of the aggregate are presented in Table 1

Table 1 – Physical properties of Aggregate

Sr. No	Property	Fine Aggregate	Coarse Aggregate
1	Specific gravity	2.69	2.80
2	Water absorption	1.04 %	0.35 %
3	Grading Zone	Zone II As per Table 4 of BIS 383	As per Table 2 of BIS 383

The hooked end steel fibres of 60 mm in length and 0.75 mm in equivalent diameter were used. The density and tensile strength of the fibre were 7850 kg/m³ and 1050 MPa respectively. The properties of steel fibre are enlisted in Table 2.

Table 2 – Properties of steel fibre

Property	Value
Wire diameter (d)	0.75 mm (± 0.04 mm)
Fibre length (L)	60.0 mm (+2/-3 mm)
Hook length (l)	1 – 4 mm
Hook depth (h)	1.80 mm (+1/-0 mm)
Bending angle (α)	45° (min. 30°)
Aspect ratio (L/d)	80
Tensile strength of drawn wire	1050 N/mm ²

3 Experimental program

3.1 Mix Proportioning

The concrete mixes were prepared and tested as per BIS 10262:2009 [15] by keeping the water-cement ratio of 0.40. To achieve the homogeneous mix, all the ingredients of concrete were first dry mixed in a mixer for 5 minutes, and then slowly the water was added. The hooked end steel fibres were added in concrete mix at different percentages 0%, 0.5%, 1%, 1.5%, 2% and 2.5% by weight of cement. Considering the addition of fibres reduced the workability of concrete, the high range water reducing admixture Parma plast- 220 super plasticizers (1% by volume of cement) was used. The mix proportions are given in Table 3.

Table 3 – Quantity material per m³ of concrete

Mix	Fibre content % by volume of cement	Fibre content (Kg)	Cement (Kg)	Fine aggregate (Kg)	Coarse Aggregate (Kg)	Water (lit)	Dose of admixture (lit)
M30	0	-	380	1032	952	152	3.8
	0.5	1.9	380	1032	952	152	3.8
	1	3.8	380	1032	952	152	3.8
	1.5	5.7	380	1032	952	152	3.8
	2.0	7.6	380	1032	952	152	3.8
	2.5	9.5	380	1032	952	152	3.8
M35	0	-	402	1009	931	161	3.8
	0.5	1.9	402	1009	931	161	3.8
	1.0	3.8	402	1009	931	161	3.8
	1.5	5.7	402	1009	931	161	3.8
	2.0	7.6	402	1009	931	161	3.8
	2.5	9.5	402	1009	931	161	3.8
M40	0	-	412	989	913	161	3.8
	0.5	1.9	412	989	913	161	3.8
	1.0	3.8	412	989	913	161	3.8
	1.5	5.7	412	989	913	161	3.8
	2.0	7.6	412	989	913	161	3.8
	2.5	9.5	412	989	913	161	3.8

3.2 Sample preparation

The experimental program consists of casting, curing, and testing of specimens. To determine the compressive and flexural strength, cubes of 150 mm and beams of size 150 mm × 150 mm × 700 mm were cast as per BIS: 516, 1959 [16]. For the determination of splitting tensile strength a cylinder of 150 mm in diameter and 300 mm in height were cast as per BIS:5816 :1999 [17]. The toughness properties were determined in terms of energy absorption capacity due to the impact load on a specimen's size of 250 mm × 250 mm × 50 mm following the procedure proposed by ACI committee 544-2R-89 (ACI.1984) [18]. The beam specimens of 140 mm × 140 mm × 850 mm were used to evaluate the modulus of rigidity of the concrete. All the specimens were de-moulded at the age of 24 ± 1 h and thereafter were cured in the water tank at room temperature up to the specified age of the test.

To investigate the influence of steel fibres on the properties of concrete subjected to blast is also studied in this paper. For this purpose, the following test specimens were prepared and tested. A rectangular specimen of size 400 mm × 400 mm × 50 mm was cast and tested in the field as per BIS:4991-1968 reaffirmed in 2003 [19]. Ammonium Nitrate Fuel Oil (ANFO)

of 125gm which is equivalent to 100 gm TNT (Trinitro Toluene) is used for the explosion of the tests panel. Testing was done in a pit of 0.5 m x 0.5 m with a depth of 1m. Two steel bars were used as support so that the specimens could experience flexural bending. The experimental setup is shown in Figure 1. The explosive charge was kept hanging at a specific distance from the specimen having its centre colliding with the centre of the plate. Then the pit was covered with steel plates so that expanding gases could not be released freely and it also ends the possibility of any flying debris.

