Effect of Metakaolin on the Structural Behaviour of Normal and Steel Fibre Reinforced Concrete Beams

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***Abstract*—Cement has a severe problem of increased consumption of raw materials and energy in addition to carbon dioxide emission during its manufacture. Metakaolin is used to replace cement. It consumes lime on hydration and causes an increase in the production of cementitious compounds leading to enhanced strength. In this experimental investigation, the mechanical properties such as compressive strength, split tensile strength, flexural strength and modulus of elasticity of concrete containing various percentages of Metakaolin – 0%, 5%, 7.5%, 10% and 12.5% by weight of cement are studied. Metakaolin concrete mix with better mechanical properties is selected as the optimum metakaolin concrete mix and an optimum Metakaolin Crimped Steel Fiber Reinforced Concrete is selected among fiber fractions of 1.5%, 2% and 2.5% by volume of concrete. Using normal concrete, optimum metakoalin concrete, optimum metakaolin crimped steel fibre concrete and optimum metakaolin concrete with hooked end steel fibers in volume fraction of 1.5% are tested under flexure and shear. The various parameters studied are first crack load, load-deflection response, crack pattern, ultimate flexural and shear strength, mid span deflection and energy absorption. It is seen that significant improvement in the structural performances is achieved by the addition of Metakaolin and steel fibers in normal concrete.**

Keywords—structural behaviour; reinforced concrete beams; mechanical properties; crimped steel fibre; hooked end steel fibre; metakaolin

I. INTRODUCTION

Concrete is a commonly used construction material worldwide due to the availability of raw materials, excellent strength and durability, ability of moulding into various shapes and low manufacturing and maintenance cost. When combined with steel reinforcements it can have unlimited structural applications. But *'cement'* the vital component of concrete posses a severe problem of increased consumption of raw materials and high emission of carbon dioxide during its manufacture. This leads to environmental hazards and increased consumption of energy during its manufacture. Due to the above mentioned reasons, there has been a need of developing concrete with reduced cement consumption combined with enhancement in strength by the addition of suitable admixtures. Some of the commonly used admixtures include fly ash, silica fume, metakaolin, ground granulated blast furnace slag, iron blast furnace slag, rice husk ash etc.,. Since these materials are naturally occurring, industrial wastes or by products from industries they are easily available and require less manufacturing effort[1].

There are many reasons in the long term, to extend the practice of partially replacing cement with wastes, by products and processed materials possessing pozzolanic properties. One such possible source of a pozzolan is calcined clay. Natural pozzolans in the form of calcined earths, blended with lime have been used to produce cementitious materials for thousands of years. The utilization of calcined clay in the form of Metakaolin (MK) as a pozzolanic additive in mortar and concrete has received considerable interest in recent years. Much of this interest has been focused on the removal of Calcium Hydrate (CH), which is produced by the hydration of cement and is associated with poor durability[2]. Reduction of CH makes the concrete and mortars more resistive to sulphate attack and reduces the effect of alkali - silica reaction[3]. This provides enhanced strength which is derived from the additional cementitious phases generated by the reaction of CH with MK[4-5].

In the past, attempts have made to impart improvement in tensile properties of concrete members by using conventional reinforcing steel bars and pre-stressing techniques. Although both these methods provided improvement in tensile strength of the concrete members, there is no increase in the inherent tensile strength of concrete. Therefore the concept of steel fibre reinforcement is to overcome this drawback by using the deformations of the matrix under stress to transfer load to the fibre. The addition of steel fibres to concrete makes it more homogeneous and isotropic and transforms it from a brittle material to a more ductile material. When concrete cracks, the random propagation improves the strength and ductility.

MK is a supplementary cementitious material derived from the heat treatment of natural deposits of kaolin by the process of calcination under a temperature of 650^0C - 800^0C. The finely divided siliceous aluminous materials within MK when combined with water, will react chemically with calcium hydroxide $Ca(OH)_2$ to form compounds that possess cementitious properties, thus reducing the production of $Ca(OH)_2$[6]. Typically MK show high pozzolanic reactivity due to their amorphous structure and high surface area[7].

