COMPORTAREA LA IMPACT DE JOASĂ ENERGIE A BETOANELOR ARMATE CU FIBRE, OBȚINUTE CU AMESTECURI CIMENTOIDE BINARE ȘI CUATERNARE DE BARBOTINĂ CALCAROASĂ, CENUȘĂ DE TERMOCENTRALĂ ȘI METACAOLIN
ON LOW-ENERGY IMPACT RESPONSE OF FIBRE REINFORCED CONCRETE MADE WITH BINARY AND QUATERNARY CEMENTITIOUS BLENDS OF LIME SLUDGE, FLY ASH AND METAKAOLIN

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This study examines the low-energy impact response of Fibre Reinforced Concrete (FRC) made of binary and quaternary cementitious blends, comprising of Lime Sludge (LS), Fly Ash (FA) and Metakaolin (MT). Hooked end steel fibres of aspect ratio 50 were used at different volume fractions of 0.5%, 1.0%, and 1.5%. Altogether 34 concrete mixes were designed using binary and quaternary cementitious systems with water-to-cementitious ratios (w/c) of 0.32 and 0.4. The binary systems were designed with various LS proportions ranging from 5% to 15%, although the quaternary system consisted of various proportions of LS (5%, 10% and 15%), 15% of FA and 5% of MT as a partial substitute of cement. Impact test was conducted on FRC specimens using drop weight facility, recommended by American Concrete Institute (ACI) Committee 544. Based on the obtained experimental results, an analytical multiple linear regression analysis was executed to evaluate the impact energy at first crack and failure of FRC made with binary and quaternary cementitious blends. These result reveals that replacing cement by optimized proportions of 10% LS, 15% FA and 5% MT as a pozzolanic material along with steelfibres has significantly enhanced the impact energy absorption capacity of concrete.

Keywords:*Impact load, Fibre, Lime sludge, fly ash, Metakaolin.*

1. Introduction

Concrete is the most widely used building material that will continue to be in ultimatum owing to its enormous applications in building constructions and many other structures [1]. Cement is used as a primary binding material in concrete and its manufacturing, produces a huge quantity of unsolicited products (e.g., CO_2emissions), which affects the environment severely [2]. Reduction of CO_2 emission during cement manufacturing is a major anxiety in today's world which has led to utilization of blended cements and it is largely attempted by replacing clinker with supplementary cementitious materials [3]. In this view, several industrial products like fly ash, blast furnace slag, lime sludge, sugarcane baggase ash and rice husk ash, etc. can be effectively utilized as supplementary cementitious materials [4-6], for enhancing the durability and mechanical properties of concrete [6-11]. The substitution of cement by fly ash and calcined clay resulted in lowering SO_3/ Al_2O_3 ratios and introduces aluminates in the system for better performance of concrete. Calcium carbonate up-to 15% and fly ash of 25 % in composite cement concrete satisfies the conventional durability requirements for shrinkage, chloride attack, sulphate attack and corrosion resistance [12,13].They are obtained from various industries as wastes or by-products and the benefits of using them in cement are well established [14-19]. The commonly used binary and ternary cementitious blends to produce sustainable concretes are fly ash, metakaolin, lime sludge and silica fume [3, 20-23], but the research based on quaternary cementitious blends is quite limited.

Though quaternary blends have the disadvantage of making the concrete brittle their role in manufacturing sustainable concrete is indispensable. Wide concern has been given by researchers to counteract this brittle nature of concrete by improving the ductility. A widely used general phenomenon to enhance the ductility of high strength concrete mixtures is incorporation of various types of fibres, especially steel fibres into the concrete [24-26]. The fibres present in the concrete mixtures performs various actions such as bridging cracks, providing ductility, transferring loads, as well as improving its compressive, flexural, tensile and impact strength etc. [27-30].