4 Results and Discussion

4.1 Compressive strength

The impact of the incorporation of steel fibres on the compressive strength of concrete is shown in Figure 2. From the figure, it was observed that the compressive strength of concrete containing fibres content showed a significant increase in strength at all grades of concrete mixes. The compressive strength of M30 concrete is increased by 9.2%, 20%, 28%, 15% and 8% at 0.5%, 1%, and 1.5%. 2% and 2.5% fibre content respectively. In concrete grade M35 and M40 the compressive strength of concrete mixes increased approximately by 8%, 16%, 22%, 14% and 6% and 8%, 14%, 18%, 13% and 5% respectively at above mentioned percentage additions. In all the concrete mixes it was observed that the compressive strength was incurring significantly up to 1.5% addition after that the decrease was seen. But still, the strength of the concrete mix at 2.0% and 2.5% is higher than that of the control concrete mix.

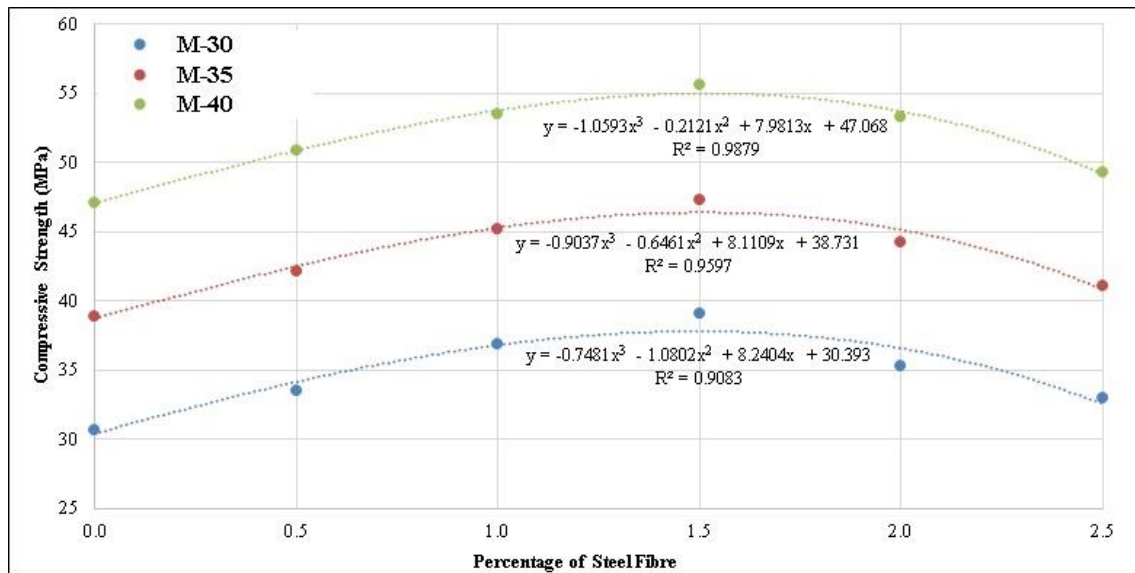


Fig. 2 – Compressive strength of concrete mixes at the various fibre content

A slight reduction in the strength is because more addition of fibre content results in congestion of fibres which leads to balling effect and improper bonding with concrete [20, 21].

4.2 Modulus of elasticity

The specimen is subjected to flexure under the four-point loading condition. When the beam was subjected to loading at $\frac{l}{3}$ from both the supports. The middle portion of the beam is subjected to pure bending action and the remaining portion under shear flexural action. The addition of a different percentage of steel fibres on the elasticity property of concrete is investigated and presented in Figure 2.

From figure 3 it was noted that the modulus of elasticity of concrete mixes produced with the addition of different percentages of steel fibres showed remarkable improvement as compared to that of the reference mix. With the addition of steel fibres from 0.5% to 1.5%, the elasticity of concrete grades M30, M35, and M40 is increased from 11% to 32%, 13% to 28%, and 14% to 24%. Whereas, at 2.0% and 2.5% addition, all the concrete mixes showed a marginal decrease in elasticity

as compared to that of 1.5% addition concrete mix. But still, all the values of concrete mixes at 2.0% and 2.5% are higher than that of the reference mix.

The addition of fibres increases the flexural strength of all concrete mixes this is due to the bridging action of fibres present in the matrix which restrict the widening of cracks and shows docile behaviour [20, 22, 23].

