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Interface Behavior between Normal Concrete and Fibre Reinforced High Performance Concrete

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Abstract
The development of an effective and durable repair system is essential due to the early and premature deterioration of reinforced concrete structures.High-performance concrete (HPC) exceeds the properties and constructability of normal concrete.Optimum percentage of metakaolin, ALCCOFINE 1203 and steel fibres are incorporated in the design mix to obtain the desired fibre reinforced high performance concrete.Mechanical and durability properties of the concrete were tested.The interfacial bond characteristics were assessed on the interface between normal concrete and fibre reinforced high performance concrete by conducting the slant shear test and splitting tensile strength.The use of fibre reinforced high performance concrete to provide an effective and durable concrete repair to normal concrete is studied.

1. Introduction
With the development of modern civil engineering structures, the need to develop higher performance construction materials with high strength, toughness, energy absorption, durability and so on have come into being.High performance concrete is a specialized series of concretes designed to provide several benefits in the construction of concrete structures.HPC exceeds the properties and constructability of normal concrete.Fibre reinforced concrete is a composite material made with Portland cement, aggregate, and incorporating discrete discontinuous fibres.Steel fibre reinforced high performance concrete is increasingly developing and making remarkable progress during recent years.It is an important high performance concrete, especially used in the repair work for highways, pavements, bridge decks etc.

The early and premature deterioration of reinforced concrete structures is a serious issue for many nations and the concrete repairs provided lack both early age performance and long-term durability.Therefore it is essential to develop an effective and durable repair system.In the field of retrofitting and strengthening of concrete structures, the need to place repair material next to old concrete often arise.A good, efficient and durable bonding is one of the main requirement for effective and successful repair.

The main objective of the study is to determine the optimum design mix for M100 grade concrete containing metakaolin, ALCCOFINE 1203 and steel fibres.The durability properties of this M100 grade concrete are studied.Also the interfacial bond characteristics between normal concrete and fibre reinforced high performance concrete are evaluated.In order to assess the bond characteristics, slant shear test and splitting tensile test is conducted.

2. Materials Used
Grade-53 Ordinary Portland Cement conforming to IS specifications was used in this study.Fine aggregate belong to ZONE II category.Nominal size of coarse aggregate used is 12mm.Water-cement ratio of 0.25 was used.Metakaolin and ALCCOFINE 1203 are the two mineral admixtures used in the design mix.The properties of metakaolin and ALCCOFINE 1203 are given in Table 1 and Table 2 respectively.The super plasticizer used is Master Glenium Sky 8233 and the properties are given in Table 3.Flat crimped steel fibres of 10mm length are also used in the mix (Fig 1).The specification of flat crimped steel fibre is given in Table 4.

TABLE 1.Properties of Metakaolin

CHEMICAL COMPOSITION (%)	
SiO_2	52.1
Al_2O_3	42.8
Fe_2O_3	1.6
CaO	0.2
MgO	0.21
SO_3	0.00
K_2O	0.32
Na^2O	0.11
PHYSICAL PROPERTIES	
Specific surface (m^2/g)	2.54
Specific gravity	2.6

TABLE 2.Properties of ALCCOFINE 1203

Fineness (cm^2/gm)	**Specific Gravity**	**Bulk Density (kg/m^3)**	**PARTICLE SIZE DISTRIBUTION**		
			d10	d50	d90
>12000	2.9	700-900	1.5 micron	5 micron	9 micron
CHEMICAL PROPERTIES					
CaO	SO_3	SiO_2	Al_2O_3	Fe_2O_3	MgO
61-64%	2-2.4%	21-23%	5-5.6%	3.8-4.4%	0.8-1.4%

TABLE 3.Properties of Master Glenium Sky8233

PROPERTY	VALUE
Aspect	Light brown liquid
Ph	>=6
Relative density	1.08±0.01 at 25^0 c
Chloride ion content	<0.2%

TABLE 4.Specification of flat crimped steel fibre

PROPERTY	SPECIFICATION
Length of Fibre (l)	10mm
Aspect ratio	45
Diameter (d)	0.6 – 0.8mm
Width (w)	2mm-2.5mm
Tensile Strength	600 MPa
Appearance and Form	Clear, bright and undulated along the length
Material Type	Low Carbon Drawn Flat Wire

Fig 1.Flat Crimped steel fibre

3. Optimum Mix

3.1 Optimum Percentage Replacement of ALCCOFINE 1203

The high performance concrete used in the experimental program is of grade M100 and it was designed according to ACI 211.4R [17].Compression test is performed on cubical specimens of size 150 X 150 X 150 mm to determine the optimum design mix for M100 grade concrete.The replacement level of metakaolin is fixed as 5% and the ALCCOFINE 1203 replacement level is varied from 4% to 12% at 2% interval.The specimen corresponding to maximum compressive strength is chosen as the optimum design mix.The mix proportions for high performance concrete are given in Table 5.

