Prediction Of Impact Energy Absorption Using Modified Regression Theory

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Abstract: In this study new mathematical models were proposed and developed by using a regression equation for the prediction of impact energy absorption of hybrid ferrocement slabs. Slabs were made up of self-compacting concrete (SCC) in order to minimize the external vibration work. Slabs of size 300 X 300 mm with varying parameters such as depth of slab (25 & 30 mm), number of layers of weld mesh (2 and 3 layers bundled), and wrapping with Glass Fiber Reinforced Polymer sheets (GFRP) (1 and 2 layers) along with a specified proportion (0 and 0.30%) of polypropylene fibers were cast. Impact load was applied by means of a hammer of weight 3.5 kg (34.335 N) and the initial and ultimate energy absorptions were evaluated. The variables used in the prediction models were the varying parameters such as number of layers of GFRP sheet, area of weld mesh and height of drop. According to the analysis, the models provide good estimation of impact energy absorption and yielded good correlations with the data used in this study.

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Key Words: mathematical model, statistical analysis, impact load, initial energy absorption, final energy absorption, self-compacting concrete, hybrid ferrocement slabs

Introduction

The investigation of fiber reinforced plates subjected to impact loads received good attention from researchers around the globe in recent years. As the ferrocement slabs are made of Self Compacting Concrete with discontinuous fibers as well as Glass Fiber Reinforced Polymer wrapping, such slabs here are defined as Hybrid Ferrocement Slabs (HF slabs). To minimize the damage and to prevent collapse, structures must possess much greater resistance to impact loading. The understanding of the impact resistance of ferrocement slabs made up of self-compacting concrete is very limited. The main difficulty is the absence of standardized test technique for testing concrete under impact. Many researchers have used different impact machines, specimen configurations, geometry and instrumentations and have also adopted different analysis schemes. The impact test procedure is in infant stage.

The characteristics of the impact load are different from those of static and seismic loads. Since the duration of loading is very short, the strain rate of material becomes significantly higher than that under static and seismic loading. Also structural deformation and failure modes will be different from those under static and seismic loading. In construction industry, strength is a primary criterion in selecting a concrete for a particular application. Concrete used for construction gains strength over a long period of time after pouring. Therefore, rapid and reliable prediction for the strength of concrete would be of great significance [1].

Sudarsana Rao et al. [2] investigated the behaviour of slurry-infiltrated fibrous concrete (SIFCON) slabs under impact loading and the test results revealed that SIFCON slabs with 12% fiber volume fraction exhibit excellent performance in strength and energy-absorption characteristics. Regression models have been developed to estimate the energy absorption for SIFCON slab specimens. Padmanaban et al. [3] worked on the impact characteristics of Indian fly ash mixes with locally available ingredients and the empirical relations were arrived between the impact strength and compressive strength. There is a good correlation between the experimental and predicted values. Zain et al. [4] carried out a research on the mathematical regression model for the prediction of concrete strength and according to the analysis; the models provide good estimation of compressive strength and yielded good correlations. Moreover, the proposed model proved to be significant tool in prediction compressive strength of different concrete in spite of variations in the results.

Ferrocement is a thin composite, made up of cement-based mortar matrix reinforced with closely spaced layers of small diameter weld mesh. The mesh may be made of metallic or other suitable materials [8, 11]. Ferrocement slabs are more ductile, when compared to the conventional reinforced concrete elements, but the post-peak behavior of ferrocement elements reveals that the failure occurs either due to mortar failure in compression or due to the failure of extreme layers of mesh. Here this Hybrid Ferrocement was made up of polypropylene fiber reinforced Self-compacting concrete (SCC) with weld mesh as reinforcement. Self-compacting concrete is developed in Japan in the late 1980s, is a highly flowable concrete that can spread into formwork of various construction elements under its own weight and achieve good compaction without vibration and segregation [16]. So, here an attempt has been made in this paper to develop a multiple regression analytical model for toughness behavior of hybrid ferrocement slabs by adding polypropylene fibers into the SCC and strengthening its tension zone with GFRP laminates under impact loads.

Experimental Investigations

The hybrid ferrocement slabs were cast in two different moulds each having fixed size of 300 x 300 mm, but thickness varying from 25mm to 30mm.The mould is made of steel sheet and it is water tight. Before casting of the slabs, the moulds are properly cleaned and applied with one coat of wax oil as mould releasing agent and to get better surface finish. Table 1 gives the test parameters and specimen identification.