Calcium hydrate or lime does not contribute any strength to concrete. By the addition of MK in concrete, the lime produced due to the pozzolanic reaction between MK and CH get reduced. As the percentage replacement of cement by MK is increased, the workability is greatly decreased. Hence super plasticizers are added in metakaolin concrete to obtain more workable concrete mixes. As the percentage replacement increases, the addition of super plasticizer also increases due to the higher surface area of MK in comparison with cement. Another reason is due to the Vander Waals in which cement particle agglomeration and electro static attraction between cement and pozzolanic particles becomes dominant due to the increase in wet surface area. In the presence of super plasticizer the surface of cement particles repel each other due to the dispersion of agglomerated cement particles and remain separated, thereby increasing the workability[8].

MK is a very effective pozzolan that results in enhanced early strength with significant contribution to the long-term strength. An optimum addition of MK modifies the pore structure in cement paste, mortar and concrete, thereby making degradation of the concrete mix. Hence MK added in an optimum percentage as partial replacement of cement results in

- lowering the heat of hydration and thermal shrinkage
- increasing water tightness
- reducing the alkali-aggregate reaction
- improving the chemical resistance
- improving the early strength, workability and extensibility.

Even though MK is more expensive than Portland Cement, moderately low temperatures are required for its processing. Therefore its overall production cost is significantly less than that of Portland Cement. Thus partial replacement of cement with MK contributes to the protection of environment and leads to a sustainable construction.

Due to loading, the micro cracks present in concrete propagate and open up leading to the effect of stress concentration and formation of additional cracks in regions where there are minor defects[9]. The development of such minor cracks is the main cause of inelastic deformation of concrete. It is seen that the addition of small, closely spaced and uniformly dispersed discrete steel fibres to concrete will make a substantial improvement in its strength, stiffness, and also its static as well as dynamic properties[10]. This type of concrete is broadly known as Steel Fibre Reinforced Concrete (SFRC).

Steel fibre is a small piece of reinforcing material possessing certain characteristic properties. Generally they are circular or rectangular in cross section. The fibres are designated by its volume fraction and aspect ratio. Volume fraction represents the volume of fibres used per cubic meter of concrete. The aspect ratio of the fibre is the ratio of length of the fibre to its diameter. Typical aspect ratio of steel fibres ranges from 30 to 150 for lengths of 1mm to 76mm[11].

The different types of steel fibres commonly used are

- Straight fibres
- Crimped fibres
- Hooked-end fibres
- Paddled fibres
- Irregular fibres

The static and dynamic strength can be improved if the fibres are strong, stiff and loaded to fracture, provided there is a minimum fibre volume fraction. The high strength and high modulus steel fibres produce strong composites, their high modulus impart strength, stiffness and dynamic properties to the composite[12-13].

Crimped and Hooked End Steel Fibres are cold drawn wire fibres which provide optimum performance in the concrete mix specially designed for the reinforced concrete, mortars and other cementitious mixes. These fibres arrest cracks by the pinching action at the end of cracks, thus delaying crack propagation in concrete.

SFRC has the following benefits.

- Increases crack resistance, ductility, energy absorption and toughness of concrete.
- Improves impact resistance, fatigue endurance, durability and shear strength of concrete.
- High tensile strength fibres provide a bridge between joints and cracks
  resulting in tighter aggregate interlocking and increased load carrying capacity.
- Provides increased ultimate load bearing capacity which allow possible reduction of concrete section.