TABLE 5.Mix design of M100

CONTENTS	VOLUME FOR 1m^3	QUANTITY (kg/m^3)
Cement	0.174	550
Coarse aggregate		1100
Fine aggregate	0.6856	672
Chemical admixture	0.00288	3.3
Water	0.1375	137.5
Water –cement ratio	0.25	
Mineral Admixture		
1. Metakaolin	5% replacement of cement	
2. ALCCOFINE 1203	Varied from 4% to 12% replacement of cement	

The 7 day and 28 day compressive strength of the specimens with various percentage levels of ALCCOFINE 1203 are given in Table 6 and Fig 2 shows the variation in compressive strength for different replacements of ALCCOFINE 1203.

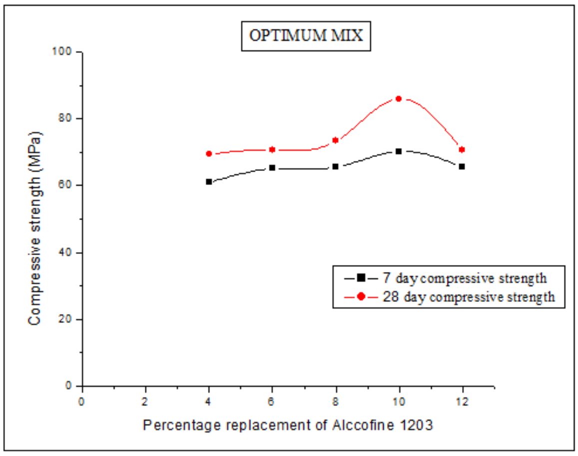

Fig 2.Compressive strength for various percentage replacement of ALCCOFINE 1203

Maximum value of 7 day compressive strength is found to be 70.22 MPa and maximum value of 28 day compressive strength is found to be 85.92 MPa.The maximum values of compressive strength are obtained for the mix containing 10% of ALCCOFINE 1203.Therefore, the optimum design mix of M100 grade concrete contains 5% replacement of Metakaolin and 10% replacement of ALCCOFINE 1203.

3.2 Optimum Percentage of Steel Fibres

In order to obtain the optimum design mix, the concrete mix is impregnated with different percentages of steel fibres.28 days compressive strength of the samples with 0.1%, 0.3%, 0.4%, 0.7% and 1% fibre variations are determined.Table 7 shows compressive strength for different percentage of steel fibre.The effect of fibre variation on compressive strength of concrete is shown on Fig 3.The percentage of steel fibre corresponding to maximum compressive strength is adopted in the design mix.

TABLE 7.Compressive strength for different percentage of steel fibre.

FIBRE VARIATION	28 DAYS COMPRESSIVE STRENGTH (MPa)
0.1 %	45.93
0.3 %	70.37
0.4 %	65.26
0.7 %	53.60
1 %	56.10

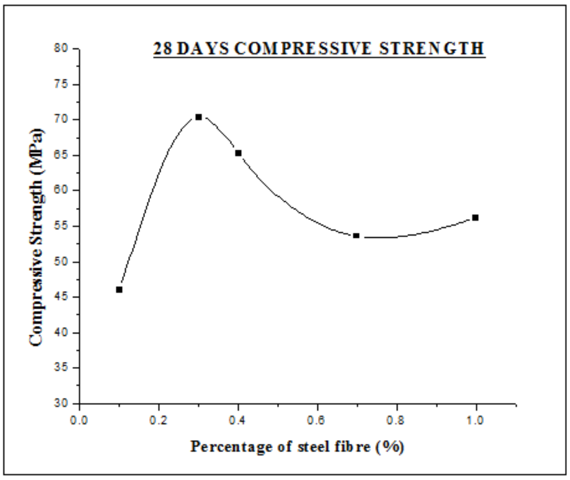

Fig 3.Effect of fibre variation on compressive strength

From Table 7, the maximum value of 28 days compressive strength is obtained to be 70.37MPa for mix containing 0.3% steel fibre.Therefore the optimum percentage of steel fibre adopted in the design mix is 0.3%.