Banthia et al. [30] investigated the dog-bone shaped concrete specimens made with straight carbon, steel and polypropylene subjected

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to direct tensile impact. The FRC specimens containing higher fibre volume fractions were strong and tough under impact, enhancing the tensile strength and fracture energy. Nili and Afroughsabet[31] studied the impact resistance of concrete made with the combined effect of 8% silica fume as a cement substitution and polypropylene fibre with two different water binder ratios of 0.36 and 0.46. The 0.46 water cement ratio specimens incorporating 0.2%, 0.3% and 0.5% of polypropylene fibre along with silica fume in concrete exhibited an upsurge in impact strength at first crack by 31%, 100% and 360% and failure by 42%, 107% and 376% respectively when compared to non-fibrous concrete. Hao et al. (2016) [32] examined the impact strength of hooked end and spiral shaped steel FRC subjected to drop weight impact test from two different drop heights, viz. 0.5 and 1.0 m. Impact test was conducted on 350 x 100 x 100 mm specimens incorporating fibres at dosages of 0.5% and 1.0 %. Results suggested that, for a specific fibre volume fraction the dissipation of impact energy is more significant in spiral steel fibres compared to hooked-end steel fibres, irrespective of the drop height. Ong et al. [33] presented that concrete containing polyolefin reinforcement had the smallest amount of energy absorption when compared to steel and VPA fibre reinforced concrete by carrying out an experimental study with polyolefin, steel and VPA fibre reinforced concrete. Badr et al. [34] examined the impact resistance of polypropylene fibre reinforced concrete by conducting a statistical analysis and the ACI recommended repeated drop weight impact testing method and concluded that at least 40 specimens would be necessary for achieving reliable statistical analysis results. In order to assess the impact behaviour of concrete structures few researchers have used the analytical and numerical methods. For instance, Habel and Gauvreau [35] carried out an experimental investigation on ultra-high performance FRC, also executed the nonlinear mass-spring models to analyse its impact performance. The experimental results and the values arrived using the theoretical model were found to be in good agreement.

Although the recent studies engrossed either on impact response or high-velocity impact response of FRC specimens [36-41], the low-energy impact performance of FRC made with binary and quaternary cementitious blends has not yet been examined. Low-energy impact is quite common in everyday life that includes accidental tool drop, impact of debris during a storm or a low-velocity impact collision against concrete structures, etc. Assessing the performance of FRC under low-energy impact applications and developing analytical models which can predict the performance accurately has become substantial in recent years. In this regard, the present study focuses on the low-energy impact performance of FRC made with binary and quaternary cementitious blends including the use of lime sludge, fly ash and metakaolin which was not yet explored by the any of the earlier researcher.

2. Experimental campaign

2.1 Materials and Mixing Procedure

The materials used in the preparation of specimens are as follows; ordinary Portland cement 53 grade was used as the clinker and gypsum (<3.5%) was added along with it to control its setting time. For preparing binary and quaternary binders, the portland cement (clinker) was partially replaced with lime sludge (LS), fly ash-F (FA) conforming to IS: 3812-2003 [42] and metakaolin. The chemical and physical properties of these supplementary cementitious materials (LS, FA, and MT) used in this study are listed in Table 1. The fine aggregate used was zone II natural river sand conforming to IS: 383-2016 [43] with a specific gravity of 2.67, a bulk density of 1811 kg/m^3, fineness modulus of 2.90 and water absorption 0.6. Crushed granite gravel of sizes 20 mm and 12.5 mm in the ratio of 60:40 respectively were used as the coarse aggregates. Crushed granite gravel is a natural coarse aggregate material that is comprised of solid granite that has been harvested, crushed and screened down to a specific particle size for use in concrete production. Granite has long been renowned for its natural, simplistic, subtle elegance and is easily available in India with low cost.The fineness modulus, specific gravity and water absorption of coarse aggregate used was 6.66, 2.73 and 0.3 respectively. In order to attain a nominal target slump value of 75 ± 10 mm, Sulphonated Naphthalene Polymer based superplasticizer (SP) Conplast 430 conforming to IS: 9103-1999 [44] with a specific gravity of 1.20 was used. Hooked end steel fibres used in this study had 50 mm length, 1.0 mm diameter, 1050 MPa tensile strength and an aspect ratio of 50. The fibre volume (FV) used were 0.5%, 1.0% and 1.5% and the mix proportions of each specimens are tabulated in Table 2. A laboratory concrete mixture machine was used for concrete production. The procedure adopted for preparing the mixtures was as follows; Initially, the cement and fine aggregates were mixed for 4 minutes after which the coarse aggregate was added and mixed for about 4 minutes. Following this, the water and SP was added and the mixing process was continued for another 4 minutes until a nearly homogeneous mixture was attained. Finally, the steel fibres were added and mixed for another 3 minutes.