The properties of SFRC are greatly influenced by the

- Geometry of fibres
- Aspect ratio (AR) of fibres
- Volume fraction (V_f) of fibres
- Yield strength of fibre reinforcement
- Fibre orientation
- Bond between fibre and matrix

From the previous research works it is seen that fibrous concrete can increase the ultimate strain in concrete. Steel Fibre Reinforced Concrete applications include airport runways, taxiways, maintenance hangers, access roads, work-shops, parking lots and play grounds. It is also suitable for tunnel linings, shotcreting of tunnel, shotcreting of underground storage for cavern, ground supported slabs, joint less floors, external roads and pavements, precast concrete production, under water concrete construction, piles, pillars etc[15-17].

SCOPE AND OBJECTIVES

In order to prevent the risk of environmental hazards caused during cement manufacture and to preserve the raw materials for future generations and at the same time due to the availability of supplementary cementitious materials such as Metakaolin which is an engineered material, an attempt has been made to study the structural performance of metakaolin steel fibre reinforced concrete beams.

Lot of research works have been carried out to determine the fresh and hardened properties of normal Concrete (CC) and Steel Fibre Reinforced Concrete (SFRC) with mineral admixtures such as fly ash, silica fume etc as cement replacing materials. But few literatures are available on Metakaolin as cement replacing materials in steel fibre reinforced concrete. Few literatures are available on the strength and structural behaviour of reinforced concrete beams strengthened using metakaolin, crimped and hooked end steel fibres.

The objectives of the present study include

- To determine an optimum percentage of MK for the partial replacement of cement in normal concrete of grade M20.
- To estimate an optimum percentage of MK and crimped steel fibre (CSF) combination.
- To study the enhancement in structural performances of metakaolin steel fibre reinforced concrete beams over normal reinforced concrete beams under flexure and shear.
- To compare the results obtained.

II. EXPERIMENTAL INVESTIGATION

A. Materials Used

The various materials used for the experimental study and their properties are given. Cement :- Ordinary Portland Cement of grade 53 conforms to IS:12262-1987, Specific gravity : 3.15, Standard consistency : 32%, Initial and final setting time : 120 and 320minutes, fineness : 7.12%. Fine aggregate :– M-Sand conforms to Zone I of IS:383-1970, specific gravity : 2.52, bulk density : 1.597g/cm3, water absorption : 1%, fineness modulus : 5.431, Coarse aggregate :- Crushed angular aggregates conforms to Table 2 of IS:383-1970, specific gravity : 2.87, bulk density : 1.45g/cm3, water absorption : 1.2%, fineness modulus : 9.746. The ultimate tensile strengths and bulk densities of crimped and hooked end steel fibres are 1100 MPa, 1000 MPa, 7.85 gm/cm3 and 8.50 gm/cm3 respectively.

MK and steel fibres are collected from English India Clay Limited, Veli, Thiruvanathapuram and Jeetmull Jaichandlall Madras Private Limited, Chennai respectively. They are shown in *Fig. 1*, *Fig. 2* and *Fig. 3*. The physical properties and chemical composition of MK are given in Table 1 and Table 2 respectively.

Fig. 1 Metakaolin

Fig 2 Crimped steel fibre

Fig. 3 Hooked end steel fibre

TABLE I. PHYSICAL PROPERTIES OF METAKAOLIN (HIMACEM)

Particulars	Values
Physical form	Off white powder
Pozzolanic Reactivity mg Ca(OH)2/gm	1000
+300 mesh w/w % (Max)	3
-2 micron w/w % (Min)	50
Moisture w/w % (Max)	0.5-1.0
BET surface area (m2/g)	19-20
Metakaolin content (% Min)	97
pH (10% solids)	4.5-5.5
Specific gravity	2.6
Bulk density (kg/lit)	0.4-0.5

TABLE II. CHEMICAL COMPOSITION OF METAKAOLIN (HIMACEM)

Composition	% by weight
SiO_2	52
Al_2O_3	46
Fe_2O_3	0.6
TiO_2	0.65
CaO	0.09
MgO	0.03
K_2O	0.03
Na_2O	0.1
LOI	1

