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Effect of Fibre Hybridisation on Mechanical Properties of Cementitious Composites

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Abstract: Conventional cement based composites have constituent materials such as Portland cement, supplementary cementitious materials, fine sand, super-plasticizer and water. To achieve high performance, these composites needs high cement content in it which will cause high cost of production. Addition of supplementary cementitious materials as partial substitutes for cement will help in reducing the cost. In this study, a pre-characterized mix proportion of cementitious composite, in which 30% of cement was substituted with lime powder. To enhance the ductility of the composite, the matrix is reinforced with 2% (by volume of composite) of crimped steel fibres. Further, hybridisation of metallic and non-metallic fibres is done in this study to bring the self-weight of the mix down and to reduce the chances of degradation due to the corrosion of fibres. Fibre hybridisation was done by replacing 25%, 50%, 75% and 100% by volume of steel fibres with poly propylene (PP) fibres. The characterisation of the fibre reinforced composites was done by assessing their workability by conducting flow test, compressive strength test, split tensile strength test, flexure test and low velocity impact test. It was observed that, the mix with 100% of steel fibres replaced with PP fibres exhibited better workability. It was also observed that, compressive strength, split tensile strength, modulus of rupture and impact resistance were maximum for the mix reinforced with steel fibre alone and the strengths got reduced gradually due to hybridisation of fibres. Based on the requirement of strength, a combination of steel and PP fibres can be used for reinforcing the matrix, which will help in improving ductility, reducing self-weight. By this, the matrix can be made more resistant to corrosion and can be used in structures especially in the marine environment.

Keywords: Composites, Fibre Reinforcement, Fibre Hybridization.

I. INTRODUCTION

Fibre Reinforced Composites (FRC) are well known for their strength and ductility characteristics. Development of Ultra High Performance Composites (UHPC) is a trending research area in which researchers tried developing composite mix with outstanding strength and durability characteristics [1].

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The method of mix proportioning has greater importance in attaining these characteristics [2]. Reinforcing the composite matrix with fibres can improve its strength characteristics.

Fibre reinforcements will help in arresting crack propagation due to loading and thereby to improve the ductility and strain hardening characteristics. The high performance characteristics make the composites more suitable especially for the repair works like overlaying deck slabs, provision of construction joints etc.

It was observed in the research articles that, the consumption of cement for the development of ultra-high performance composites is very high as about 1000 kg/m^3. It was also observed that, for attaining high strength, a very low water to binder ratio is to be adopted. Hence, it is obvious that, only a part of the cement used is getting hydrated and the remaining will contribute as a reactive filler for the mix. This will help in densifying the microstructure of the mixes. As production of cement is a major source of CO_2 emission, it is desirable to replace the filler part of the cement, which is not taking part in hydration, with suitable supplementary materials. It will also help in reducing the cost of the mix. Previous researchers suggested the usage of quartz powder as an effective filler [3]. Also, the effect of use of lime stone powder as a substitute material for cement was discussed by many researchers [4][5][6].

The use of materials available in the vicinity, for the replacement of cement, is also one of the trending areas, as it opens opportunities to attain sustainability [7]. Locally available, ground slaked lime was the substitute material in this study. 30 % of the cement was replaced using hydrated lime powder. Steel fibres at 2% by volume of the mix was used for the reinforcement of composites. The random dispersal of the steel fibres will help in improving he ductility of the composite[8]. Further, hybridisation of fibres was done, to reduce the usage of steel fibres. Steel fibres imparts heaviness to the mix. Also, steel fibres are prone to corrosion. Hybridisation, by replacing the steel fibres partially with poly propylene (PP) fibres, was done which will help in reducing self-weight. PP fibres are not susceptible to to corrosion also.

Many researchers have suggested to cure the specimens in accelerated conditions to attain maximum strength in minimum period of time[9],[10]. Curing methods like steam curing, boiled water curing etc. are quite common. But, these methods are less suitable for in-situ conditions and are much effective in the case of precast elements[11]. For this research normal water curing, which is applicable in the case of in-situ conditions, was adopted.

II. MATERIALS USED AND MIX PROPORTION

A. Materials Used

Ordinary Portland Cement (OPC) of grade 53, conforming to IS 12269, was used in this study. Initial setting time for OPC was 32 minutes and the specific gravity was 3.15. The cement was also tested for its fineness as per the recommendations of IS 4031. It was observed that 92% of the particles were smaller than 90 microns. Supplementary cementitious material used for the mix was silica fume (SF). Specific gravity of SF was 2.63 with 99.8% active silica (SiO_2) content. Ground hydrated lime (LP) with 68% of active CaO was also used for the partial replacement of cement. Specific gravity of LP was 2.24 and the average size of particles was 250 microns.