2.2 Test procedure

As per IS: 516-1979, the compressive strength test was performed after 28 days on

Table 1

Chemical and physical characteristics

Constituents	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	Na_2O (%)	LOI (%)	SO_3 (%)	Specific gravity	Blaine's Fineness m^2/kg
Clinker	63.85	21.53	5.39	4.24	1.01	0.11	0.68	1.02	-	-
FA	1.46	64.01	23.40	6.63	1.4	-	0.48	0.55	2.5	324
LS	51.53	0.43	-	-	3.64	-	42.46	0.25	2.4	550
MT	1.20	52.10	43.10	1.01	0.10	0.05	0.40	0.21	2.5	15200
GYP	32.12	1.06	0.08	0.20	0.60	0.01	20.15	45.62	2.3	-

Table 2

Mix proportions of compositions.

Mix ID	W/C	Cement content (kg/m^3)	Clinker + Gypsum %	LS (%)	FA (%)	MT (%)	Aggregate		FV (%)	SP (%)
							Fine (kg/m^3)	Coarse (kg/m^3)		
PC		410	100	0	-	-	801	1113	-	0.6
B5		389.5	95	5	-	-	801	1113	-	0.6
B10		369	90	10	-	-	801	1113	-	0.6
B15		348.5	85	15	-	-	801	1113	-	0.7
QL0		328	80	0	15	5	801	1113	-	0.8
QL5		307.5	75	5	15	5	801	1113	-	0.8
QL10		287	70	10	15	5	801	1113	-	0.8
QL15		266.5	65	15	15	5	801	1113	-	0.9
QL5-F 0.5	0.4	307.5	75	5	15	5	801	1113	0.5	1.1
QL5-F 1.0		307.5	75	5	15	5	801	1113	1	1.3
QL5-F 1.5		307.5	75	5	15	5	801	1113	1.5	1.5
QL10-F 0.5		287	70	10	15	5	801	1113	0.5	1.1
QL10-F 1.0		287	70	10	15	5	801	1113	1	1.3
QL10-F 1.5		287	70	10	15	5	801	1113	1.5	1.5
QL15-F 0.5		266.5	65	15	15	5	801	1113	0.5	1.2
QL15-F 1.0		266.5	65	15	15	5	801	1113	1	1.4
QL15-F 1.5		266.5	65	15	15	5	801	1113	1.5	1.6
PC		530	100	0	-	-	801	1113	-	0.8
B5		503.5	95	5	-	-	801	1113	-	0.8
B10		477	90	10	-	-	801	1113	-	0.8
B15		450.5	85	15	-	-	801	1113	-	0.9
QL0		424	80	0	15	5	801	1113	-	0.9
QL5		397.5	75	5	15	5	801	1113	-	0.9
QL10		371	70	10	15	5	801	1113	-	0.9
QL15		344.5	65	15	15	5	801	1113	-	1
QL5-F 0.5	0.32	397.5	75	5	15	5	801	1113	0.5	1.2
QL5-F 1.0		397.5	75	5	15	5	801	1113	1	1.4
QL5-F 1.5		397.5	75	5	15	5	801	1113	1.5	1.6
QL10-F 0.5		371	70	10	15	5	801	1113	0.5	1.2
QL10-F 1.0		371	70	10	15	5	801	1113	1	1.4
QL10-F 1.5		371	70	10	15	5	801	1113	1.5	1.6
QL15-F 0.5		344.5	65	15	15	5	801	1113	0.5	1.3
QL15-F 1.0		344.5	65	15	15	5	801	1113	1	1.5
QL15-F 1.5		344.5	65	15	15	5	801	1113	1.5	1.7

150 x 150 x 150 mm cubic specimens [45]. Simulating the dynamic loading is quite challenging till today which makes it difficult to define a standardized test setup. In the report published by the ACI committee 544 [46], a device works according to the principle of steel hammer that repeatedly blows onto the cylindrical specimens in order to produce certain amount of energy. A blow was introduced through 4.45 kg compaction steel hammer that repeatedly drops from a height of 457 mm on 64 mm steel ball that was located at the centre of the top surface of the cylindrical

specimen. The cylindrical specimens of size 150 mm diameter and 64 mm height was placed on a base plate with four positioning lugs, and the test was executed based on ACI Committee 544 and the test setup as shown in Figure 1[47]. For each specimen, the number of blows required to produce the first visible crack (N1) and failure (N2) were noted. Totally 102 cylindrical specimens were prepared and tested under the impact load.