Materials used

The cement used in this work was Portland Pozzolonas cement conforming to the requirements of IS 1489: 1991[6]. The specific gravity of cement is 3.15. The initial and final setting times were found as 35 and 400 min, respectively. Fine aggregate used was river sand passing through IS sieve 4.75 mm obtained from a local source [5]. The specific gravity of sand was found to be 2.63. The coarse aggregate which passed through 6mm sieve, but retained on 4.75mm sieve were used for the self-compacting concrete mix. The specific gravity of Coarse aggregate is 2.73. In this experimental programme, square weld mesh of diameter 1.2 mm with a grid size of 20 X 20 mm was used as the reinforcement for the hybrid ferrocement slabs.

Table 1 Test Parameters and Specimen Identification

S. No.	SLAB ID	Thickness (mm)	Number of weld mesh layers in the bundle	Number of GFRP wrapping	% of fiber
1	B1	25	2	0	0
2	B2	25	3		
3	B3	30	2		
4	B4	30	3		
5	B5	25	2	1	
6	B6	25	3		
7	B7	30	2		
8	B8	30	3		
9	B9	25	2	2	
10	B10	25	3		
11	B11	30	2		
12	B12	30	3		
13	C1	25	2	0	0.3
14	C2	25	3		
15	C3	30	2		
16	C4	30	3		
17	C5	25	2	1	
18	C6	25	3		
19	C7	30	2		
20	C8	30	3		
21	C9	25	2	2	
22	C10	25	3		
23	C11	30	2		
24	C12	30	3		

A mineral admixture Micro Silica was used in the present work. It is a fine material and it fills all voids in the concrete mix.Cement is partially replaced with silica fume by 25 % by weight of cement. Potable fresh water available from local sources was used for mixing and curing of slabs. To eliminate external vibration work, Glenium B233 - 0.85 % by weight of cementitious material had been used. It is a light the brown liquid with the relative density of 1.09 ± 0.01 at 25°C and pH > 6. To improve the stability during transport and placing, Glenium stream 2 - 0.23% by cementitious material were added.

Polypropylene fibers of cut length 6 mm were used. The ultimate tensile strength of fiber was 550 – 700 MPa. GFRP sheets were wrapped at the bottom of the slab by means of Polyester resin. An accelerator and catalyst (10 ml) for 1 kg of polyester resin is used for this purpose. The ultimate tensile strength of GFRP sheets was found to be 360 N/mm2.

The Mix Proportions

A total of twenty four slab specimens were cast with two series of mixes with different combinations. Specimens of the 1st Series, Series A was mixed with silica fume by 25% partial replacement of cement, whereas the 2nd Series, Series B was prepared with addition of polypropylene fibers with that of the Series A. All the mixes were maintained with self-compacting character. The mixers for SCC were confirmed with the fresh concrete properties as per EFNARC guidelines [7] and Figures 1 and 2 shows the tests conducted to evaluate fresh concrete properties of SCC mixes. The mix proportions and material details are given in Table 2.

Table 2 Mix Proportions and Material details

Series B		Series C	
Constituent	**Content**	**Constituent**	**Content**
Cement content (kg/m^3)	465	Cement content (kg/m^3)	465
Water content (kg/m^3)	186	Water content (kg/m^3)	154
Coarse aggregate (kg/m^3)	495	Coarse aggregate (kg/m^3)	495
Fine aggregate (kg/m^3)	743	Fine aggregate (kg/m^3)	743
W/C ratio	0.40	W/C ratio	0.40
Silica Fume (kg/m^3)	154	Silica Fume (kg/m^3)	154
		Polyproylene fibers(kg/m^3)	1.74

Figure.1 SCC - Slump Flow test

Figure.2 SCC - V-Funnel Test

Casting of Slabs

A weld mesh of size 294 x 294 mm with a minimum cover of 3mm [10] on each side and placed inside the slab mould of size of 300 x 300 mm. The cement, fine aggregates, coarse aggregates and the silica fume are mixed thoroughly in dry condition. For addition of water, initially 75% of the water was added to dry mix and mixed thoroughly. The HP and VMA were added to remaining 25% of the water which are then added to the mix along with polypropylene fibers and the mixing was carried out for about two to three minutes.

The self-compacting concrete mix was then placed in the slab moulds without vibration ensuring a minimum clear cover of 3 mm for the slab specimen. All these specimens were cured up to 28 days [9]. For GFRP wrapping, the specimens are taken out of curing pond and dried well. The surface was cleaned well to remove any dirt. The fiber sheets were cut to the required measurement and saturated in the resin or wetted out. Resins are color-coded two part materials that are premeasured to simplify mixing. The wetted sheet is positioned on the surface with the correct orientation in the required number of layers. A tap coat of resin was also applied over the GFRP sheet allowed to dry prior to testing.