Natural river sand (RS) with an average particle size of 2 mm was used in this study. RS was with fineness modulus of 2.55 and bulk density of 1500 kg/m^3. Microsand (MS) was also used to arrive at better packing density. The grain size of MS was ranging from 100 micron to 1 mm. MS was having 99% of active silica (SiO_2) content. Specific gravity of MS was 2.6. For the hydration cementitious materials, normal potable water was used. Polycarboxylate ether based super-plasticizer (SP), also known as High Range Water Reducer (HRWR) was used to ensure better flowability of the composites even with low water to binder ratio (W/B). Steel fibres used in this study were crimped type with length 12.5 mm and diameter 0.45 mm. Aspect ratio was 27.77 for the steel fibres. Further, PP fibres of average length 12 mm and average diameter 0.04 mm were used for hybridisation of fibres. Aspect ratio was about 300. Unit weight of the PP fibres was about 920 kg/m^3. The chemical composition of OPC, SF, LP and MS are provided in the Table I.

Table – I: Chemical Composition of the Constituents

Materials / Component	OPC	LP	SF	MS
	Chemical Composition (% by mass)			
SiO_2	20.49	2.94	92.5	99.5
Al_2O_3	5.91	3.08	0.72	0.08
Fe_2O_3	4.07	3.94	0.96	0.04
CaO	62.90	91.57	0.48	0.01
MgO	1.13	1.68	1.78	0.01
SO_3	1.87	--	0.2	--
LOI	2.29	--	1.5	0.28

B. Mix Proportion

High performance of the composites was achieved by refining the microstructure. Performance of the composites will be higher if the particle packing is denser. Linear Packing Density Model (LPDM) is a tool to optimize the packing of the constituents. Yu et. al. presented a research article, in which the optimisation of the use of lime stone powder as filler in the composite mix was done [4]. Having the particle sizes of the constituent materials are almost comparable with those presented by Yu et. al., their optimum mix proportion was taken as the control mix proportion (MC) for this study. As suggested by the authors 30% of the OPC by mass was substituted with lime powder. The details of the mix proportion adopted for the study is given in the Table II. SP content in the mix was as high as 7.5% of the total mass of the binder. This will help in achieving adequate workability of the mix.

Table – II: Mix Proportion

Constituent	Proportion
OPC	1
LP	0.42
MS	0.357
RS	1.72
SF	0.07
W/B	0.33
SP	0.075
Fibres[a]	0.02

[a] Fibres are added percentage by volume of the mix.

Control mix was reinforced with 2% steel fibres by volume of the mix. Fibre hybridisation was done by replacing the steel fibres partially with PP fibres. Various replacements done for the hybridisation is comprehended in the following Table III.

Table – III: Details of Fibre Hybridisation

Mix Designation	Steel Fibre (% by volume)	Polypropylene Fibre (% by volume)
MC	0	0
M0[a]	100	0
M25	75	25
M50	50	50
M75	25	75
M100	0	100

[a] Letter 'M' designates the mix and the number represents the PP fibre content (% by volume) in the mix. 'MC' denotes the conventional mix with no fibre in it.

C. Preparation of Mix

The mix was prepared in a sequential order. The sand was made in to saturated surface dry condition. To the saturated sand, the micro sand was added and mixed thoroughly for 10 minutes in a high shear mixer. To this homogenously mixed aggregate part, silica fume, lime powder and cement were added and mixed thoroughly for another 10 minutes. Then the required quantity of fibres were added and mixed thoroughly until the fibres were well dispersed. The required amount of water was mixed with the super-plasticizer and the mixture was made in to three parts. The first one-third was added to the dry mix of constituents and mixed thoroughly for 10 minutes. Another one-third was then added and mixed well. Addition of the third part and mixing will make the mix highly workable.

III. EXPERIMENTAL PROGRAM

The experimental program comprises of the following tests to evaluate the workability and strength parameters of the mixes modified by hybridizing the fibre matrix.

A. Workability Test

Workability of the mixes were evaluated by performing flow table test as recommended by IS 1199 and the average flow diameter is recorded.

B. Compression Test

Compression test was carried out as per IS 516 to evaluate the Unconfined Compressive Strength (UCS) of the composites. Cube specimens of side 150 mm were cast for the compression test. The specimens were tested on a compression testing machine.