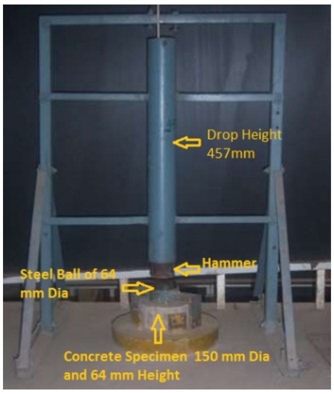

Fig.1- Experimental Setup for the Impact test.

3. Results and discussion

3.1. Compression strength

Table 3 displays the average compressive strength values of various combination of binary and quaternary composites incorporated with steel fibres which are grouped based on W/B ratio (0.4 and 0.32). For both the control and blended cement FRC, decreasing the W/B ratio significantly increased its compressive strength.For the W/B ratio 0.4, the compressive strength increased by 1% for both 5% and 10% LS replacement in binaryblendedcementitious system (B5 and B10) as compared to plain concrete (PC) [48-51]. On the other hand, the compressive strength decreased by 3% while replacing with 15% LS in binary blended cementitious system (B15). In the case of 0%, 5%, 10%, 15% LS and 15% FA and 5% MT replacement of cement in quaternary blended cementitious system (QL0, QL5, QL10 and QL15) the compressive strength increased by 11%, 12%, 13%, 9% respectively when compared to PC. The increase in compressive strength was comparatively reduced in 15% LS and 15% FA and 5% MT replacement specimens (QL15) and it was lesser than 0%, 5%, 10% LS and 15% FA and 5 % MT replacement specimens (QL0, QL5 and QL10) by 20%, 28% and 33% respectively.

As shown in Table 3, with reference to PC, the compressive strengths of 5% LS, 15% FA and 5% MT quaternary cementitious blended FRC specimens with fibre dosage of 0.5%, 1.0% and 1.5% (QL5-F 0.5, QL5-F 1.0 and QL5-F 1.5) increased by 20%, 25% and 31% respectively. For 10% LS, 15% FA and 5% MT quaternary cementitious blended FRC specimens with fibre dosage of 0.5%, 1.0% and 1.5% (QL10-F 0.5, QL10-F 1.0 and QL10-F 1.5) the compressive strength increased by 22%, 27% and 34% respectively as compared with PC. Also, the 15% LS, 15% FA and 5% MT quaternary cementitious blended FRC specimens with fibre dosage of 0.5%, 1.0% and 1.5% (QL15-F 0.5, QL15-F 1.0 and QL15-F 1.5) showed an increase in compressive strength by 19%, 22% and 30% respectively when compared to PC. For the w/b ratio 0.32, a similar trend in the results was observed and is shown in Table 3. The result shows that higher the fibre dosage in the quaternary cement concrete mixtures, the higher is its compressive strength [51].

The replacement of cement by LS which has a higher surface area significantly enhances the compressive strength and other mechanical

