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EXPERIMENTAL INVESTIGATION ON HIGH STRENGTH STEEL FIBER REINFORCED CONCRETE WITH METAKAOLIN

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ABSTRACT

The paper presents the results of an experimental investigation on the properties of structural concrete using steel fiber (SF) and metakaolin (MK). Crimped steel fibers of aspect ratio 85 and metakaolin were used. The effects of these fiber and metakaolin on workability, density, and on various strengths of M60 grade concrete are studied. Fiber content varies from 2.5% to 10 % by weight of cement and metakaolin content varies from 5% to 20% by weight of cement. The various strengths considered for investigation are compressive strength, flexural strength, split tensile strength, and shear strength. Cubes of 150mm for compressive strength, cylinders of size 150mm diameter x 300mm length for split tensile strength, beams of 100 x100 x 500 mm for flexural strength, push-off specimens of size 150 x 150 x 450 mm for shear strength were cast. All the specimens were water cured and tested after 28 days. Workability of wet mix is found to be reduced with increased fiber content. Ductility of steel fiber reinforced metakaolin concrete (FRMC) is found to increase as observed from the study of load–deflection behavior. A significant improvement in the various strengths is observed due to inclusion of fibers and metakaolin in the concrete.

Keywords: Crimped steel fiber; metakaolin; M60 grade concrete; shear strength of concrete.

1. INTRODUCTION

The utilization of calcined clay, in the form of metakaolin (MK), as a pozzolanic material for mortar and concrete has received considerable attention in recent years. This interest is a part of the wide spread attention directed towards the utilization of wastes and industrial by-products in order to minimize Portland cement (PC) consumption, the manufacture of which being environmentally damaging as reported by Sabir et al. [1].

Rashiddadash et al. [2] reported that the fiber reinforced concrete (FRC) has been widely used due to its advantages over plain concrete. It can be an appropriate material for the repair of structures in a variety of situations. However, there is a weak zone between fibers

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and paste in fiber reinforced concretes and this weak zone is full of porosity, especially in hybrid fiber reinforced concretes. Therefore, use of pozzolanic materials is required to reduce the porosity. Pumice and kaolin are two pozzolanic materials that have been found abundantly in some regions of the world. Metakaolin with highest substitution of cement had the best performance of mechanical properties of concrete. Moreover, this pozzolan caused increase in compressive strength in comparison with control mixture. However, replacing pumice into the specimens had negative effect on the mechanical properties.

Rashad [3] presented that the Kaolin can satisfy the world demand for filler, paper and ceramic industries. Kaolin converts into a pozzolan material named metakaolin (MK) after suitable thermal treatment. MK can be used in mortar and concrete to improve their properties. In addition, MK can be used as a source of cementing materials in alkali activation or geopolymer. Ding et al. [4] investigated the strength and flexural toughness of hybrid fibre reinforced self-compacting high performance concrete. It is shown that the combination of steel and polypropylene fibres represents an optimal fibre reinforcement for self compacting high performance concrete. Guneyisi et al. [5] studied the mechanical properties of plain and metakaolin (MK) concretes with and without steel fiber. The results revealed that incorporation of MK and utilization of different types of steel fibers significantly affected the mechanical properties of the concretes, irrespective of w/c ratio. Banthia et al. [6] studied the toughness enhancement in steel fiber reinforced concrete through fiber hybridization with large diameter crimped steel fibers and shown the significant improvement in toughness of concrete composite compared to smaller diameter fibers.

Shelorkar et al. [7] observed that concrete blocks incorporated with steel fibre increased its compressive strength by 8.91% and tensile strength by 26.94%. Metakaolin and steel fiber blocks exhibited an increase in flexural strength of concrete by 58.28%. Ghugal et al. [8] studied the properties of alkali-resistant glass fiber modified structural concrete. Workability of wet mix is found to be reduced with increased fiber content. Ductility of concrete is found to increase in glass fiber reinforced concrete (GFRC) as observed from the study of load–deflection behavior. New expressions for various strengths are proposed. Results of elastic constants obtained by various methods and newly proposed expressions are presented. A significant improvement in the various strengths is observed due to inclusion of glass fibers in the concrete. Rashad [9] studied a feasibility of metakaolin (MK) as fine aggregate replacement in concrete. Test results indicated that compressive strength, splitting tensile strength and abrasion resistance of concrete increased with increasing content of fine aggregate replacement with MK up to 40% then decreased at 50% replacement level. Dias et al. [10] studied fracture toughness of geopolymeric concretes reinforced with basalt fibers. It is shown that the geopolymeric concretes have better fracture properties than conventional Portland cement concretes.