Test Setup and Testing

Impact test was conducted on the square slabs after 28 days of curing by using a drop weight and the test setup shown in Figure 3. It consisted of a rigid welded steel frame square in plan and supported by short columns. The specimen was laid flat resting on four 20 mm diameter bars to provide line support along the four edges. A hammer having a mass of 3.5 kg (34.335 N) was used for applying repeated impact on the specimen from a pre-determined height. The test setup consists of a cylindrical ball of 90 mm dia, 80mm height (the plunger) with hemispherical blunt tip to a height of 20mm. The height of the drop was kept as 1.185 m and 1.18m for 25mm and 30 mm thick slab respectively. To prevent the specimen from lifting up during impact due to rebound under impact, the edges of the panel were clamped down to the supporting frame by C – clamps as shown in Figure 4. The plunger which loads the panel has a spherical tip enabling a point contact to be made. A rope and pulley arrangement with a pipe guide, which enables a central impact in the vertical direction, was used to manually raise the hammer to the required height for repeatedly dropping it on the specimen surface. Grease was applied on the rollers to reduce friction and to ensure a smooth fall

For each slab specimen, the hammer was dropped repeatedly and the number of blows required to cause the first visible crack on the top and to cause ultimate failure were recorded. Ultimate failure is defined as the opening of cracks in the specimen sufficiently so that the pieces of concrete are touching three of the four positioning lugs on the base plate.

Energy absorption

The total energy absorbed by the hybrid ferrocement slabs when struck by a hard impactor depends on the local energy absorbed both in contact zone and by the impactor.

The energy absorption can be obtained by using the following formula [3]:

$$E = N \times (w \times h) \text{ joules} \quad \ldots\ (1)$$

where

E= energy in joules

w= weight in Newton

h= drop height in meter

N= blows in numbers

Figure 3 Impact testing machine

Figure 4 Slabs restrained with C – Clamps

In the above equation, the weight of the ball as 34.34 N and the height of fall 1.18m and 1.185 m for 25 mm and 30 mm thick slabs respectively were maintained constant throughout the experiment. The energy absorption capacities of HF slab specimens at first crack and at ultimate failure stages are presented in Table 3.

Table 3 Experimental Results

S. No.	Slab ID	Initial Energy Absorption (Nmm X10^3) (E1)	Final Energy Absorption (Nmm X10^3) (E2)
1	B1	569.62	2237.78
2	B2	691.68	3295.64
3	B3	769.79	4213.59
4	B4	891.34	5023.90
5	B5	813.74	4923.12
6	B6	854.43	8422.20
7	B7	891.34	8832.34
8	B8	972.37	9723.67
9	B9	854.43	6225.11

10	B10	854.43	8544.26
11	B11	1053.40	10615.01
12	B12	1337.00	13856.23
13	C1	732.37	4597.63
14	C2	854.43	5736.86
15	C3	972.37	6644.51
16	C4	1174.94	8062.54
17	C5	1220.61	10497.24
18	C6	1261.30	12775.71
19	C7	1418.04	15476.84
20	C8	1458.55	16246.64
21	C9	1342.67	11799.22
22	C10	1627.48	16640.97
23	C11	3160.19	34802.64
24	C12	3727.41	42662.61

Modeling

Statistical models were developed from the experimental result shown in Table 4. Studies on response surface methodology revealed that a polynomial regression model is adequate for fitting responses which are functions of mix components [12, 14]. For a polynomial model, four types of models are available: linear, interaction, pure quadratic and full quadratic models. The model with highest coefficient is the full quadratic model, where three variables are involved.

The expression for full quadratic model is as follows:

$Y = bo + a_1X_1 + a_2 X_2 + a_3 X_3 + a_4 X_1 X_2 + a5 X_1 X_3 + a_6 X_1^2 + a_7 X_1^2 X_2$ (1)

where, Y is a response or dependent variable of interest. Here, Y_1 is the initial energy absorption and Y_2 is final energy absorption for the two series.

X_1 is number of GFRP layers

X_2 is height of fall

X_3 is area of weld mesh in mm2.

Equation (1) has eight coefficients and a minimum of ten experimental data are adequate to fit the polynomial model. The experimental results of 24 slabs with two different series (mix proportions) in this work are capable of generating models for the desired response predictions. The quadratic term in equation (1) give account of curvature in the response surface. This manifest when a region under study has a minimum or maximum response [12]. Strategies for choosing the order of polynomial model include forward and backward selection [13]. Forward selection approach was adopted in this work. Statistical software, SPSS (Statistical Package for the Social Sciences) package, was used for the analysis. Possible models were established by identifying the terms in the model that are significant by using a t-test and carrying out an analysis of variance (ANOVA) to determine the adequacy of the fitted model. The best model for initial energy and final energy for each series are shown in Table 4, with the model statistics and coefficients of the equations.