Table 3

Comparison of Strength, Number of blows and Impact energy

Mix ID	Compressive Strength	Number of Blows		Impact Energy	
	28 Days	N1	N2	N1	N2
PC	48.72	34	42	692	854
B5	49.31	37	44	753	895
B10	49.2	36	43	732	875
B15	47.1	33	40	671	814
QL0	55.32	72	108	1465	2197
QL5	55.94	75	118	1526	2401
QL10	56.45	78	121	1587	2462
QL15	53.4	66	105	1343	2136
QL5-F 0.5	57.21	95	164	1933	3337
QL5-F 1.0	59.65	112	204	2279	4150
QL5-F 1.5	61.03	121	222	2462	4517
QL10-F 0.5	58.68	101	170	2055	3459
QL10-F 1.0	60.23	122	209	2482	4252
QL10-F 1.5	61.62	130	229	2645	4659
QL15-F 0.5	56.42	94	158	1912	3215
QL15-F 1.0	57.12	99	179	2014	3642
QL15-F 1.5	57.09	101	188	2055	3825
PC	69.2	74	98	1506	1994
B5	70.5	79	103	1607	2096
B10	70.68	78	104	1587	2116
B15	67.1	71	91	1444	1851
QL0	75.29	99	150	2014	3052
QL5	75.8	99	159	2014	3235
QL10	76.12	105	162	2136	3296
QL15	74.62	81	130	1648	2645
QL5-F 0.5	78.61	149	221	3031	4496
QL5-F 1.0	80.58	168	254	3418	5168
QL5-F 1.5	81.92	173	265	3520	5391
QL10-F 0.5	79.16	151	223	3072	4537
QL10-F 1.0	81.28	174	260	3540	5290
QL10-F 1.5	82.51	177	268	3601	5452
QL15-F 0.5	75.13	121	171	2462	3479
QL15-F 1.0	76.45	137	195	2787	3967
QL15-F 1.5	76.87	161	235	3276	4781

properties [52]. The replacement effect of LS did not contribute to the pozzolanic reaction [53-54] but seemed to act as additional nucleation sites for cement hydration, filler effect or shearing conditions and in addition these contributes little to the strength development [52,55-62]. Thus, LS was not efficient in binary blends due to lack of aluminates in the cementitious system and was likely to be more appropriate in a quaternary cementitious system along with FA and MT [58-59,63-64]. Quaternary blends demonstrated the synergic effect of LS, FA and MT. This is attributed to (i) carbo aluminate hydrates formation & stabilization of ettringite in the system [63] (ii) Increase in volume of hydrates and decrease in porosity in system [58-62,64] and (iii) Increased packing density and shearing conditions or effect [62].

3.2. Impact resistance under drop weight test

The impact resistance performance of FRC made with binary and quaternary cementitious blends for two different w/b ratios (0.32 and 0.4) was noted in terms of numbers of blows at first visible crack (N1) and failure (N2) and it is shown in Table 3. The first crack was noted based on visual observation while the failure was noted by crack opening that leads to failure of the specimen.

The impact energy delivered by the compaction hammer per blow is determined by the following equation:

$$\text{Impact energy } U = \left(\frac{n\,m\,V^2}{2}\right) \quad (1)$$

$$H = \left(\frac{gt^2}{2}\right) \quad (2)$$

$$V = g\,t \quad (3)$$

$$m = W/g \quad (4)$$

where, N; Number of blows, *V*; Hammer velocity at impact, *g*; Acceleration due to gravity, *t*; time required for the hammer to free fall from a 457-mm height. *H*; Drop height of hammer, *m*; Drop hammer mass (4.45 kg) and *W*; Drop hammer weight. Substituting the appropriate values in Eq. (1) yields:

$$457 = \frac{9810t^2}{2}$$

$$t = 0.3052 \text{ s and } V = 9810 \times 0.3052 = 2994.01 \text{ mm/s}$$

The impact energy delivered by the hammer per blow (U) can be obtained by substituting the values in Eq. (1)

$$U = \frac{44.5x2994.01^2}{2x9810} = 20.345 \text{ kN mm}$$

Table 3 displays that impact energy at first crack and failure was higher in both binary and quaternary cementitious concrete when compared to plain concrete (PC) excluding the 15% LS substitution of cement in binary cementitious concrete specimens (B15) and 15% LS, 15% FA and 5% MT substitution of cement in quaternary cementitious concrete specimens (QL15). With reference to PC, the impact energy at first crack and failure for B5 concrete specimens were increased by 9% and 5% respectively; for B10 concrete specimens it was increased by 6% and 2 % respectively; while the B15 concrete specimens exhibited a 3% and 7.7% reduction in impact energy at first crack and failure respectively. Therefore, the impact energy at first crack and failure for B15 concrete specimens were insignificant.