B. Nomenclature & Mix Proportioning

The designation of concrete mixes for different MK contents and steel fibre fractions, tested for mechanical and structural behaviour are given in Table III, Table IV, Table V and Table VI respectively. The mix design is based on IS:10269-2009. A concrete of grade M20 using OPC is developed for a water-binder ratio of 0.55. For various percentage replacement of cement by MK i.e, 5%, 7.5%, 10% and 12.5% by weight of cement, the slump is maintained to be in the range of 100-150mm by adding SP in various dosages. CSF in volume fractions 1.5%, 2.0% and 2.5% by volume of concrete are added to the optimum metakaolin concrete mix (MKC). A concrete mix using Hooked End Steel Fibres (HESF) in volume fraction as obtained for CSF is also developed and is designated as MKHSFRC. The mix proportioning for concrete mixes for various MK contents and steel fibres are given in Table VII.

TABLE III. DESIGNATION OF CONCRETE MIXES FOR VARIOUS REPLACEMENT PERCENTAGES OF CEMENT BY MK

% of MK replacing cement	0	5	7.5	10	12.5
Designation of mix	CC	MKC 5	MKC 7.5	MKC 10	MKC 12.5

TABLE IV. DESIGNATION OF OPTIMUM METAKAOLIN CONCRETE MIX FOR DIFFERENT STEEL FIBRE FRACTIONS

Volume fraction of fibre (%)	1.5	2	2.5
Designation of mix	MKCSFRC 1	MKCSFRC 2	MKCSFRC 3

TABLE V. DESIGNATION OF BEAM SPECIMENS IN FLEXURE

	Designation			
	CB-F	*MKB-F*	*MKCSFB-F*	*MKHSFB-F*
Beams in flexure	Control beam	RC beam with optimum MK	RC beam with optimum MK and crimped Steel fibre combination	RC beam with optimum MK and hooked end steel fibre

TABLE VI. DESIGNATION OF BEAM SPECIMENS IN SHEAR

	Designation			
	CB-S	*MKB-S*	*MKCSFB-S*	*MKHSFB-S*
Beams in shear	Control beam	RC beam with optimum MK	RC beam with optimum MK and crimped steel fibre combination	RC beam with optimum MK and hooked end steel fibre

TABLE VII. MATERIALS REQUIRED FOR CONCRETE MIXES FOR VARIOUS REPLACEMENT PERCENETAGES OF CEMENT BY MK

% of MK	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (liters/m^3)	SP (kg/m^3)
0	320	723.240	1185.310	218.61	-
5	304	722.200	1183.610	218.58	-
7.5	296	720.140	1189.670	218.56	-
10	288	720.140	1180.230	218.52	2.4
12.5	280	719.107	1178.536	218.51	3.2

C. Specimen Details

The details of concrete specimens tested for mechanical properties are given in Table VIII. In case of beams, they are cast in flexure and shear using normal concrete, MKC, MKCSFRC and MKHSFRC with volume fraction of HESF same as that of optimum percentage of CSF.

TABLE VIII. DETAILS OF SPECIMENS TESTED FOR MECHANICAL PROPERTIES

Standard tests	Cube compressive strength	Split tensile strength	Flexural strength	Modulus of elasticity
Specimen	***Cubes***	***Cylinders***	***Prisms***	***Cylinders***
Size	150mm x 150mm x 150mm	150mm diameter x 300mm	100mm x 100mm x 500mm	150mm diameter x 300mm height

D. Preparation of beams

Wooden moulds of size 150mm x 200mm x 1000mm are used for preparing the beams. Reinforcement cages for beams in flexure and shear are shown in *Fig. 4* and *Fig. 5* respectively. Beam specimens are cast in flexure and shear as shown in *Fig. 6* and *Fig. 7.*