TABLE 6.Compressive Strength for various percentage replacements of ALCCOFINE 1203

SPECIMEN	SAMPLE	7 DAYS			28 DAYS		
		LOAD (kN)	COMPRESSIVE STRENGTH (MPa)	AVERAGE	LOAD (kN)	COMPRESSIVE STRENGTH (MPa)	AVERAGE
E4 (4% ALCCOFINE 1203)	1	1450	64.44	60.89	1570	69.77	69.48
	2	1310	58.22		1530	68.00	
	3	1350	60.00		1590	70.67	
E6 (6% ALCCOFINE 1203)	1	1460	64.88	65.03	1580	70.22	70.67
	2	1540	68.44		1590	70.67	
	3	1390	61.78		1600	71.11	
E8 (8% ALCCOFINE 1203)	1	1550	68.88	66.07	1620	72.00	73.33
	2	1470	65.33		1660	73.77	
	3	1440	64.00		1670	74.22	
E10 (10% ALCCOFINE 1203)	1	1590	70.67	70.22	1930	85.77	85.92
	2	1570	69.78		1980	88.00	
	3	1580	70.22		1890	84.00	
E12 (12% ALCCOFINE 1203)	1	1460	64.88	65.48	1580	70.22	70.67
	2	1510	67.11		1670	74.22	
	3	1450	64.44		1520	67.56	

4. Mechanical Property of HPC

4.1 Compressive Strength

To study the influence of Metakaolin, ALCCOFINE 1203 and steel fibres on M100, compressive test was performed on cubical specimens of size 150 X 150 X 150 mm.The mix contains 5% replacement of Metakaolin, 10% replacement of ALCCOFINE 1203 and 0.3% of flat crimped steel fibres.The test was conducted according to IS 516 (1989) [11].The compressive test results of the samples on 7, 28 and 90 days are summarized in Table 8.

TABLE 8.Compressive strength

SPECIMEN	SAMPLE	WEIGHT (kg)	LOAD (kN)	COMPRESSIVE STRENGTH (MPa)	AVERAGE COMPRESSIVE STRENGTH (MPa)
ES-7 DAYS	1	8.288	1885.50	83.8	84.930
	2	8.310	1993.50	88.6	
	3	8.205	1854.00	82.4	
ES-28 DAYS	1	8.420	2349.00	104.4	101.867
	2	8.350	2281.50	101.4	
	3	8.295	2245.50	99.8	
ES-90 DAYS	1	8.302	2448.00	108.8	109.267
	2	8.321	2411.00	111.6	
	3	8.325	2416.50	107.4	

4.2 Discussions

The 28 day compressive strength of M100 concrete containing 5% Metakaolin, 10% ALCCOFINE and 0.3% steel fibre is obtained as 101.867 MPa which is found to attain the target strength of 100MPa.

5. Durability Properties of HPC

5.1 Water Absorption

The water absorption test was conducted on concrete cubes of size 150 x 150 x 150 mm.The water absorption test was carried according to ASTM C 642 [13].Three specimens each were tested at the ages 28, 56 and 90 days and the average values are reported in Table 9.

5.2 Chloride Ion Penetration

Cube specimens of size 150 x 150 x 150 mm were cast and the effect of sea water was tested after a period of 28, 56 and 90 days.The test is conducted according to the specifications in ACI 201.2 [14].The test results are summarized in Table 10.

5.3 Sulphate Attack

To study the effect of sulphate solution on the durability of concrete, cube specimens of size 150 x 150 x 150 mm were cast.Compressive strength of the specimens are determined after 28, 56 and 90 days of immersion in magnesium sulphate solution with concentration of 50000 ppm.The test is conducted according to the specifications in ASTM-C-452 and ASTM-C-1012 ([15], [16]).The test results are summarized in Table 11.