On the other hand, the increase in impact strength at first crack for 0%, 5%, 10%, 15% LS and 15% FA and 5% MT substitution of cement in quaternary cementitious concrete (QL0, QL5, QL10, QL15) were 112%, 121%, 129%, 94% respectively. Similarly, the increase in impact energy at failure for QL0, QL5, QL10, QL15 concrete specimens were 157%, 181%, 188%, 150% respectively. It is inferred that the impact energy of QL15 samples reduced considerably. Though impact energy at the first crack and failure was higher than PC, the specimens exhibited a negative effect compared to QL10. The positive effect in quaternary cementitious concrete was based on the properties of FA and MT, and its proportions. As the results suggest, replacement of cement by 15% LS in binary cementitious concrete (B15) and 15% LS, 15% FA, 5% MT in quaternary cementitious concrete (QL15) lead to negative effect in impact energy and a similar trend was observed in w/b ratio of 0.32 which is illustrated in Table 3.

It can also be noted from Table 3 that, when compared with PC, there is an increase in number of blows at first crack and failure in FRC specimens made with binary and quaternary cementitious blends for both w/b ratio 0.40 and 0.32. When compared to PC, the impact energy at first crack for 5% LS, 15% FA and 5% MT quaternary cementitious blended FRC specimens with fibre dosage of 0.5%, 1.0% and 1.5% (QL5-F 0.5, QL5-F 1.0 and QL5-F 1.5) increased by 179%, 229% and 256% respectively. Correspondingly, the impact energy at failure increased by 290%, 386%, and 429% respectively. In the same way, the impact energy at first crack for 10% LS, 15% FA and 5% MT quaternary cementitious blended FRC specimens with fibre dosage of 0.5%, 1.0% and 1.5% (QL10-F 0.5, QL10-F 1.0 and QL10-F 1.5) increased by 218%, 306% and 347% respectively when compared to PC; Also, the increase in impact energy at failure was 305%, 398% and 445% respectively. For the 15% LS, 15% FA and 5% MT quaternary cementitious blended FRC specimens with fibre dosage of 0.5%, 1.0% and 1.5% (QL15-F 0.5, QL15-F 1.0 and QL15-F 1.5) the increase in impact energy at first crack and failure were 197%, 259%, 282% and 290%, 360%, 426% respectively. As the w/b ratio was decreased from 0.4 to 0.32, increased impact strength and lower ductility of non-fibrous concrete specimens were observed. The impact

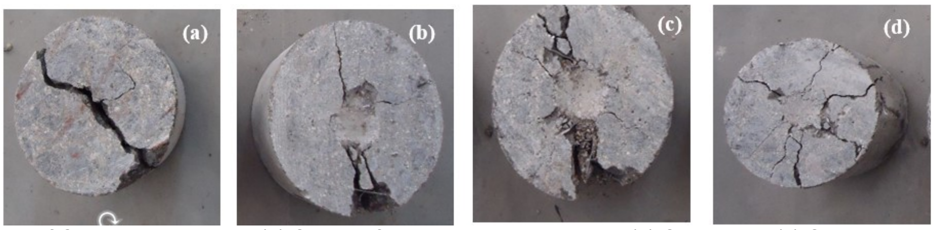

Fig. 2 - Failure Pattern of Concrete specimens (a) QL0non-fibrous concrete specimen (b) QL10-F 0.5 (c) QL10-F 1.0 and (d) QL10-F 1.5.

strength results of specimens with w/b ratio of 0.32 are shown in Table 3 and the similar trend was observed as that of 0.40 w/b ratio. These results reveal that simultaneous use of LS, FA, MT along with steel fibres can greatly increase the impact energy and reduce the brittleness of concrete with an increased fibre dosage.

3.3. Failure Patterns

The failure patternsof quaternary cementitious blended non-fibrous and fibrous concrete specimens under impact loading are shown in the Figure 2 (a)-(d). Brittle mode of failure was observed in both binary and quaternary cementitious blended non-fibrous concrete specimens, which was broken into two halves as shown in Figure 2 (a). From the Figure 2 (b)-(d),addition of steel fibres to concrete at a dosage of 0.5% to 1.5% resulted in an increasing a group of narrow cracks, which changed the failure pattern from brittle to ductile [65-66]. This displays the positive effect of quaternary cementitious blended FRC subjected to impact load.