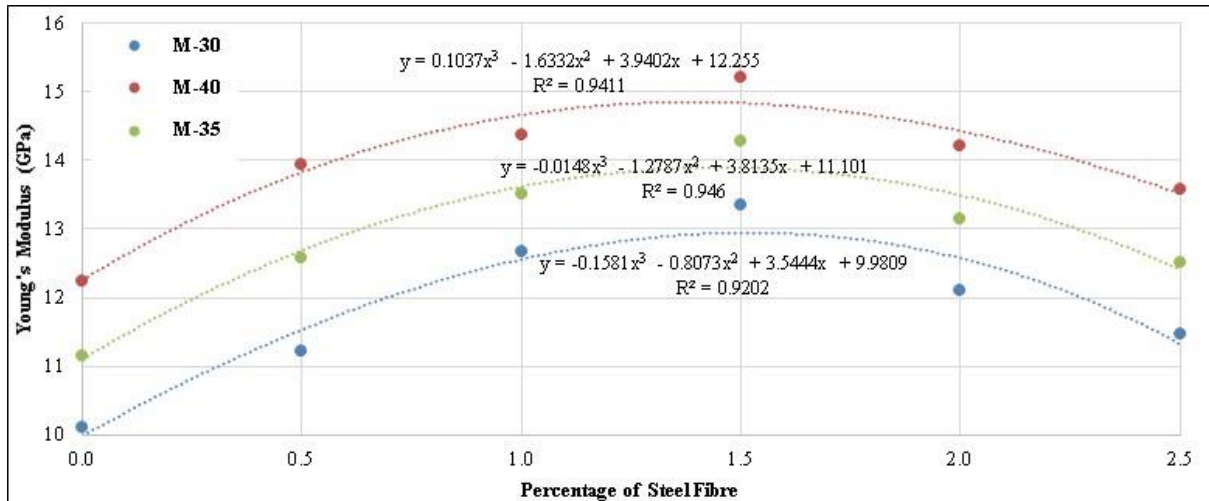


Fig. 3 – Flexural strength of concrete mixes at various fibre content

4.3 Split Tensile Strength

The results of the split tensile strength of reference concrete and concrete are produced with the addition of steel fibres shown in Figure 4.

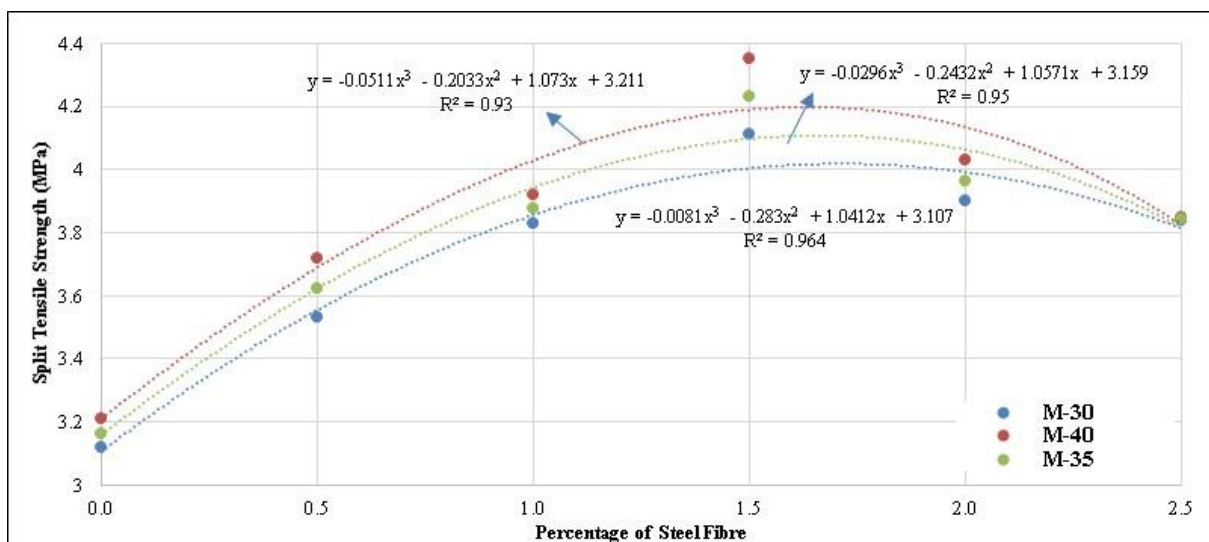


Fig. 4 – Split Tensile strength of concrete mixes at the various fibre content

The results of the split tensile strength show that the addition of steel fibres in concrete mixes increases the split tensile strength. The peak strength is obtained at 1.5% fibre content. The findings of this test show a similar trend as that of the compressive and flexural strengths. The bridging effect is the main which enhanced the split tensile strength of concrete prepared with the addition of fibres [24]. Another possible reason for the increase in the tensile strength of concrete mixes is due to the mechanical property i.e. tensile strength of steel fibres. The full tensile strength is utilized when the load is applied. This prevents the propagation of cracks in the specimens. The same phenomenon was reported by Iqbal et al. [25], in their study.