Soroushian et al. [11] reported the results of an experimental study on the relative effectiveness of different types of steel fiber in concrete. The overall workability of fresh fibrous mixes was found to be largely independent of the fiber type, with crimped fibers producing only slightly higher slumps. Hooked fibers were found to be more effective than straight and crimped ones in enhancing the flexural and compressive behavior of concrete. Under flexural loads, crimped fibers (rectangular or circular) were slightly less effective than straight ones in improving the strength and energy absorption of concrete.

Ding et al. [12] studied the effects of metakaolin and silica fume on properties of concrete. Metakaolin-modified concrete showed a better workability than silica fume-modified concrete. As the replacement level was increased, the strength of the metakaolin-modified concrete increased at all ages similarly to that of the silica fume-modified concrete. Both mineral admixtures reduced free drying shrinkage and restrained the shrinkage cracking width. However, the cracking time was earlier for these two concretes. These admixtures also greatly reduced the chloride diffusivity of the concrete. Soulioti et al. [13] presented the effects of fibre geometry and volume fraction on the flexural behavior of steel-fibre reinforced concrete. The improvement in the mechanical properties, in particular the toughness, was observed with the increase of the volume fraction of steel-fibres in the concrete. The fibre geometry was found to be a key factor affecting the mechanical performance of the material.

Moulin et al. [14] studied the influence of key cement chemical parameters on the properties of metakaolin blended cements using cement pastes and mortars containing MK . Gruber et al. [15] presented the performance of high-reactivity metakaolin (HRM) for its applications in bridge decks, bridge deckoverlays, industrial flooring, high strength concrete and masonry products. Graybeal [16] studied the uniaxial compressive behavior of an ultra-high performance fiber-reinforced concrete. Cylinders were tested in compression to determine the strength, modulus of elasticity, strain capacity, and overall stress-strain behaviors of both untreated and steam-treated concrete. It is shown that this concrete exhibits exceptional compressive strength and enhanced stiffness.

In the present work, the effects of crimped steel fibers and metakaolin on the properties of fresh concrete and on various strengths of structural concrete are investigated and the results obtained experimentally are presented.

2. EXPERIMENTAL PROGRAMME

Ordinary Portland cement of 53 grade confirming to IS12269 [17] and fine and coarse aggregates confirming to IS 383 [18] were used. The fineness moduli of fine and coarse aggregates were 2.7 and 7.9, respectively. The crimped steel fibers and metakoalin having physical and mechanical material properties as shown in Tables 1 and 2 were used.

Table 1: Properties of crimped steel fiber

Sr. No.	Property	Value
1.	Diameter (d_f)	0.7 mm
2.	Length of fiber (l_f)	60 mm
3.	Aspect ratio of fiber (l_f/d_f)	85
4.	Appearance and form	Clear, bright and undulated along length
5.	Modulus of Elasticity	200 GPa
6.	Tensile strength	1000 MPa

Table 2: Properties of metakaolin

Item	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Loss on Ignition	Specific Gravity	Bulk Density
% by Weight	52.8	36.3	4.21	0.81	< 0.10	1.41	3.53	2 ± 0.1	320 ± 20

The M-60 grade of concrete having mix proportions 1: 0.8518: 1.1481 i.e., cement: fine aggregate: coarse aggregate with w/c ratio of 0.3 was used throughout the experimental investigation. The concrete mix design was carried out according to I.S.10262 [19]. Fibers and metakoalin in powder form were added in wet state of concrete and again mixed thoroughly. Cubes of 150mm size for compressive strengths, cylinders of size 150mm diameter x 300mm length for split tensile strength, beams of size 100 x 100 x 500 mm for flexural strength and pushoff specimen of 450 x 150 x 150 mm for shear strength were cast incorporating 0–10% crimped fibers at an interval of 2.5% and 0-20% metakoalin at an interval of 5% by weight of cement. For each test, three specimens were cast. Compaction of all the specimens was done using a table vibrator to avoid balling of fibers. All the specimens were water cured for 28 days at room temperature and were tested in surface dry condition on a 1000 kN Universal Testing Machine (UTM) and Compression Testing Machine (CTM) of capacity 2000 kN. Totally, 60 specimens were cast and tested to evaluate the strength performance. Each value of the results presented in this study is the average of three test samples.