3.4. Multiple Linear Regression

The impact energy at first crack and failure of specimens were considered as dependent variables and was calculated based on function of four input independent variables as follows.

i. Compressive strength of concrete (x_1)
ii. Water binder ratio w/b (x_2)
iii. Fibre dosage (%) (x_3) and
iv. Lime sludge content (%) (x_4) and

The impact energy at first visible crack and failure of specimens are largely reliant upon the four variables (x_1 to x_4) and hence these variables were used to form the multiple linear regression equation as given below:

$$y = a_0 + \sum a_i x_i \quad {}_{(i=1\ to\ n)} \qquad (5)$$

The mathematical model for predicting the impact energy at first crack and failure is expressed by a linear equation (6) and by redrafting the equation (5) in the expanded form as,

$$U = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 \qquad (6)$$

Where U is the estimated impact energy at first crack and failure, a_0 to a_4 are the regression coefficients, and x_1, x_2......x_4 are the independent variables. The statistical model was developed using SPSS software package as given in equation 7 and 8 and the correlation coefficients for U (N1) and U (N2)were found to be 0.963 and 0.982 respectively.

$$U\ (N1) = -11817.8 + (110.128 * x_1) + \\ +(17789.56 * x_2) + \\ +(441.474 * x_3) + (3679 * x_4) (7)$$

$$U\ (N2) = -25890.7 + (207.296 * x_1) + \\ +(41797.22 * x_2) + \\ +(731.105 * x_3) + (8.276 * x_4) (8)$$

The impact energy at first crack and failure were calculated using the multiple linear regression equations 7 and 8 respectively. The predicted values were in good agreement with the experimental values. Also, the difference between experimental and predicted value was less than 15% and hence a higher accuracy has been achieved as shown in Figure 3. Since the proposed multiple linear equations possessed the determination coefficient (R^2) values higher than 0.7, it was considered as equitable as suggested by most statisticians [67]. Nevertheless, the validity of appropriate equations was also based on the determination coefficient (R^2) values [68], the R^2 value alone would not be adequate to validate the developed equations [68] and these results should be combined with numerous reliable statistical indicators to assess the accuracy of the proposed equations.

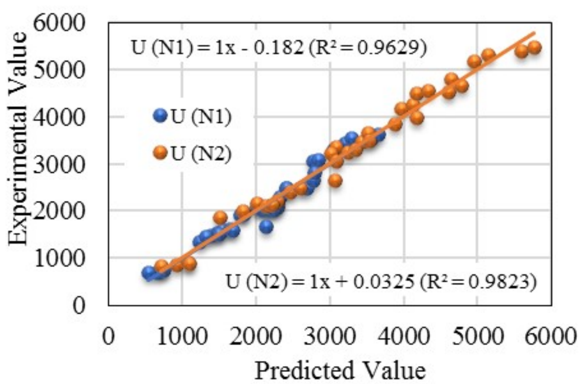

Fig. 3 - Experimental against predicted value.

3.5. Statistical Indicators used for Performance Evaluation

To assess the performance of proposed multiple linear regression equations for estimation of impact energy at first crack and failure, different statistical approaches including five reliable statistical indicators have been used. Five statistical parameters consisting root mean squared error, mean absolute percentage error, mean absolute deviation, integral absolute error and relative root mean square error have been employed to offer an appropriate comparative assessment. A brief description of the considered statistical indicators is offered below.

3.5.1. Root Mean Squared Error (RMSE)

RMSE identifies the model's accuracy by comparing the variation between experimental value (E_V) and predicted values (P_V) and it can be determined from Eq (9). If RMSE has positive value and it is closer to zero it indicates, a good fit [69].