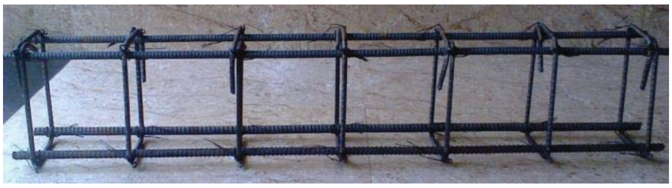

Fig. 4 Reinforcement cage - beams in flexure

Fig. 5 Reinforcement cage - beams in shear

Fig. 6 Casting of beams – Flexure

Fig. 7 Casting of beams - Shear

III. TESTING

All the concrete specimens with various metakaolin and crimped steel fibre contents are tested for mechanical properties as per standard IS methods. Beams are tested under third point loading as shown in *Fig. 8.*

Fig. 8 Test set up of beams in Universal Compression Testing Machine(UTM)

IV. RESULTS AND DISCUSSIONS

A. *Fresh Properties*

The workability for each mixes in terms of slump is tested and the details are given in Table VIII.

TABLE VIII. SLUMP AND SP REQUIREMENT FOR VARIOUS CONCRTE MIXES

Mix	Slump (mm)	SP (%)
CC	150	-
MKC 5	135	-
MKC 7.5	120	-
MKC 10	110	0.75
MKC 12.5	105	1
MKCSFRC 1	108	3
MKCSFRC 2	106	5
MKCSFRC3	103	7

It is seen that as replacement percentage of cement by MK increases the slump decreases and the requirement of SP increases. This is due to the increased surface area of MK by which it absorbs more SP to maintain the required workability. Another reason is that the Vander Walls Effects, in which cement particle agglomeration and electrostatic attraction between cement and pozzolanic particles becomes dominant due to the increase in wet surface area. In the presence of dispersant such as super plasticizer, the surface of cement particles repel each other due to the dispersion of agglomerated cement particles and remain separated, thereby increasing the workability.

In steel fibre reinforced concrete mixes also, the dosage of SP increases as the volume fraction of fibre increases. The reason for the reduction of slump in metakaolin steel fibre reinforced concrete is that, when steel fibres are added it creates a network structure in concrete which restrain the flow of concrete[18-19].

Another reason is that, due to the increased surface area of steel fibres, it absorb more cement paste to wrap around it thus reducing the slump and increasing viscosity. Hence the requirement of SP for MKC with steel fibre fractions varying from 1.5% to 2.5% tend to increase. Thus more SP is required for maintaining the required workability (slump) for steel fibre reinforced concrete mixes.

B. *Mechanical Properties*

The mechanical properties of various concrete mixes are given in Table. IX. For cement replacement by MK, 10% replacement level is found as optimum since it exhibits better mechanical properties. The decrease in mechanical properties after this percentage is due to the poor dilution effect due to which the width of the interfacial zone between cement paste and aggregate become higher.

The percentage increase in compressive strength, split tensile strength, flexural strength and modulus of elasticity of MKC from normal concrete are 22.19%, 24.13 %, 34.72% and 17.57% respectively.

TABLE IX. MECHANICAL PROPERTIES OF DIFFERENT CONCRETE MIXES

Mix	Compressive strength (MPa)	Split tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity ($x10^4$MPa)
CC	26.22	1.98	4.7	2.2
MKC 5	31.55	2.18	6	2.39
MKC 7.5	31.77	2.4	6.12	2.45
MKC 10	33.7	2.61	7.2	2.669
MKC 12.5	30.22	2.12	7	2.3
MKCSFRC 1	40	3.53	8	2.8
MKCSFRC 2	32.33	2.63	7	2.15
MKCSFRC 3	31	2.6	6.9	2.1

At 10% MK and 1.5% volume fraction of CSF, maximum mechanical properties are achieved. This is because there is a maximum quantity of fibre which can be added into the concrete without causing balling and interlocking of fibres[20]. Here the maximum fibre fraction is 1.5 % at which increased strength is achieved due to the ductile nature of CSF.