3. PHYSICAL PROPERTIES OF CONCRETE COMPOSITE

The properties of fiber reinforced metakaolin concrete composite evaluated include the properties of fresh or green concrete and those of hardened concrete. For green concrete workability, wet density and temperature of the are measured and studied. For hardened concrete strength properties such as compressive strength, flexural strength, split tensile strength and shear strength are obtained experimentally. Other properties such as toughness indices and Poisson’s ratio are derived from the deformation behaviour of this composite. For destructive testing of hardened concrete Compression Testing Machine and Universal Testing Machine were used as test-setups.

3.1 Tests conducted on fresh FRMC

In this experimental work steel fiber and metakaolin are used to design high strength concrete of M60 grade. Workability of wet concrete is determined by slump cone test, inverted slump cone test and compaction factor test. Temperature of green mix and wet density were also measured using standard procedures. Test results are presented in Table 3.

3.2 Tests conducted on hardened FRMC

Compressive Strength: It is determined using standard cubes by applying compressive load at the age of 28 days using compression testing machine (CTM) of capacity 2000 kN.
This strength was determined by carrying out a cube compressive test on 150 mm size cubes. The compressive strength was calculated by the formula

$$f_{cu} = \frac{P_c}{A} \tag{1}$$

where f_{cu} = Compressive Strength, MPa
P_c = Failure load in compression, N
A = Loaded area of cube, mm^2

The compressive strength results and percentage increase in compressive strength of FMRC compared to that of normal concrete (NC) are shown in Table 4.

Flexural Strength: This strength is determined by carrying out four point flexure test according to IS 516 [20] on standard beam of size 100 x 100 x 500 mm. A beam is supported symmetrically over a span of 400 mm and subjected to two point loads in middle third of beam. The beams were loaded till failure. The load and deflections were measured at certain intervals. The deflection at the centre of the beam is measured with the sensitive dial gauge on UTM. The flexure strength was determined by the formula,

$$f_{cr} = \frac{P_f L}{bd^2} \tag{2}$$

where f_{cr} = Flexure strength, MPa
P_f = Central load through two point load system, N
L = Span of beam, mm
b = Width of the beam, mm
d = Depth of the beam, mm.

The flexural toughness indices were calculated based on load-deformation behaviour for each fiber volume fraction. Thes results are reported in Table 5.

Split Tensile Strength: The split tensile test is well known indirect test used to determine the tensile strength ofconcrete as per I.S.5816 [21]. Due to difficulties involved in conducting the direct tension test, a number of indirect methods have been developed to determine the tensile strength of concrete. In these tests, in general a compressive force is applied to concrete specimen in such way that the specimen fails due to tensile stress induced in the specimen.

The tensile strength at which failure occurs is the tensile strength of concrete. In this investigation, the test is carried out on cylinder by splitting along its middle plane parallel to the edges by applying the compressive load to opposite edges. Split tensile strength of cylinder was calculated by the following formula:

$$f_t = \frac{2P_{sp}}{\pi DL} \tag{3}$$

where

f_t = Tensile strength in Mpa,

P_{sp} = *Compressive* Line Load at failure in N,

L = Length of cylinder in mm,

D = Diameter of cylinder in mm.

The results of split tensile strength obtained using this expression are presented in Table 4.

Shear Strength: The study of direct shear strength has been carried out using push-off specimens with dimensions of 450 x 150 x 150 mm i.e., (length x width x thickness), with shear plane length of 150 mm and area 150. The nominal steel reinforcement of 6 mm diameter bar was provided away from shear plane to prevent failure other than shear mode. Details of specimen are shown in Fig. 1. All the specimens are air dried prior to testing. All the specimens were tested under direct compression on UTM. Test results are present in Table 5.

The direct shear strength of push-off specimens was calculated by following formula,

$$\tau_s = \frac{P}{A_s} \tag{4}$$

where

τ_s = Shear Strength in direct shear, Mpa,

P= Failure load in direct shear, N,

A_s = Shear plane area in direct shear, mm^2 (150 mm x150 mm).

