Journal of Building Pathology and Rehabilitation (2019) 4:2
https://doi.org/10.1007/s41024-018-0041-5

RESEARCH ARTICLE

Study on strength and durability characteristics of lime sludge based blended cement concrete

V. V. Praveen Kumar[1] · D. Ravi Prasad[1]

Received: 3 September 2018 / Accepted: 29 November 2018 / Published online: 11 December 2018

Abstract

The present investigation is focused on developing ternary blended cement concrete mix of different grades 30 MPa, 50 MPa and 70 MPa containing fly ash, silica fume and lime sludge in different proportions. The optimum content of these materials was obtained after several trails. Mechanical properties such as compressive, flexural and split tensile strength of ternary blended cement concrete were determined and compared with the control mix (without any supplementary cementitious material). The chemical resistance of ternary blended cement concrete was also studied by exposing it to acids HCl and H_2SO_4 at 5% concentration. Acid mass loss factors (AMLF), acid strength loss factor (ASLF) and acid durability factor were determined, and the results were compared with control mix. Short term chloride ions penetration was also investigated like rapid chlorination penetration test and accelerated corrosion penetration test on control mix and ternary blended cement concrete. The results indicated that there is a significant improvement in the mechanical properties, shown better resistance in an acid environment and chloride ion penetration.

Keywords Strength characteristics · Fly ash · Silica fume · Lime sludge · Ternary blended concrete · Rapid chlorination penetration test · Accelerated corrosion penetration test · Acid attack study

1 Introduction

Cement concrete composite consisting of cement, aggregates, water and special materials is the most commonly used material in the construction industry all over the world possessing good strength and durability characteristics. It is reported that the increase in demand for cement has led to the massive emission of greenhouse gases. The production of 1 t of cement is producing a massive amount of CO_2 which is about 6% of all man-made carbon emissions which is extremely hazardous, and there is a definite need to reduce the emissions to maintain the sustainability and alternative materials available such as industrial by-products which gives us same strength as that of Portland cement without compromising durability aspects. This usage can reduce the usage of cement production and also reduce the disposal problems caused these industrial by-products [1–4]. Fly ash is the most common material that is being used as a partial replacement of cement in concrete due to its pozzolanic property for structural applications. Much research is carrying out on supplementary cementitious materials like ground granulated blast furnace slag, metakaolin, silica fume, fly ash as a partial replacement for standard and high strength concretes [5, 6].

Experimental investigations revealed that pozzolanic materials like silica fume are rich in silica and consist of tiny solid spherical particles significantly enhances the strength characteristics of concrete. Fly ash is also popular pozzolana which improves real properties in both fresh and hardens state with high fineness. Rice husk ash in concrete as partial replacement of cement up to 20% can achieve high strength concrete with better durability characteristics and excellent chemical resistance to chlorides compared to control mix. It is evident from the literature that rice husk ash concrete shows better strength characteristics and silica fume concrete enhances durability characteristics like reduction in chloride ions penetrability [7–11]. Investigations in the similar research area of supplementary cementitious materials and concluded that materials like Palm oil fuel ash, when used as partial replacement of

✉ V. V. Praveen Kumar
praveen.vemu123@gmail.com

D. Ravi Prasad
drprasadravi@gmail.com

[1] Department of Civil Engineering, National Institute of Technology, Warangal, India

cement up to 20%, can achieve strength like that of 5–10% silica fume concrete. It was also concluded that certain natural pozzolanic and silica fume combinations could improve the strength of concrete more than natural pozzolana or silica fume concrete [12, 13].

Studies on pozzolanic materials and results inferred that these materials substantially improve the durability characteristics of concrete like impermeability, resistance to chloride ion penetration into the structural members which protects corrosion of reinforcement steel inside concrete [14–16]. Incorporation of pozzolanic materials was very beneficial and it significantly performed against degradation in an aggressive environment and also enhanced durability. Binary blended cement concrete with pulverized fly ash and metakaolin with various combinations of optimization technique cementitious system in conventional curing and air curing showed enhanced strength, durability, carbonation depth and development of high-performance concrete. It is reported that chloride ions ingress was one of the primary reasons for the corrosion of provided steel reinforcement and new materials are to be utilized to safeguard reinforcement [17–19].

Investigation on ternary blended concrete with cement, fly ash and silica fume was done and concluded that there is a significant increase in strength and enhanced durability compared to control mix [20]. Binary blended limestone filler with natural pozzolana in cement concrete showed high early strength and contributing to average and later ages with better performance under sulfate attack and chloride ions permeability [21]. Long-term resistance to sulphate attack for blended concrete with fly ash and silica fume was analyzed in H_2SO_4 2% concentration and it was observed that the pozzolana are very good in chemical resistance and both the mineral admixtures in concrete are making concrete more impermeable which indicates less porous and as a result of less ingress of ions into the concrete specimens at acid attack study. Durability is also one of the crucial aspects to be studied. Many papers reveal that fly ash and silica fume when used as a partial replacement in certain combinations enhances the durability of concrete [22, 23]. Many supplementary cementitious materials (SCM's) like fly ash, slag cement, rice husk ash metakaolin, palm oil fuel ash, silica fume are being used extensively, but in the current investigation an attempt was made to check the suitability of using lime sludge (by-product from paper industry) as a partial replacement of cement along with two other pozzolanic materials and trying to prepare a ternary blended cement concrete.

2 Materials and methods

2.1 Materials

2.1.1 Cement

Cement used in the investigation was 53 Grade Ordinary Portland cement conforming to IS 12269-1987 [24]. The specific gravity of cement was 3.14, and the specific surface area was 225 m^2/kg having initial and final setting time of 40 min and 560 min respectively.