4.4 Torsion Test

The torsional properties of steel fibre reinforced concrete are becoming extremely important in the construction of modern days. Modulus of rigidity or shear modulus is determined by using torsional empirical formula $G = \frac{TL}{J\theta}$. The contribution of the increase of shear modulus after the addition of steel fibres for different grades of the concrete as shown in Figure 5.

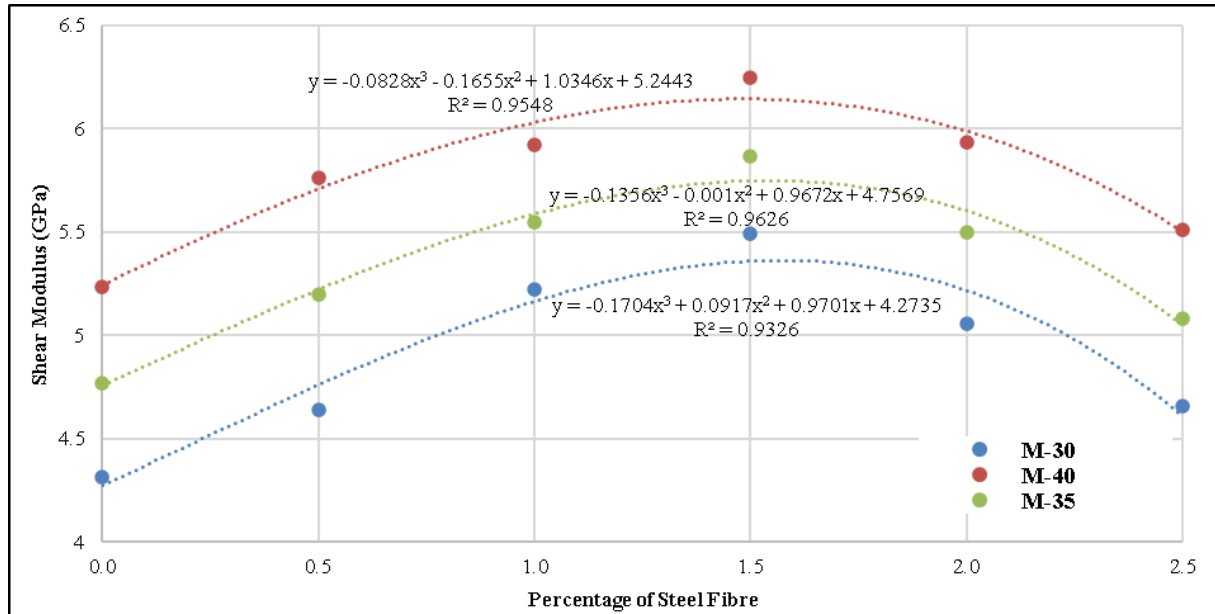


Fig. 5 – Shear Modulus of concrete mixes at the various fibre content

From the above figure, it was observed that the shear modulus of concrete mixes produced with the addition of fibres shows remarkable improvements. The shear modulus of 1.5% fibre added concrete mixes increased by 27%, 23%, and 19.43% for M30, M35, and M40 grades of concrete respectively. The contribution of 1.5% of steel enhances the diagonal tensile strength of the concrete which helps to minimize the angle of twist due to the increase of the torque. This helps in increasing the shear modulus of steel fibre reinforced concrete for the random distribution of steel fibres [26, 27].

4.5 Impact Test

The toughness of the material in terms of energy absorption capacity is measured by using a drop-weight impact test. Steel fibres plays important role in the concrete to form the proper bonding and resist the formation of cracks or arrest the further widening of the crack. Energy absorption capacity of the fibre-reinforced concrete after adding steel fibres from 0%, 05%, 1%, 1.5%, 2.0% & 2.5% for different grades of the concrete composites is as shown in Figure 6.