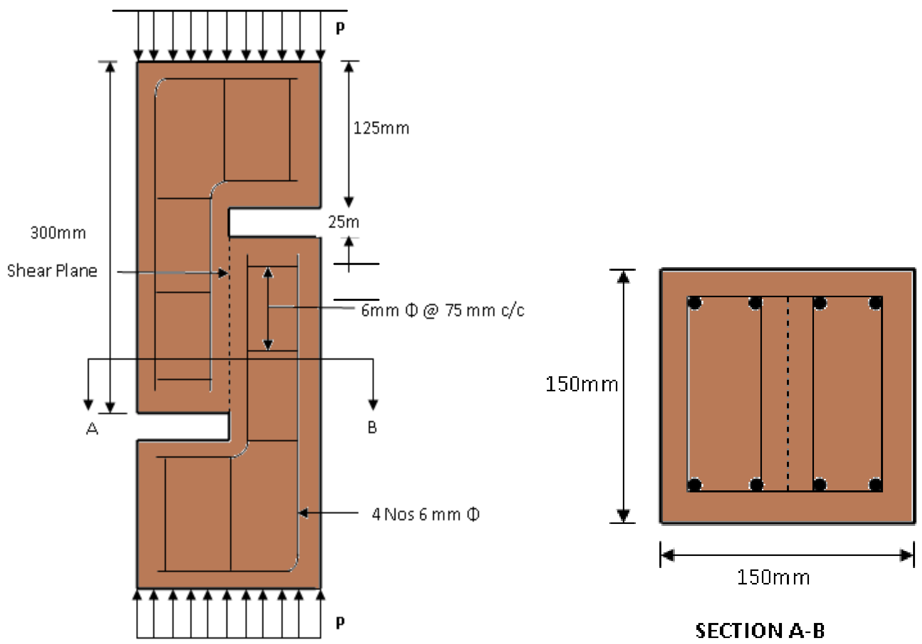


Figure 1. Reinforcement details and test set up for shear test by using push-off specimen

Toughness: Primary reason for adding fibers to concrete is to improve the energy absorbing capacity of the matrix, which can be evaluated by determining the area under the stress- strain curve or the load-deflection curve. It is used to estimate the energy absorbing capacity or toughness of the material. Increased toughness also means improved performance under fatigue, impact, and impulse loading. The toughness mechanism provides ductility. The composite's ability to undergo larger deformation before failure is often measured using a toughness index. The toughness was calculated for compression and flexure. In flexure, toughness was calculated by integrating equations of load-deflection curves. The toughness indices are presented in Tables 4 and 5.

4. DISCUSSION OF RESULTS

4.1 Workability

Workability of concrete with and without fiber and metakaolin is measured by slump cone test, compaction factor test and inverted slump cone test. Results of slump cone test and compaction factor test of normal concrete (NC) and fiber reinforced metakaolin concrete (FRMC) are as shown in Table 3.

The results from Table 3 indicate that with increase in fiber and metakaolin contents, decreases the workability. This decrease is attributed to increased percentage of metakaolin and its fineness. Since metakaolin is much more finer than cement, it increase the water demand for workable mix. Hence, for a designed w/c ratio, addition of metakaolin reduces the workability of mix. Also, addition of steel fiber reduces the workability due mechanical adhesion between fibers and matrix. It is observed that wet density of FRMC is increased and temperature is decreased with increase in fiber and metakaolin contents.

Table 3: Fresh properties of normal concrete (NC) and FRMC

Mix designation	**Wet Density (kg/m^3)**	**Temp (^0C)**	**Slump (mm)**	**Compaction factor**	**Inverted slump in sec.**
NC	2618.33	29	22	0.84	5.36
NC+2.5% SF+5%MK	2632.53	28	16	0.81	4.43
NC+5% SF+10%MK	2643.37	27.5	0	0.787	3.15
NC+7.5% SF+15%MK	2663.08	27	0	0.768	2.40
NC+10% SF+20%MK	2687.37	26	0	0.758	1.96

4.2 Compressive strength

Results of compressive strength are as shown in Table 4. The 28 days compressive strength is maximum at 2.5% steel fiber and 5% of metakaolin over the normal concrete. Hence, 2.5% steel fiber and 5% metakaolin is more suitable for improving compressive strength of structural concrete.