The percentage increase in compressive strength, split tensile strength, flexural strength and modulus of elasticity of MKCSFRC from normal concrete are 34.45%, 42.22%, 41.25% and 21.42% respectively.

C. *Flexural Behaviour*

The structural behaviour of reinforced concrete beams in flexure are given in Table X.

TABLE X. ULTIMATE LOAD IN FLEXURE

Beam Specimen	First crack load (kN)	Flexural strength (kN)	Maximum mid span deflection (mm)		Energy absorbed (N-m)
			At yield load	*At ultimate load*	
CB-F	5	85	1.49	5.8	260
MKB-F	21	107	1.6	10.14	960
MKCSFB-F	25	120	1.9	11.5	1030
MKHSFB-F	22.5	110	1.75	10	972

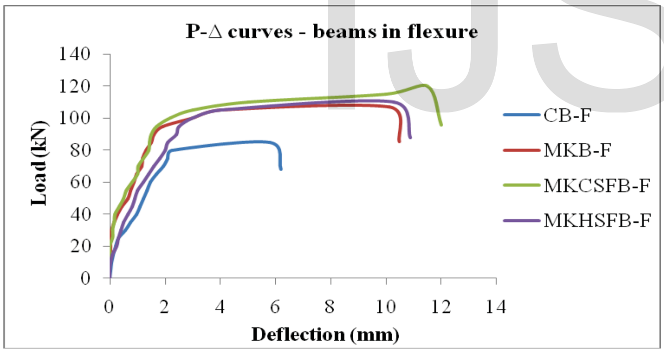

Fig. 9 Load deflection curves for beams in flexure

Fig. 10 Crack pattern of CB-F

Fig. 11 Crack pattern of MKHB-F

Fig. 12 Crack pattern of MKCSFB-F

Fig. 13 Crack pattern of MKHSFB-F

The load deflection curves and crack patterns for beams in flexure are shown in *Fig. 9, Fig. 10, Fig. 11, Fig. 12* and *Fig. 13.*

It is observed that better load carrying capacity is exhibited by beams strengthened with MK. The beams strengthened with MK and CSF have the greatest load carrying capacity with finer number of cracks. The performance of metakaolin hooked end steel fibre beams is slightly lesser than that of crimped steel fibre reinforced concrete beams with same volume fraction. This is due to the better bond strength and anchorage of CSF as compared to HESF[21-22].

D. *Shear Behaviour*

The structural behaviour of reinforced concrete beams in shear are given in Table XI.

The load deflection curves and crack patterns for beams in shear are shown in *Fig. 14, Fig. 15, Fig. 16, Fig. 17* and *Fig. 18.* Here also beams strengthened with MK exhibit greater load carrying capacity than CB-S. This is due to the strength contributed by metakaolin concrete as a result of the pozzolanic reaction. Here again metakaolin crimped steel fibre concrete beam show greater structural performance[23-25]. Metakaolin hooked end steel fibre reinforced concrete beam performed lesser than that with CSF.

TABLE XI. ULTIMATE LOAD IN SHEAR

Beam Specimen	Initial crack load (kN)	Shear Strength (kN)	MAXIMUM MID SPAN DEFLECTION (MM)		Energy absorbed (N-m)
			At yield load	*At ultimate load*	
CB-S	5	80	1.4	3.5	250
MKB-S	10	95	1.6	7.5	610
MKCSFB-S	17	119	2.3	9	880
MKHSFB-S	15	105	2.5	8	805