C. Split Tension Test

Split tensile strength test was carried out as per IS 5816. Cylinder specimens of diameter 150 mm and length 300 mm were cast for the split tensile strength test.

D. Flexure Test

Prism specimens of length 500 mm and cross-section 100 mm × 100 mm were cast for the flexure test. The test was performed conforming to IS 516. The specimens were subjected to four point loading and the modulus of rupture was evaluated.

E. Drop Hammer Low Velocity Impact Test

The impact test was performed on slab specimens of length 600 mm, breadth 600 mm and thickness 60 mm. The low velocity impact test (Drop Hammer Test) conforming to ACI Committee 544 was performed to assess the impact resistance. A steel ball, weighing 2860 g, was used as the hammer for the test. The weight was dropped on to the slab specimens from a height of 0.73 m. The number of blows required to develop the first crack as well the for the complete failure were noted. The impact energy was calculated as follows.

$$\text{Impact energy} = N \times m \times g \times h \quad (1)$$

Where 'N' represents the number of blows, 'm' represents the mass of the drop-weight, 'g' represents the acceleration due to gravity which is 9.81 m/s^2 and 'h' is the height from which the weight is dropped.

Three specimens per each mix were cast and cured for the specified periods (7 and 28 days). Strength tests were carried out at the maturity and mean value of the strength was reported. Impact test was done on the mixes cured for 28 days.

IV. RESULTS AND DISCUSSIONS

A. Flow Test

The average flow diameters for the mixes were observed as detailed in the Table IV

Table IV. Average flow dimeter

Mix Designation	Average diameter (mm)
MC	255
M0	200
M25	210
M50	225
M75	240
M100	245

It is to be noted that, the mix with zero fibre reinforcement showed better flow compared to the fibre reinforced mixes. It was also observed that the flow diameter was getting increased gradually as the PP fibre content increased. The mix with 100% steel fibre replace with PP fibres exhibited maximum flow. This may be due to reduction in the stiffness of the mix due to the addition of more flexible PP fibres.

B. Compressive Strength

Compression tests were carried on cube specimens to evaluate the Unconfined Compressive Strength(UCS) of the mixes. The results are detailed in the Table V and illustrated with the help of the Fig. 1.

Table V. UCS of the mixes

Mix designation	7 days (MPa)	28 days (MPa)
MC	26.4	46
M0	37.13	61.39
M25	33.81	58.02
M50	32.59	55.65
M75	30.44	52.4
M100	28.2	49.3

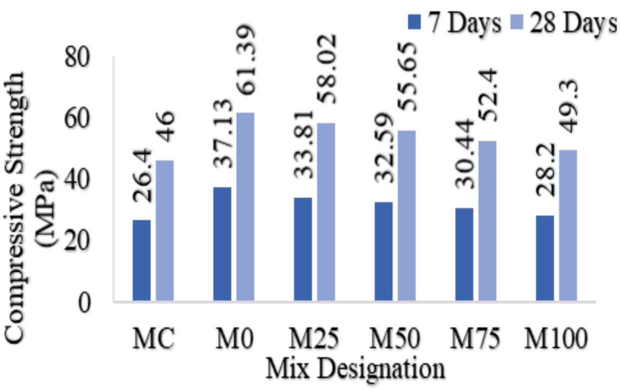

Fig. 1.Compressive strength test results

Betterment of compressive strength of the composite was observed as the matrix is reinforced with fibres. It was observed that mixes with 0% PP fibres in it were exhibiting maximum compressive strength after both the curing ages. The strength was gradually getting reduced as the content of PP fibres increased. The percentage decrease in strength with reference to the mix M0 is illustrated in the Fig. 2.

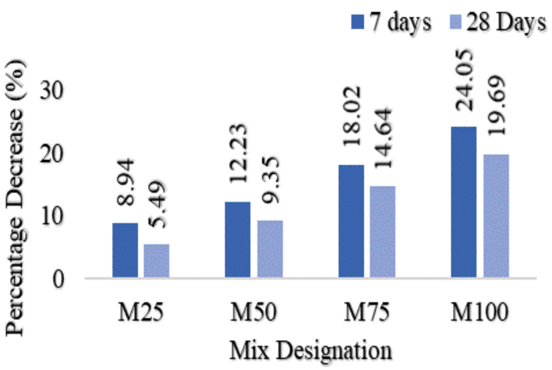

Fig. 2.Reduction in Compressive strength.