The typical variation of compressive stress with strain is shown in Fig. 2. The compressive toughness indices are obtained using stress-strain curves. This index can be directly obtained by mesearing the area under a stress-strain graph. It can also be obtained by integrating the equations of best fit curves of stress-strain in ascending and descending directions. In this study these indices are found out by integrating separate equations of the ascending and descending curves. The results of the compressive toughness indices are presented in Table 4. The compressive toughness indices increased continuously with increase in the fiber content. The maximum value of compressive toughness index is observed at 10% of fiber content and its maximum value is 1.6844 kNmm.

4.3 Split tensile strength

The variation of split tensile strength with respect to fiber content and metakaolin is shown in Table 4. It is observed that 28 days split tensile strength increased continuously with increase in percentage of steel fiber and metakaolin. The maximum split tensile strength is obtained at 10% of steel fiber and 20% of metakaolin. This increase in strength may be attributed to the improved properties of matrix and strong interphase bond between the fiber and the matrix as synergistic effect of fibers and metakaolin.

Table 4: Compressive strength (f_{cu}), compressive toughness index (I_T^C) and spilt tensile strength $\left(f_t \right)$ of normal concrete (NC) and FRMC

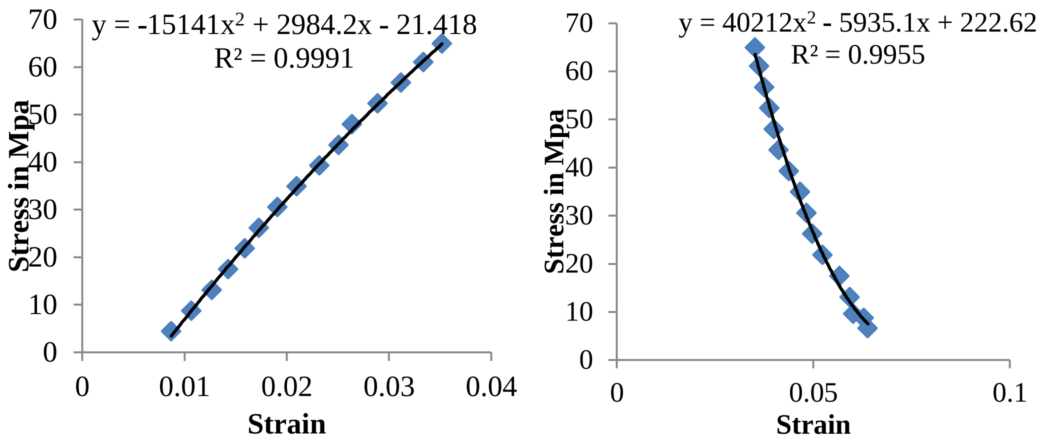
% Fiber Content	**% of MK**	f_{cu} **(MPa)**	I_T^C **(kNmm)**	f_t **(MPa)**	**% increase in Compressive Strength (f_{cu}) (MPa)**	**% increase in Compressive Indies (kNmm)**	**% increase in Split Tensile Strength (f_t) (MPa)**
0	0	67.83	1.0934	5.81	--	--	--
2.5	5	**69.65**	1.2534	7.13	2.68	14.63	22.72
5	10	66.85	1.4743	7.64	-1.44	34.84	31.50
7.5	15	65.18	1.5153	8.82	-3.91	38.59	51.80
10	20	64.29	1.6844	**9.10**	-5.22	54.05	56.60

4.4 Flexural strength

It is observed that 28 days flexural strength increased continuously up to 10% of fiber and 20% of metakaolin, as compared to normal concrete. Hence, fibers are best suitable for improving flexural strength of structural concrete. The increase in flexural load and deflections is observed with increase in fiber and metakaolin contents. This indicates the increase in ductility of concrete. It is seen that failure of beams occurred in maximum bending moment (flexural) zone i.e., the middle third zone of the beam. The typical load deflection behaviour is shown in Fig. 3. The flexural toughness indices are obtained by integrating the equations of load–deflection curves. The results of the flexural toughness index are presented in Table 5. The flexural toughness indices increased continuously with increase in the fiber and metakaolin content continuously.