From figure 6, it was observed that impact energy increases from zero to 1.5% and again decreases up to 2.5%. An optimal increase in impact strength up to 218% for 1.5% of steel fibres was observed. The decrease in the impact strength beyond 1.5 % of the steel fibres was observed mainly due to the non-homogeneity of the concrete mix. The balling tendency of the steel fibres may occur beyond 1.5% of steel fibres which decreases the workability of the concrete. The concrete specimen was observed to be completely damaged due to its poor energy absorption capacity.

The addition of fibres in concrete increases the toughness which leads to an increase in the energy absorption capacity of the concrete mixes [26, 28].

4.6 Shear Strength

Shear causes diagonal cracking of the concrete. The cracking starts from the supports and increases towards the loading point. This is resisted by the contribution from the shear capacity of the concrete and resistance due to the interlocking of

aggregates. The addition of steel fibres in the concrete composite helps to increase the shear capacity of the beam which prevents diagonal cracking of the beam. The results of the study are shown in Figure 7.

From figure 7 it was observed that the shear capacity of all the concrete mixes is enhanced due to the addition of steel fibres. The shear capacity of all concrete mixes shows a significant increase up to 1.5% fibre addition and after that gradually decreases. However, the shear capacity at 2% and 2.5% addition was observed to be higher than that of the reference mix. The random distribution of steel fibres restricts the propagation of cracks from all the directions. While mixing and casting, proper care should be taken to maintain the homogeneity of the mix so that there should not be stress concentration in the weaker portion of the specimen to avoid crack formation.