The mix with 25% of PP fibres showed 8.94 % and 5.49 % reduction in the compressive strength after the curing periods of 7 days and 28 days respectively, with reference to the control mix M0.

The mix with 100% PP showed maximum reduction in strength of 24.05% and 19.69% after the curing ages of 7 days and 28 days respectively, compared with the control mix M0. The reduction in strength is due to the weakness of the PP fibres, more precisely due to the inferior ductility of the PP fibres compared with that of steel fibres.

C. Split Tensile Strength

Indirect tensile strength test, also known as split tensile test was carried out to evaluate the tensile strength of the composite mixes. The results of the test are given in the Table VI and illustrated in the Fig. 4.

Table VI. Split tensile strength of the mixes

Mix designation	7 days (MPa)	28 days (MPa)
MC	2.57	4.52
M0	3.49	6.1
M25	3.23	5.79
M50	3.13	5.56
M75	2.91	5.13
M100	2.79	4.87

The tensile strength of the conventional mix was also low and got improved as fibre is used to reinforce the matrix. Tensile strength was maximum for the mix with 100% steel fibre in it. Gradual decrease in strength was observed as the hybridisation percentage increased. The percentage decrease in tensile strength with reference to the mix M0 is illustrated in the Fig. 5.

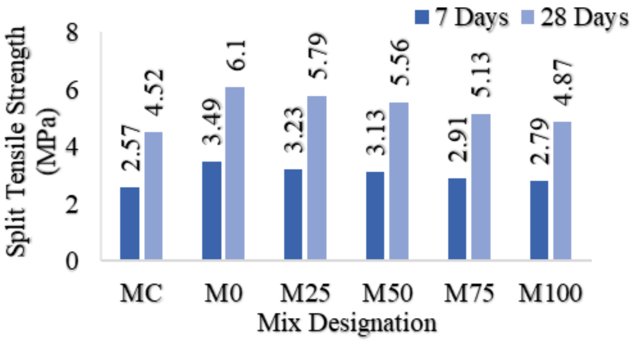

Fig. 4.Split tensile strength

The mix with 25% of PP fibres showed 7.45 % and 5.08 % reduction in the tensile strength at the curing ages of 7 days and 28 days respectively, with reference to the control mix. The mix with 100% PP showed maximum reduction in strength of 20.06% and 20.16% after the curing ages of 7 days and 28 days respectively, compared with the control mix. The reduction in tensile strength is also due to the inferior elastic properties of the PP fibres.

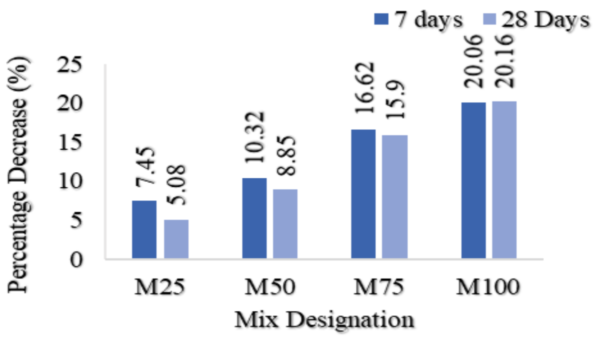

Fig. 5. Reduction in split tensile strength.

D. Modulus of Rupture

Flexure tests were carried out to evaluate the modulus of rupture of the mixes. The results are given in the Table VII and illustrated in the Fig. 6.

Table VII. Flexural strength of the mixes

Mix designation	7 days (MPa)	28 days (MPa)
MC	2.73	4.89
M0	4.21	7.35
M25	3.68	6.47
M50	3.47	6.12
M75	3.2	5.61
M100	2.96	5.28

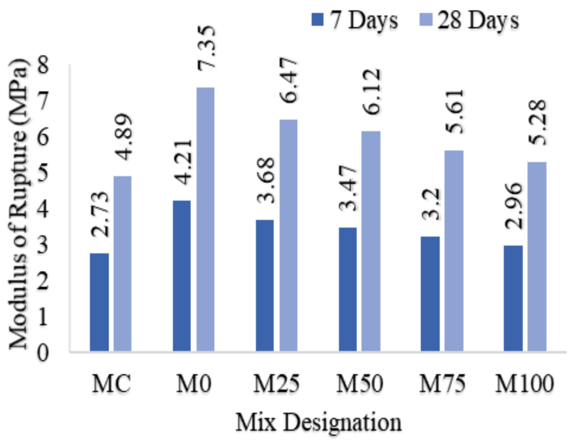

Fig. 6. Modulus of rupture

Modulus of rupture was maximum for the mixes reinforced with steel fibres alone. The modulus was getting reduced as the PP fibre content was increased in the mix. The percentage decrease in strength is illustrated in the Fig. 7.