TABLE 9.Water Absorption

SPECIMEN	SAMPLE	WET WEIGHT W_1 (kg)	OVEN DRY WEIGHT W_2 (kg)	WATER ABSORPTION (%)= (W_1-W_2) *100/W_2	AVERAGE WATER ABSORPTION (%)
WA 28 DAYS	1	8.209	8.05	1.975	1.783
	2	8.244	8.12	1.527	
	3	8.250	8.10	1.847	
WA 56 DAYS	1	8.234	8.055	2.222	1.964
	2	8.327	8.196	1.598	
	3	8.273	8.105	2.073	
WA 90 DAYS	1	8.347	8.144	2.492	2.057
	2	8.205	8.057	1.836	
	3	8.284	8.134	1.844	

TABLE 10.Chloride ion penetration

SPECIMEN	SAMPLE	WEIGHT (kg)	LOAD (kN)	RESIDUAL COMPRESSIVE STRENGTH (MPa)	AVERAGE RESIDUAL COMPRESSIVE STRENGTH (MPa)
ES-SA 28 DAYS	1	8.352	2200.50	97.8	86.53
	2	8.377	2232.00	99.2	
	3	8.250	2151.00	95.6	
ES-SA 56 DAYS	1	8.302	2178.00	96.8	85.67
	2	8.229	2106.00	93.6	
	3	8.214	2142.00	95.2	
ES-SA 90 DAYS	1	8.256	2119.50	94.2	92.86
	2	8.219	2061.00	91.6	
	3	8.250	2088.00	92.8	

TABLE 11.Sulphate Attack

SPECIMEN	SAMPLE	WEIGHT (kg)	LOAD (kN)	RESIDUAL COMPRESSIVE STRENGTH (MPa)	AVERAGE RESIDUAL COMPRESSIVE STRENGTH (MPa)
ES-SA 28 DAYS	1	8.385	2173.50	96.6	96.73
	2	8.335	2155.50	95.8	
	3	8.355	2200.50	97.8	
ES-SA 56 DAYS	1	8.294	2133.00	94.8	94.86
	2	8.365	2151.00	95.6	
	3	8.255	2119.50	94.2	
ES-SA 90 DAYS	1	8.224	2020.50	89.8	91.20
	2	8.265	2052.00	91.2	
	3	8.301	2083.50	92.6	

5.4 Discussions

1) The percentage of water absorption for the samples are obtained as 1.783%, 1.964% and 2.057% for 28days, 56days and 90 days of immersion in water respectively.The water absorption values obtained is less than 5% and hence it is regarded as low absorption type as per ASTM C-642.
2) After 28 days of water curing the samples are immersed in sea water to study the effect of chloride ion penetration.The percentage reductions in the strength of the samples are observed to be 4.257%, 6.545% and 8.842% for 28 days, 56 days and 90 days of immersion in sea water.Therefore there is a slight reduction in strength with immersion in sea water.
3) Similarly after 28 days of water curing the samples are immersed in $MgSO_4$ solution to study the effect of sulphate attack on concrete.The percentage reductions in the strength of the samples are observed to be 5.043%, 6.878% and 10.470% for 28 days, 56 days and 90 days of immersion in sulphate solution.Therefore there is a slight reduction in strength with immersion in sulphate solution.

6. Study on Interfacial Bond Characteristics

Each of the tested specimens comprised two materials: NC as substrate and HPC as repair material.Mix proportion for HPC is given in Table 5.The normal concrete is of grade M30 and it was designed according to IS 10262:2009 [7].The mix design adopted for M30 normal concrete is shown in Table 12.

TABLE 12.Mix design of M30

CONTENTS	VOLUME FOR 1m^3	QUANTITY (kg/m^3)
Cement	0.119	375
Coarse aggregate		1218.83
Fine aggregate	0.7136	704.109
Chemical admixture	0.000375	0.375
Water	0.167	167
Water –cement ratio	0.45	

NC substrate specimens were cast and bonded to HPC.In this study, the type of surface roughening method adopted is grooved (GR) surface, with 10 mm width and 5 mm depth.Fig 4 shows the NC substrate halves of the test samples with grooved surface preparation.

Fig 4.NC substrate halves of the samples with grooved surface texture.

6.1 Test Procedure

6.1.1 Slant Shear Test

The slant shear test method as per ASTM C882 [4] was adopted.This test was used in this study to determine the bond strength between the NC substrate and the HPC.Following this test procedures, HPC was cast and bonded to the NC substrate specimens on a slant plane inclined vertically at an angle of 30^0 to form composite prism specimens of size 100 mm x 100 mm x 300 mm.Fig 5 shows the composite specimen for slant shear test and Fig 6 shows the slant shear test set-up for the composite specimen.

Fig 5.Composite specimen for slant shear test.

Fig 6.Slant shear test set-up for the composite specimen.

HPC is casted with and without steel fibre.The bond strength of the composite specimen with and without steel fibre is shown in Table 13.Fig 7 shows the variation in slant shear bond strength for samples with and without steel fibre.