Model Validation

In an attempt to validate the regression model 24 slabs made up of two mixes were conducted and their responses compared with the values from the developed models. These values are indicated in Table 5. The model values are not too far away from the experimental results, confirming the validity of the developed models.

Table 4 Model Statistics and co-efficient of the terms

Regression Coefficient	Initial Energy(Y_1)		Final Energy(Y_2)	
	Series B	Series C	Series B	Series C
Constant	24175.17	33949.29	220542.33	264047.01
X_1	-32421.40	-119383.04	4048.751	-841060.77
X_2	-19991.50	-28025.5	-185203.52	-218627.99
X_3	1.75	1.39	18.74	9.22
X_1X_2	27471.75	100506.50	-716.91	708515.48
X_1X_3	0.17	2.36	16.52	45.40
X_1^2	20444.58	109634.13	87193.74	1083829.8
$X_1^2X_2$	-17257.25	-92215.00	-74614.03	-912413.99
Statistics				
R2 adjusted (%)	94	98.43	99.3	99.58
F	8.957	81.182	35.91	134.69

Table 5 Experimental and Model Data

S. No.	SLAB ID	Initial Energy Absorption (N mm X10^3) (E1)		Final Energy Absorption (N mm X10^3) (E2)	
		Experimental	Model	Experimental	Model
1	B1	569.62	581.6251	2237.78	2243.365
2	B2	691.68	679.8094	3295.64	3290.162
3	B3	769.79	781.5401	4213.59	4095.401
4	B4	891.34	879.7244	5023.90	5142.197
5	B5	813.74	756.2605	4923.12	5687.762
6	B6	854.43	864.442	8422.20	7657.592
7	B7	891.34	854.2305	8832.34	8293.107
8	B8	972.37	962.412	9723.67	10262.94
9	B9	854.43	747.8055	6225.11	5938.246
10	B10	854.43	865.9841	8544.26	8831.108
11	B11	1053.40	1088.976	10615.01	10789.18
12	B12	1337.00	1207.154	13856.23	13682.04
13	C1	732.37	754.5152	4597.63	4909.721
14	C2	854.43	832.3143	5736.86	5424.826
15	C3	972.37	1034.77	6644.51	7096.001
16	C4	1174.94	1112.569	8062.54	7611.106
17	C5	1220.61	1136.169	10497.24	10110.27
18	C6	1261.30	1345.83	12775.71	13161.47
19	C7	1418.04	1333.509	15476.84	14335.54
20	C8	1458.55	1543.17	16246.64	17386.74
21	C9	1342.67	1314.388	11799.22	11425.22
22	C10	1627.48	1655.911	16640.97	17012.51
23	C11	3160.19	3273.113	34802.64	35937.76
24	C12	3727.41	3614.636	42662.61	41525.04

Results and discussions

The validation of models for initial energy absorption is shown in Table 5. The models contain both linear, interaction and square terms**.** These models are described as follows:

Initial Energy Absorption

The multiple regression model indicated that out of the explanatory variables under study, 3 Variables namely, X_1, X_2, and X_3 have all significantly contributing to Y. The analysis of variance of multiple regression model for Y indicates the overall significance of the model fitted. The coefficient of determination R^2 value showed that these variables put together explained the variations of Y_1 to the extent of 94% and 99.3% for series A and B respectively. Table 4 shows the model statistics and regression coefficients of terms for series A and B for Y_1.

Final Energy Absorption

Three variables namely X_1, X_2 and X_3 significantly contribute to Y_2 in the multiple regressions analysis. The coefficient of determination R^2 value showed that these variables put together explained the variations of Y_2 to the extent of 98.43 % and 99.58% respectively. Table 4 shows the model statistics and regression coefficients of terms for series A and B for Y_2.

Conclusion

The polynomial models made up of three parameters have been used to describe the capacity of initial and final energy absorption of hybrid ferrocement slabs. From this study, a mathematical regression model was developed. The failure pattern of the tested specimen is shown in figures 5 and 6.

i) The mix M4 (1:1.2:0.8), which satisfies the fresh concrete properties as per EFNARC guidelines is used in the present study.
ii) As the percentage of polypropylene fiber increases, the strength characteristic of concrete also increases.
iii) In the mathematical model, the main parameters influencing the energy absorption of HF slabs are number of layers of GFRP sheet (X_1), height of drop (X_2) and area of weld mesh (X_3).
iv) The correlation coefficients were 0.9400, 0.9930, 0.9843 and 0.9958 for the prediction of initial and final energy absorption of series B and series C respectively.

v) The R^2 value indicates that the model is significant and the predicted results were found to be in good agreement with the experimental results.
vi) The HF slab C12 showed the maximum amount of energy absorption and ductility index, when compared to other specimens.

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