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_V - P_V)^2} \qquad (9)$$

3.5.2. Mean absolute percentage error (MAPE)

The MAPE shows the mean absolute percentage difference between E_V and P_V. The MAPE is calculated as follows [70]:

$$MAPE = \left(\frac{1}{n}\sum_{i=1}^{n}\left|\frac{E_V - P_V}{E_V}\right|\right) \times 100\% \qquad (10)$$

3.5.3. Mean Absolute Deviation (MAD)

MAD denotes the average quantity of errors between the E_V and P_V. The MAD is calculated as follows [71].

$$MAD = \frac{\sum|E_V - P_V|}{n} \qquad (11)$$

3.5.4. Integral Absolute Error (IAE)

IAE is employed to evaluate the deviation between the E_V and P_V curves. This is written as [72].

$$IAE = \sum\frac{[(E_V - P_V)^2]^{1/2}}{E_V} \times 100 \qquad (12)$$

3.5.5. Relative Root Mean Square Error (RRMSE)

The RRMSE is obtained by dividing the RMSE to the average of impact energy obtained experimentally as follows:

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_V - P_V)^2}}{\frac{1}{n}\sum_{i=1}^{n}E_V} \qquad (13)$$

The model's precision can be signified with help of RRMSE ranges. The model's different ranges of RRMSE can be well-defined to signify the models' precision as: Excellent when RRMSE < 10%; Good when 10% < RRMSE < 20%; Fair for 20% < RRMSE < 30%; Poor for RRMSE > 30%.

Based on the statistical analysis the proposed equations have the highest R^2 and the lowest values for RMSE, MAD, MAPE, IAE, RRMSE and RPE for both U (N1) and U (N2) is shown in Table 4, which ensures that it is the most accurate validation for the developed equations to predict the impact energy at first crack and failure.

Table 4

Comparison of results obtained from five statistical indicators.

Impact Energy	RMSE	MAD	MAPE	IAE	RRMSE	R^2
U (N1)	1.158	-0.199	0.000	0.000	0.055	0.963
U (N2)	0.217	0.037	0.000	0.000	0.007	0.982

4. Typical applications of FRC

Fiber reinforced concrete is recommended in all types of concretes which demonstrate a need for enhanced resistance to intrinsic cracking, toughness characteristics and improved water tightness such as:-industrial floorings, canal linings, bridge decks, pavements, precast structures, tilt-up panels, reinforced cement concrete elements, walls and thin sections.

5. Conclusions

From the results presented in this investigation on impact response of FRC made with binary and quaternary cementitious blends, including the use of LS, FA and MT, the following conclusions are derived:

- The substitution of 5% and 10% LS in binary cementitious blended concrete (B5 and B10), led to slight increase in compressive strength by 1% respectively with reference to PC for the w/b ratio of 0.40, while the 15% substitution (B15) led to reduction in compressive strength by 3%. Beyond 10% LS replacement in binary cementitious blended concrete, the reduction in compressive strength was larger and hence 10% LS replacement (B10) was optimum for binary cementitious blended concrete.
- In quaternary cementitious blended concrete mixtures, the cement replaced with 5%, 10% and 15% of LS along with 15% FA, 5% MT (QL5, QL10, QL15), conceded an increase in the compressive strength by 12%, 13% and 9% respectively with reference to PC for w/b ratio of 0.40. It is ideal to replace 10% LS along with 15% FA and 5% MT in quaternary blends as it increases the compressive strength to a greater extent for both the w/b ratios. When the fibre dosage was increased in the quaternary cementitious blended concrete mixtures, higher compressive strength was achieved.
- The result reveals that the maximum increase in impact energy at first crack and failure for both the w/b ratio was observed for 10% LS in quaternary cementitious blended FRC specimens (QL10-F 0.5, QL10-F 1.0, QL10-F 1.5). For w/b ratio 0.4, the increase in impact energy at first

crack for QL10-F 0.5, QL10-F 1.0, QL10-F 1.5 were 218%, 306% and 347% respectively and the corresponding increase in impact energy at failure were 305%, 398% and 445% respectively with reference to PC.

- Brittle failure was observed in non-fibrous binary and quaternary cementitious concrete specimens while it was exhibited to ductile failure in case of FRC specimens. These results reveal that replacing cement by optimized proportions of LS, FA and MT as a pozzolanic material along with steel fibres has significantly enhanced the impact energy absorption capacity of concrete.
- The proposed multiple linear equations were precise to evaluate impact energy at first crack and failure and the coefficients of determination (R^2) values hitting 0.963 and 0.982 respectively. The validity of the proposed equations using RMSE, MAD, MAPE, IAE and RRMSE had the values closer to zero and highest values of R^2 nearer to 1 indicates a good fit and higher accuracy.

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