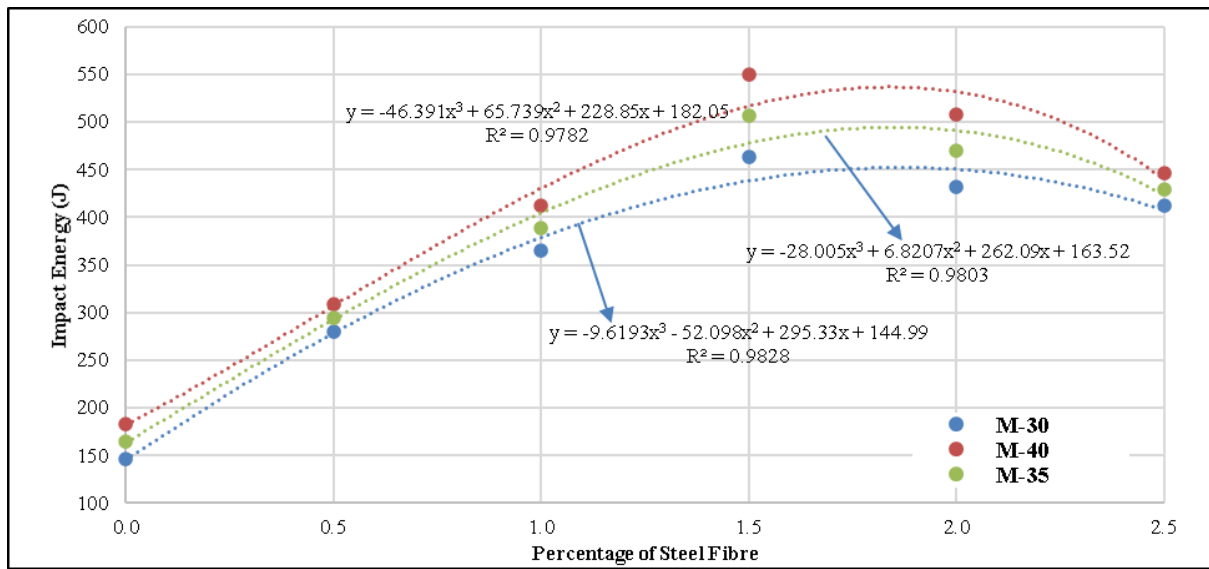


Fig. 6 – Impact Strength of concrete mixes at the various fibre content

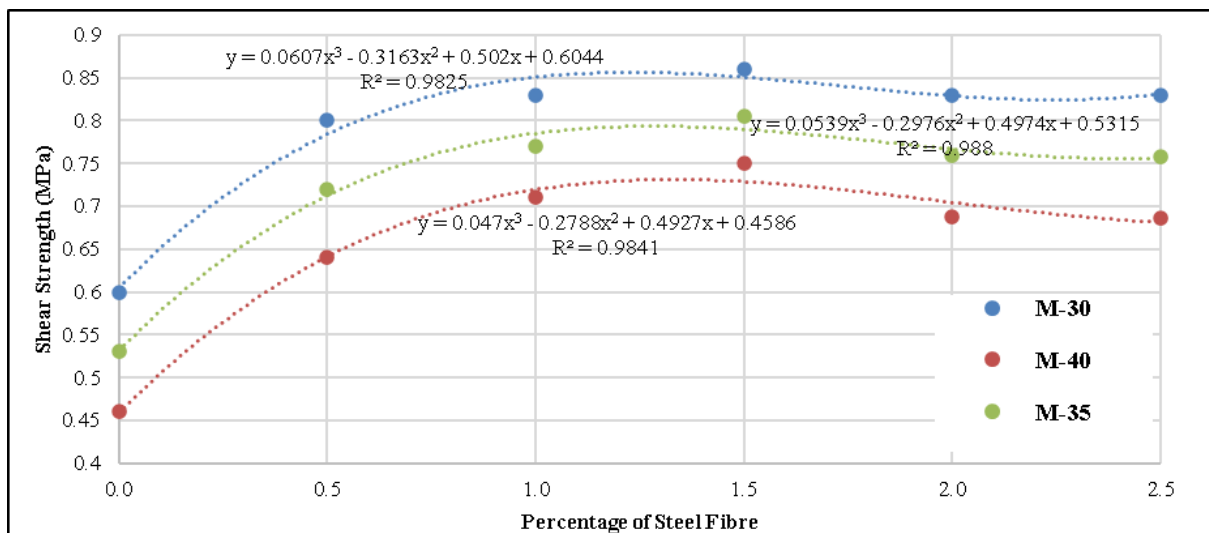


Fig. 7 – Shear Strength of concrete mixes at the various fibre content

4.7 ANOVA analysis

The results of the concrete mixes prepared with the addition of fibres show remarkable improvements in engineering properties. An attempt had been made to develop a mathematical equation using the Analysis Of Variance (ANOVA) technique. The output of ANOVA analysis is shown in Table 4.

Table 4 – a) Regression Statistics

Multiple R	0.99254
R Square	0.98514
Adjusted R Square	0.97895
Standard Error	1.10967
Observations	18

Table 4 b) ANOVA Statistics

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	5	979,80932	195.96186	159.14135	1.54683E-10
Residual	12	14.77643	1.23136	--	--
Total	17	994.58576	--	--	--

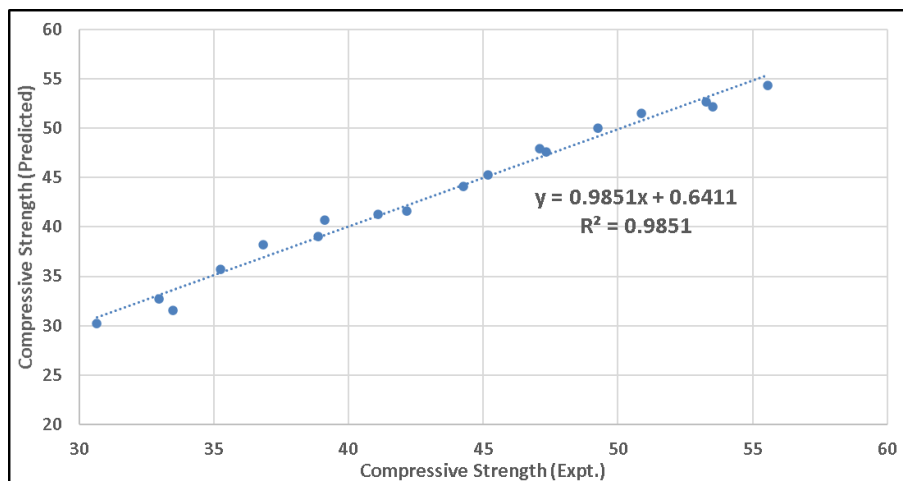
Table 4 c) ANOVA Coefficient Calculations

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	-17.83382	7.29800	-2.44365	0.03095	-33.7348	-1.9328	-33.7348	-1.93283
Split Tensile	-7.52912	4.88764	-1.5404	0.14939	-18.1783	3.1201	-18.1783	3.12013
Flexural (E)	6.75023	2.16456	3.11851	0.00887	2.03405	11.4664	2.03405	11.4664
Torsion (G)	-3.06792	5.50761	-0.55703	0.58774	-15.0679	8.9321	-15.0679	8.93213
Log10 (Impact Energy)	17.63312	6.75957	2.60861	0.02285	2.90527	32.3609	2.90527	32.3609
Shear Strength	-35.85980	7.28425	-4.92292	0.00035	-51.7308	-19.9887	-51.7308	-19.9887