Generally the failure modes are grouped into three distinct forms.

a) TYPE A: Pure interfacial failure where no cracking and fracturing can be observed at both the NC substrate and HPC overlay.

b) TYPE B: Interfacial failure combined with minor NC substrate cracking or damage.

c) TYPE C: Interfacial failure combined with substrate fracture.

TABLE 13.Slant Shear Test results

SPECIMEN		SAMPLE	WEIGHT (kg)	LOAD (kN)	BOND STRENGTH (MPa)	AVERAGE BOND STRENGTH (MPa)	TYPE OF FAILURE
HPC with fibre	SS 7 DAYS	1	7.688	261.8	13.090	12.572	TYPE B
		2	7.326	240.0	12.000		TYPE C
		3	7.455	252.5	12.625		TYPE B
	SS 28 DAYS	1	7.492	273.2	13.660	14.195	TYPE C
		2	7.524	290.0	14.500		TYPE C
		3	7.455	288.5	14.425		TYPE C
HPC without fibre	S 7 DAYS	1	7.531	77.6	3.88	3.793	TYPE A
		2	7.456	74.4	3.72		TYPE A
		3	7.445	75.6	3.78		TYPE A
	S 28 DAYS	1	7.563	171.8	8.59	8.573	TYPE C
		2	7.571	168.4	8.42		TYPE C
		3	7.587	174.2	8.71		TYPE C

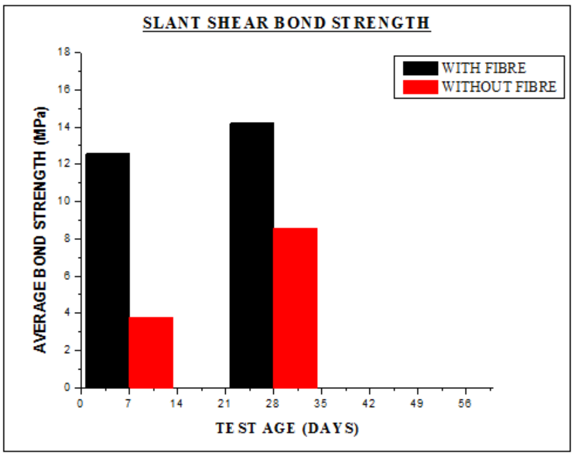

Fig 7.Slant shear bond strength for samples with and without steel fibre

6.1.2 Splitting Tensile Strength

The splitting tensile test as per ASTM C496 [5], as an indirect tensile test, was conducted to evaluate the bond strength between the NC substrate and HPC.In this test procedures, HPC was cast and bonded to the NC substrate specimens to form a cylindrical composite sample of 100 mm diameter and 200 mm height.Fig 8 shows the composite specimen for splitting tensile test and Fig 9 shows the splitting tensile test set-up for the composite specimen.

Generally the failure modes are grouped into 2 distinct forms.

a) TYPE A: Pure interface failure where no cracking and fracture can be observed at both NC substrate and HPC overlay.

b) TYPE B: Interface failure combined with partial substratum failure.

Fig 8.Composite specimen for splitting tensile test.

Fig 9.Splitting tensile test set-up for the composite specimen.

HPC is casted with and without steel fibre.The splitting tensile strength of the composite specimen with steel fibre is shown in Table 14.Fig 10 shows the variation in splitting tensile bond strength for samples with and without steel fibre.

TABLE 14.Splitting Tensile Strength for specimens

SPECIMEN		SAMPLE	WEIGHT (kg)	LOAD (kN)	SPLITTING TENSILE STRENGTH (MPa)	AVERAGE SPLITTING TENSILE STRENGTH (MPa)	TYPE OF FAILURE
HPC with fibre	CS 7 DAYS	1	4.325	75	2.387	2.302	TYPE A
		2	4.352	70	2.228		TYPE A
		3	4.325	72	2.291		TYPE A
	CS 28 DAYS	1	4.200	95	3.024	2.981	TYPE A
		2	4.250	92	2.928		TYPE A
		3	4.315	94	2.992		TYPE A
HPC with out fibre	C 7 DAYS	1	4.357	48	1.527	1.347	TYPE B
		2	4.447	37	1.177		TYPE B
		3	4.355	42	1.337		TYPE B
	C 28 DAYS	1	4.300	72	2.291	2.397	TYPE B
		2	4.350	76	2.419		TYPE B
		3	4.405	78	2.483		TYPE B