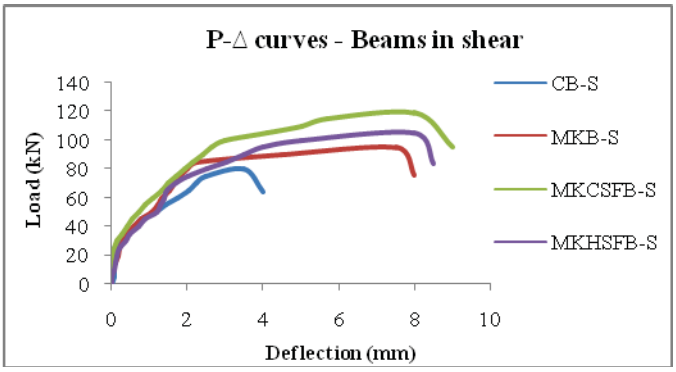

FIG. 14 LOAD DEFLECTION CURVES – BEAMS IN SHEAR

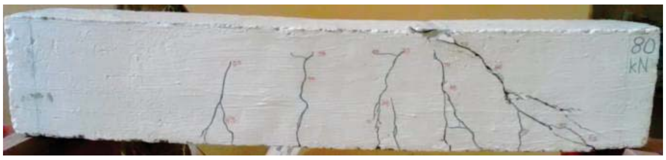

Fig. 15 Crack pattern of CB-S

Fig. 16 Crack pattern of MKB-S

Fig. 17 Crack pattern of MKCSFB-S

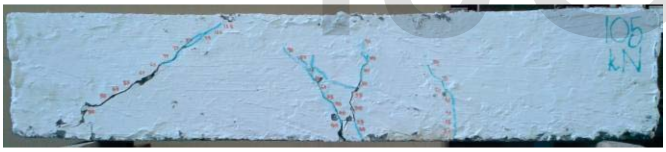

Fig. 18 Crack pattern of MKHSFB-S

V. CONCLUSIONS

[1] As the replacement percentage of MK increases, the dosage of SP also increases, due to the higher surface area of MK.

[2] The mechanical properties of concrete mixes with various replacement percentages of cement by MK increase when the percentage of MK is varied from 0% to 10%. Beyond 10% replacement all the mechanical properties have a decreasing trend. This is due to the poor dilution effect of MKC after this percentage of MK. As a result the difference between the mechanical properties of CC and MKC become smaller. Therefore the optimum replacement percentage of MK selected is 10.

[3] A concrete mix with 10% MK and 1.5% CSF exhibits greater mechanical properties and is selected as the optimum percentage combination of MK and CSF. This is because, for a given mix of specific proportions and w/c ratio, there is a maximum quantity of fibre which can be introduced into the concrete without causing balling and interlocking of the fibres. Beyond 1.5% volume fraction of fibre, the strength decreases due to balling of fibres. Therefore the presence of MK in addition to CSF results in greater strength

[4] The percentage increase in first crack load for beams strengthened with 10% MK and 1.5% CSF in flexure and shear are 80% and 70% greater than that of corresponding control beams, because of the excellent tensile and bond strength of CSF.

[5] The load deflection pattern of metakaolin crimped steel fibre reinforced concrete beams show greater load carrying capacity and deflection than that of control specimens in flexure and shear due to the effective bridging action of CSF.

[6] More number of finer cracks with slightly greater load carrying capacities are observed for beams incorporating optimum metakaolin crimped steel fibre combination than that with HESF under flexure and shear.

[7] The ultimate flexural and shear strengths of metakaolin crimped steel fibre reinforced concrete beams are 29% and 32% greater than control beams.

[8] The reinforced concrete beams using 10% MK and 1.5% CSF have higher energy absorption and ductility than that of HESF of same volume fraction in flexure and shear. This is due to the better anchorage of CSF with concrete matrix.

[9] Reinforced concrete beams strengthened with MK and CSF provided better structural performance in terms of first rack load, load deflection response, ultimate load carrying capacity, mid span deflection, energy absorption and ductility index. Beams in shear also followed the same trend.

SCOPE FOR FUTURE STUDIES

- The same work can be carried out in other grades of concrete with mineral additives like silica fume, fly ash, rice husk ash separately or by its combination.
- This work can be extended to concrete having fibres such as glass fibres, poly propylene fibres, coconut fibres etc.

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