Table 5: Flexural strength (f_{cr}), flexural toughness index (I_T^f), shear strength (τ_s) and maximum central deflection of NC and FRMC

% Fiber Content	**% of MK**	f_{cr} **(MPa)**	I_T^f **(kNmm)**	τ_s **(MPa)**	**Maximum central deflection, mm**	**% increase in Flexural Strength (MPa)**	**% increase in Shear strength ((MPa)**
0	0	8.688	9.70	4.30	1.2	--	--
2.5	5	9.175	11.78	5.02	1.4	5.60	16.74
5	10	11.557	27.99	5.64	2.3	33.02	31.16
7.5	15	14.288	40.07	**7.72**	2.7	64.46	79.5
10	20	**17.393**	49.12	7.09	3.1	100	64.88



Ascending branch of curve Descending branch of curve

Figure 2. Variation of compressive stress Vs strain for 10% fiber content and 20 % metakaolin (V_{fm}%)

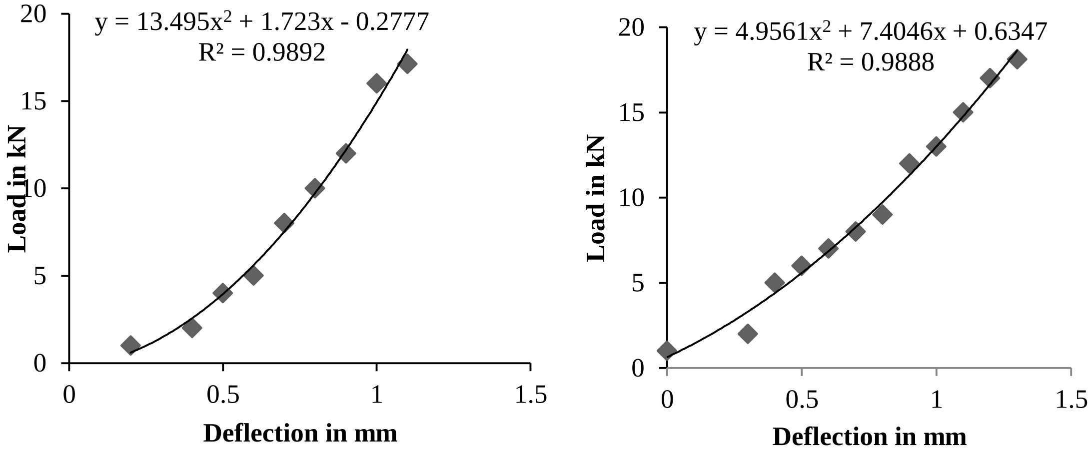


Figure 3. Variation of load Vs deflection of beam under flexure for NC and (NC + 2.5% SF + 5% MK)

4.5 Shear strength using push-off specimen

The variation of shear strength with respect to fiber content and metakaolin is shown in Table 5. It is observed that shear strength increased continuously with increase in percentage of steel fiber and metakaolin upto 7.5 % of steel fibers and 15 % of metakaolin and then decreased. The maximum shear strength under direct shear test is observed at 7.5 % of steel fibers and 15 % of metakaolin. It may be attributed to the improved properties of composite.

4.6 Optimum fiber and metakaolin (*MK*) *content*:

The optimum fiber and MK contents for various strengths of FRMC is presented in Table 6. The results from Table 6 indicate that the optimum fiber content is strength dependent.

Table 6: Optimum fiber and metakaolin content and maximum percentage increase in various strengths

Strength	**Fiber content %**	**Metakoalin Content %**	**Maximun value of strength**	**Maximum % increase in strength**
Compressive strength	2.5	5	69.65	2.68
Split tensile strength	10	20	9.10	56.60
Flexural Strength	10	20	17.391	100
Shear Strength	7.5	15	7.72	79.5

5. CONCLUSIONS

The following conclusions are drawn from the experimental investigations high strength metakaolin fiber reinforced concrete.

1. Decrease in workability and temperature of green concrete composite is observed with increase in fiber and metakaolin contents. However, wet density is found to be increased.
2. The maximum percentages of increase in compressive, flexural, split and shear strengths of the concrete composite achieved are 2.68 %, 100 %, 56.60 % and 79.50 %, respectively at 2.5 %, 10 %, 10 % and 7.5 % of fiber content over the normal concrete.
3. The toughness indices increased continuously with increase in the fiber content. The maximum value of these toughness indices is found at 10 % of fiber content.
4. Ductility of concrete composite is found to be enhanced due to synergistic influence steel fibers and the metakaolin compared to the normal concrete.

In general, the experimental investigation on the strength and toughness of high strength steel fiber reinforced metakaolin concrete exhibited the exceptionally enhanced performance due to the synergistic influence of steel fibers and the metakaolin.

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