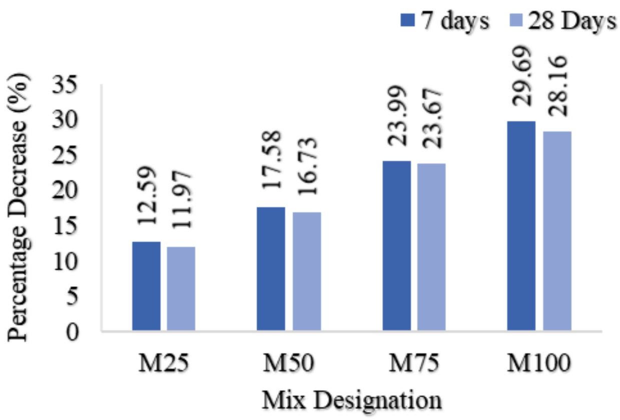

Fig. 7.Reduction in flexural strength

The mix with 25% of PP fibres showed 12.59% and 11.97% reduction in the flexural strength at the curing ages of 7 days and 28 days respectively, with reference to the control mix. The mix with 100% PP showed maximum reduction in the modulus of 29.69% and 28.16% after the curing ages of 7 days and 28 days respectively, compared with the control mix. The reduction in the modulus is also attributed to the inferior elastic properties of the PP fibres.

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E. Impact Resistance

Low velocity impact test was performed and the number of blows required to develop the first crack (N1) as well as the number of blows for the final failure (N2) are tabulated in the Table VIII. The impact energy is calculated as discussed earlier. The energy corresponding to blows N1 and N2 are also tabulated as E1 and E2 respectively in Table VIII. The difference between the energy adsorbed at failure and that at the development of first crack can be a measure of ductility of the mixes. Fig. 8 and 9 illustrates the same which will be helpful in comparison of responses.

It was observed that the number of blows required to develop the first crack was gradually reduced as the proportion of PP fibre increased in the mix. The mix reinforced with steel fibre alone showed the first crack by 71 blows and got failed completely by 177 blows. For the mix with 100 % steel fibres replaced with PP fibres, the specimen showed first crack by 38 blows and failed completely after 58 blows. However, the response of this mix was way better than that of conventional mix with zero fibres in it.

Table VIII. Impact Test Results

Mix Designation	N1	N2	E1 (Joules)	E2 (Joules)	E2 (Joules)
MC	27	42	553.00	860.22	307.22
M0	71	177	1454.17	3625.19	2171.02
M25	110	116	2252.94	2375.83	122.89
M50	80	108	1638.51	2211.98	573.47
M75	44	64	901.18	1310.8	409.62
M100	38	58	778.29	1187.92	409.63

Considerable reduction in the impact energy absorption was also observed. It is obvious that, the fibre hybridisation weakened the mixes. The energy absorbed by the mix reinforced with steel fibre alone was of 3625.19 J at failure whereas that exhibited by the mix reinforced with 100 % of PP fibres was only 1187.92 J at failure, after 28 days of curing.