From the ANOVA analysis, a mathematical equation was developed by equating the compressive strength of concrete with various engineering properties of concrete as follows:

$$f = -7.529(S_p) + 6.751(E) - 3.068(G) + 17.633(\log_{10}(I_E)) - 35.8599(S) - 17.834 \quad (1)$$

where, f : Compressive Strength (MPa); S_p : Split Tensile (MPa); E : Young's Modulus (GPa); G : Shear Modulus (GPa); I_E : Impact Energy (J) and S : Shear Strength (MPa)

**Fig. 8 – Validation of predicted compressive strength**

From the analysis, the coefficient of correlation was observed as 0.98, which shows a very good relation between the compressive strength of concrete with other engineering properties of concrete. Table 4 shows the results obtained from laboratory testing of various grades of concrete and the predicted compressive strength using the mathematical equation formed through the ANOVA technique.

Table 5 – Experimental and predicted compressive strength of concrete

Concrete Mix	Percentage of Steel Fibre	Split Tensile strength	Flexural strength (E)	Torsion (G)	Impact Energy	Shear Strength	Compressive strength	
							Experimental	Predicted
M-30	0	3.12	10.10	4.32	145.87	0.60	30.66	30.22
	0.5	3.53	11.22	4.64	279.72	0.80	33.48	31.54
	1.0	3.83	12.67	5.22	364.57	0.83	36.82	38.22
	1.5	4.11	13.36	5.49	463.77	0.86	39.11	40.74
	2.0	3.90	12.11	5.06	431.85	0.83	35.25	35.73
	2.5	3.84	11.47	4.66	412.24	0.83	32.95	32.73
M-35	0	3.17	11.15	4.77	164.50	0.53	38.88	39.04
	0.5	3.63	12.59	5.20	294.37	0.72	42.17	41.62
	1.0	3.88	13.52	5.55	388.30	0.77	45.17	45.27
	1.5	4.23	14.29	5.87	506.56	0.81	47.33	47.56
	2.0	3.97	13.15	5.50	469.94	0.76	44.27	44.10
	2.5	3.85	12.51	5.08	429.30	0.76	41.11	41.32
M-40	0	3.21	12.24	5.23	183.12	0.46	47.10	47.97
	0.5	3.72	13.94	5.77	309.01	0.64	50.86	51.53
	1.0	3.92	14.37	5.92	412.02	0.71	53.51	52.13
	1.5	4.35	15.21	6.25	549.35	0.75	55.55	54.39
	2.0	4.03	14.21	5.94	508.03	0.69	53.28	52.68
	2.5	3.85	13.57	5.51	446.35	0.69	49.26	49.99

From Table 5, it was observed that there is a close resemblance between experimental and predicted values of compressive strength in all concrete mixes. Furthermore, the regression analysis was carried out and the R values were found to be within the limit. Figure 8 shows the comparison of predicted compressive strength concerning the experimental values of compressive strength. It was observed that the coefficient of correlation between these values is 0.98.

4.8 Blast Test

From the experimental results, it was found that the maximum results were obtained at 1.5% addition of fibres in all concrete mixes. Therefore, to investigate the impact of the addition of fibres on blast resistant concrete was proposed to study. For this purpose, the concrete grade M 40 with 0%, 1.25%, 1.5%, and 1.75% fibre addition was selected. The standoff distance from the test specimens was kept at 15 cm, 17 cm, and 20 cm. Whereas, the blast charge Ammonium Nitrate Fuel Oil (ANFO) of 125gm which is equivalent to 100 gm TNT (Trinitro Toluene) was used for the explosion of the tests panel.

All the concrete mixes show a variable pattern of cracking, partial and complete damage on the specimens after being subjected to blast load. Because of the blast, a sudden shock wave was developed on the specimens. The reference concrete “A0” shows complete damage after being subjected to blast as seen in Figure 9 a. The specimens were broken into several pieces in the diagonal pattern after being subjected to blast at all standoff distances and the complete damage of the specimens was observed.

The concrete specimen “A1” prepared with 1.25% fibre addition shows comparatively better performance as compared to that of the A0 specimen. Some minor cracks were observed on the surface of the specimens after being subjected to blast as shown in Figure 9b.