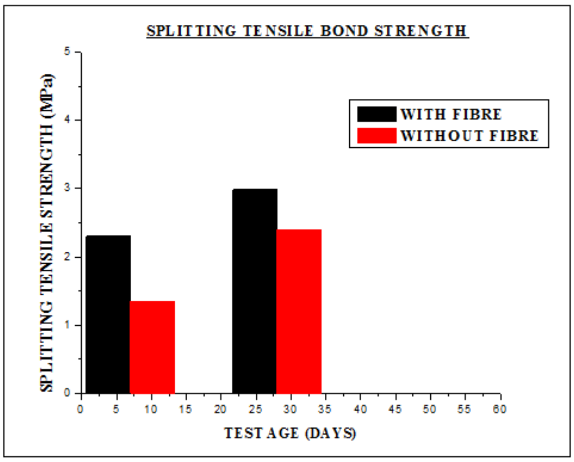

Fig 10.Splitting tensile bond strength for samples with and without steel fibre.

6.2 Discussions

6.2.1 Slant shear bond strength

From the slant shear test of the samples impregnated with steel fibres, the average slant shear bond strength was observed to be 12.573MPa and 14.195MPa for 7 days and 28 days testing respectively.Whereas for the samples without steel fibre, the average slant shear bond strength was observed to be 3.793MPa and 8.573MPa for 7 days and 28 days testing respectively.Therefore the average bond strength for the samples with fibre is observed to be greater than those without fibre.The interfacial bonding is found to be strong for HPC with steel fibre.

The results generally exhibit a gradual increase in interfacial bond strength with age which could be due to increase in strength of HPC as well as the interfacial bond strength of the composite.The tremendous enhancement in the shear bond strength could generally be attributed to greater adhesion and interlocking between the HPC and the roughened NC substrate surfaces.

According to ACI Concrete Repair Guide [2], materials used in concrete repair work shall have a specified minimum acceptable bond strength based on the slant shear strength as given in Table 15.This guide is useful in the selection of appropriate type of repair materials for rehabilitating deteriorated concrete structures.

TABLE 15.Minimum acceptable bond strength range

DAYS	BOND STRENGTH (MPa)
1	2.76-6.9
7	6.9-12.41
28	12.41-20.68

From the study it is evident that the average bond strengths obtained were able to meet the minimum bond strength as specified in Table 15.

6.2.2 Splitting tensile bond Strength

From the splitting tensile test of the samples impregnated with steel fibres, the average splitting tensile bond strength was observed to be 2.302MPa and 2.981MPa for 7 days and 28 days testing respectively.Whereas for the samples without steel fibre, the average splitting tensile bond strength was observed to be 1.347MPa and 2.397MPa for 7 days and 28 days testing respectively.Therefore the average bond strength for the samples with fibre is observed to be greater than those without fibre.The interfacial bonding is found to be strong for HPC with steel fibre.

Comparing the measured tensile splitting strength of the composites with the quantitative bond strength quality proposed by Sprinkel and Ozyildirim[3] as shown in Table 16, it is very obvious that strength level achieved for 28 days test fall under an ‘‘Excellent’’ bonding category since the measured bond strength is higher than 2.1 MPa.

TABLE 16.Quantitative bond quality in terms of bond strength

BOND QUALITY	BOND STRENGTH (MPa)
Excellent	≥2.1
Very good	1.7-2.1
Good	1.4-1.7
Fair	0.7-1.4
Poor	0-0.7

7. Conclusions

The experiments were performed inorder to determine optimum design mix for M100 grade concrete and to study the interface behavior between normal concrete and fibre reinforced high performance concrete.

- The optimum design mix for M100 grade concrete was determined.The mix contains 5% replacement of Metakaolin, 10% replacement of ALCCOFINE 1203 and 0.3% of flat crimped steel fibres.

The mechanical and durability properties of high performance concrete were studied.

- The strength of concrete was found to attain the target strength of 100MPa.
- The concrete is less reactive to sulphate and chlorides as the reduction in compressive strengths were observed to be less than 10%.Therefore, the concrete is highly resistant to sulphate attack and chloride ion penetration under severe conditions.
- The water absorption of sample is observed to be less than 5% and hence the concrete is less porous.

The interfacial bond characteristics between normal concrete and fibre reinforced high performance concrete were studied.

- The slant shear bond strength and the splitting tensile bond strength were observed to be sufficiently strong for specimens with steel fibre than those specimens without steel fibre.
- Hence fibre reinforced high performance concrete can be used to provide an effective and durable concrete repair to normal concrete.

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