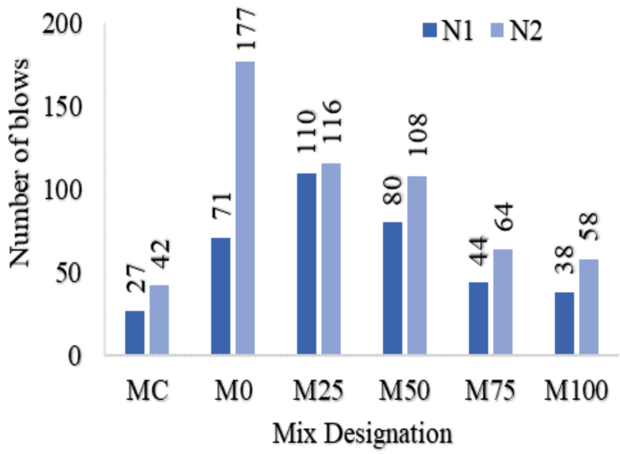


Fig. 8.Number of blows for first crack and failure

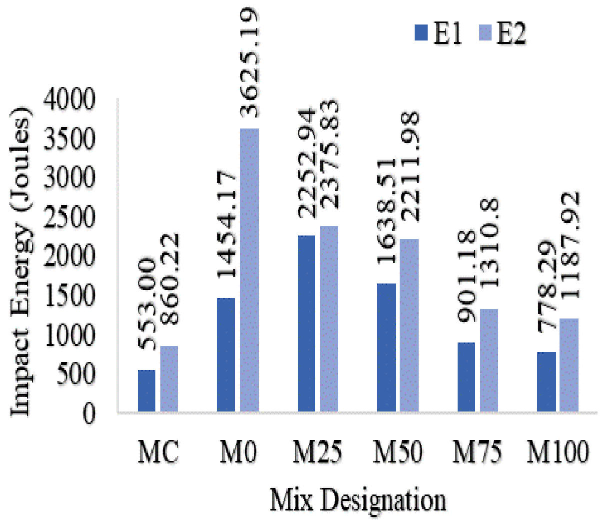
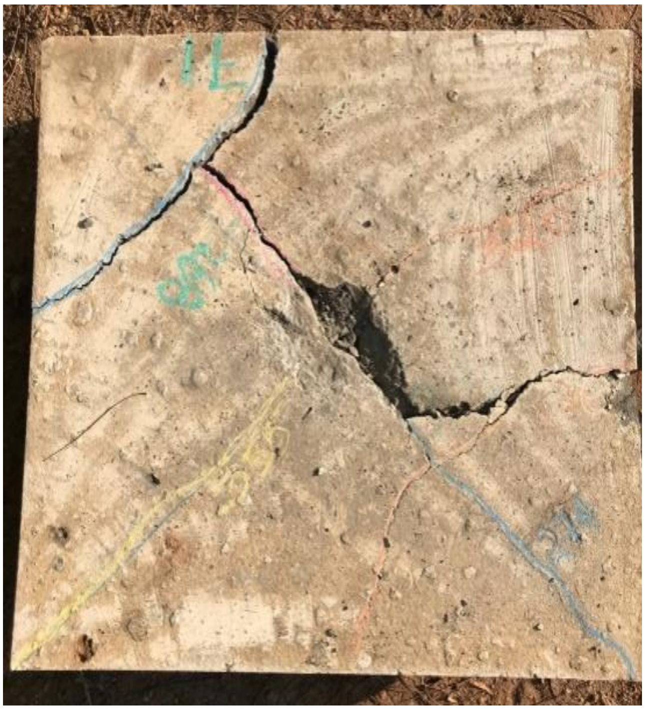


Fig. 9.Impact energy values

The difference E between E1 and E2 was also considerably less for the mix reinforced with PP fibres alone. This indicates that, the hybridisation considerably affected the ductile nature of the composites. This is due to the weakening of the fibre matrix, which is reinforcing the mix, due to the hybridisation. Compared with steel fibres, PP fibres are inferior in the tensile strength and ductility. The domination of PP fibres will lead to the inability of composites to arrest the propagation of cracks. The following Fig. 10 describes the failure patterns for different mixes. The slab made of mix with zero fibre in it exhibited a brittle failure (Complete collapse).



M0

M25

M50

M75

M100

Fig. 10. Failure patterns

The slab made of mix M0 undergone a ductile failure. The cracks were propagated gradually. It was also observed that, for mixes in which the quantity of PP fibres is dominating, failure was localised and the cracks were less propagated. The slabs made of M25 and M50 showed 100 % localized failure at the point of impact, with zero propagation of major cracks. This makes these mixes more suitable for overlaying.

V. SUMMARY AND CONCLUSIONS

With the support of experimental data, the following are the conclusions made.

1. Flow test performed indicated that addition of PP fibres improved the workability of mixes. Even though there was a marginal difference in the flow diameter, mix with 100 % steel fibre also exhibited very good workability.
2. Compression, split tensile and flexural tests indicated that fibre hybridisation weakened the mix. Strength results were maximum for the mix reinforced with steel fibre alone.
3. Impact resistance of mixes was also considerably reduced due to the fibre hybridisation. The mix reinforced with steel fibre alone possessed high impact energy absorption compared to all the mixes with hybridised fibres. However, the mixes M25 and M50 showed localised failure and considerable impact strength. This makes the mix more suitable for overlaying.
4. Concisely, hybridisation of fibre will weaken the matrix of the composite. Even though for the required strength, to reduce self-weight of the mix and to reduce the chances of corrosion of fibres, hybridisation can be considered. Composites with hybridised steel fibres with non-metallic fibres such as PP fibres will be less prone to the deterioration of the matrix due to corrosion of fibres. These can be used in structures exposed marine environments.

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