(a) Reference concrete -A0



(b) Concrete with 1.25% fibre content-A1



(c) Concrete with 1.5 % fibre content –A2



(d) Concrete with 1.75% fibre content –A3

Fig. 9 – Visual observations of test panels after the blast

These cracks were propagated from the center to the corners of the specimens in all directions. The crack width is measured with the help of a demountable mechanical strain gauge. The concrete specimens show major cracks on the surface at a standoff distance of 17cm and 20cm, whereas at 15 cm distance complete damage of the specimen was observed. At a distance of 17 cm and 20cm, a crack width of 1.41 mm and 1.23 mm was observed on the surface of the specimen.

Some additional fractures were also observed at the corners of the specimens where the specimens are supported by steel plates as shown in Figure 1 (the experiment's setup). Failure of the rear face of the specimen was characterized by three major cracks. The front face of the plate undergoes a small deflection of 1.5 mm at the center of the specimen. One of the cracks extended towards the lateral side of the specimen with full depth of the specimen. The specimen was prevented from break due to additional strength created by steel fibres.

On the other hand, the concrete specimens “A2” with 1.5% of steel fibre showed better performance as compared to that of control concrete as shown in Figure 9c. At a distance of 15 cm, 17cm, and 20cm the cracks were observed on the surface and the crack width was 1.11mm, 1.09mm, and 1.15mm were seen which is marginally lower than that of the specimen A0 and A1. Crack widths of 1.1 mm were seen in the middle portion of the specimen in the vicinity of the detonator. The specimen was damaged however, the lesser deflection was observed as compared to the A1 specimen.

On the specimen “A3” only hair cracks were observed on the rear side surface of the concrete after being subjected to blast as shown in Figure 9d. The crack width was very less as compared to all other concrete mixes. It was observed that the fibres present in the concrete tried to restrict the propagation of cracks. The addition of fibres in concrete mixes show substantial benefit against blast.

Table 6 – Observation Table for Blast Load Test

Concrete Mix	Standoff Distance (cm)	Peak overpressure (MPa)	Extent of Damage	Crack width (mm)
A0 -Reference concrete	15	8.81	Complete Damage	-
	17	7.32	Complete Damage	-
	20	5.65	Complete Damage	-
A1 -concrete with 1.25% fibre	15	8.81	Complete Damage	-
	17	7.32	Cracks	1.41
	20	5.65	Cracks	1.23
A2 -concrete with 1.5% fibre	15	8.81	Cracks	1.11
	17	7.32	Minor Cracks	1.09
	20	5.65	No Damage	1.15
A3 -concrete with 1.75% fibre	15	8.81	Cracks	1.07
	17	7.32	Minor Cracks	1.0
	20	5.65	No Damage	-

In this study, the findings were in line with the results obtained by the various authors in the study of different types of fibre content [29-32]. The addition of fibres in the concrete enhanced the blast performance of concrete. The fibres present in the concrete produces a bridge effect and increase the energy absorption capacity

The reference concrete could not withstand blast tests, as it damaged completely. In the case of 1.5% fibres, the concrete performed well to withstand the blast loading. The extent of damage is very less. The fibres present in the concrete prevent the flexure failure [33]. The flexural cracks in the specimen A2 and A3 decreased because of the increase in flexural strength and toughness property of the specimens due to the addition of fibres.

5 Conclusions

The influences of the addition of different percentages of hooked end steel fibres in concrete have been studied. The performance of the concrete with various grades was studied against static and blast load. The following conclusions were drawn from the above study. The addition of steel hooked fibres in the concrete improved the properties of concrete, viz. compressive strength, flexural strength, impact strength, shear strength, torsion, and split tensile strength. The optimum percentage of the addition of fibres in the concrete mixes was observed to be 1.5%. Beyond that, the significant reduction in the static properties was observed. However, the results were observed to be higher than the reference concrete mixes. It may be attributed to the influence of statistical parameters applied to experimental data. The FRC strength prediction model is developed based on experimental parameters and empirical relation using statistical tools. The model predicts the values in line with the experimental results. The performance of concrete under blast loading was also observed to be increased due to the addition of steel fibres. The addition of fibres has changed the cracking and failure pattern of the concrete against blast. The addition of 1.5% and 1.75% of steel fibres show optimal performance against blast. The addition of steel fibres in the concrete increases the tensile toughness needed for blast resistance. Hence shows lesser cracking, spalling, gives enough protection before failure. This property can be used for applications to light weight, FRC precast components of structure. Such Precast components can be used for construction of temporary shelters required for defence activities.

Furthermore, it must be highlighted that the results obtained for the blast test in this study are indicative. These results cannot be inferred from the actual elements of the structure. It may vary because the material has not scaled down for the test.

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