2.1.2 Fine aggregate

The fine aggregate conforming to zone-2 according to IS: 383-1970 [25] was used. The fine aggregate used was obtained from a nearby river source. The specific gravity was 2.65; the bulk density of fine aggregate was 1.45 g/cc.

2.1.3 Coarse aggregate

Well graded crushed granite having 20 mm nominal size was obtained from a local crushing unit having 20 mm nominal size according to IS: 383-1970 [25]. The specific gravity was 2.8, and the bulk density was 1.50 g/cc.

2.1.4 Fly ash

For the present investigation, fly ash of low calcium confirming IS 3812: 2003 part 1 and 2 [26] was used. It was obtained from Ramagundam Thermal Power Plant, India. Specific gravity and fineness of fly ash used are 2.12 and 318 m^2/kg respectively.

2.1.5 Silica fume

Silica fume conforming to IS 15388-2003 [27] obtained from Elkam Company having a specific gravity of 2.22.

2.1.6 Lime sludge

Lime sludge consists of cellulose, and moisture content is nearly about 40%. The material is hard to dry, sticky, viscous and can vary in lumpiness and viscosity. Lime sludge was obtained from ITC Badrachalam (India) and stored correctly. The initial setting time, final setting time, specific gravity and normal consistency, are respectively 42 min, 620 min, 1.98 and 32%, respectively.

Table 1 Chemical composition of mineral admixtures

Chemical composition	Cement	Fly ash	Silica fume	Lime sludge
CaO	61.90	4.32	1.40	48.20
SiO_2	18.50	63.13	92.80	12.55
Fe_2O_3	3.65	5.18	1.20	15.92
Al_2O_3	4.18	25.93	4.60	16.55
MgO	2.38	1.44	0.8	6.78

Table 2 Mix proportions of concrete (Kg/m^3)

Material	30 MPa	50 MPa	70 MPa
Cement	394	418	440
Fine aggregate	775	816	847
Coarse aggregate	1140	1082	1045
Water	197	167	144

2.1.7 Water

For curing and mixing potable water was used as per IS 456-2000 [28].

2.1.8 Chemical admixtures

Polycarboxylate based high range water reducing admixture conforming to ASTM C 494 [29] was used as a superplasticizer as 1.5% by weight of binder content to improve workability throughout the investigation.

Chemical composition of the mineral admixtures used in the present investigation is shown in Table 1.

2.2 Mix proportions

The mix proportions of control mix for three different strengths of 30 MPa, 50 MPa and 70 MPa were designed using IS 10262: 2009 [30] as shown in Table 2.

2.3 Preparation and casting of specimens

In this study, an attempt was made to incorporate lime sludge as one of SCM's in ternary blended cement concrete to evaluate its mechanical properties, chemical resistance against chlorides and sulfates compromising strength and durability aspects. The objective of the current investigation is to establish blended cementitious concrete using three materials namely flyash, silica fume and lime sludge and comparison to control mix (without any supplementary cementitious materials) and to evaluate mechanical and durability properties. In the present investigation, an attempt was made to incorporate mineral admixtures namely fly ash, silica fume and lime sludge as replacement of cement. A detailed experimental program was planned to achieve the objectives of the investigation. The purpose of the investigation is to determine the optimum dosages of fly ash, silica fume and lime sludge that can be replaced in cement using the guidelines of IS 10262:2009 [30]. Concrete mix proportions of target compressive strength of 30 MPa, 50 MPa and 70 MPa concrete designed without any mineral admixtures. Firstly, fly ash was optimized varying it from 0 to 25% of cement. Later, keeping optimized fly ash content as constant silica fume was optimized by varying it from 0 to 10% of cement. Later, keeping optimized fly ash and silica fume content as constant, lime sludge was optimized by varying it from 0 to 20% of cement. Ternary blended cement concrete mix design was developed using all the optimized contents of fly ash, silica fume, and lime sludge as partial replacement of cement. This optimization technique dramatically reduces the amount of cement utilization and can reduce at least some amount of greenhouse gases emission caused by production due to the production of cement. The mechanical and durability characteristics of ternary blended cement concrete were evaluated and compared with that of control mix. In order to carry out optimization of mineral admixture to develop ternary blended cement concrete, a total of 144 cubes of standard size 150 × 150 × 150 mm were cast for all grades of concrete. A comparison of ternary blended cement concrete and control mix was performed by evaluating mechanical properties by casting a total of 54 specimens which includes 18 cubes, 18 cylinders and 18 prisms of standard sizes. All the tests on the concrete specimens were conducted as per IS: 516-1959 [31]. Acid resistance of ternary blended cement concrete and control mix in 5% concentration HCl and H_2SO_4 was conducted by casting a total of 126 cubes of standard size were cast, immersed in acid tubs and tested at the end of 7, 28 and 56 days. RCPT was conducted by casting 18 specimens of size 100 mm diameter and 50 mm height, and ACPT was conducted by casting 18 specimens of size 100 mm diameter and 200 mm height and placing an 8 mm steel reinforcement bar at the center of the specimen in fresh concrete state to a depth of 100 mm.

3 Results and discussions

3.1 Effect of mineral admixtures in ternary blended cement concrete

3.1.1 Effect of flyash on workability and strength

The optimization of mineral admixtures was done consecutively. Initially fly ash was varied from 0, 5, 10, 15, 20 and 25% replacement of cement. The workability of blended concrete mix consisting of cement and fly ash enhanced with the increase in fly ash proportion in the binder content due to the increase of finer particle size distribution, spherical shape and smooth glassy texture providing a plasticizing effect of fly ash. The inclusion of flyash as a partial replacement is beneficiary in terms of workability compared to control mix concrete. The optimum content of fly ash was determined at 15% based on the compressive strength aspect and further replacement the adverse effect (compared to optimum content) was noticed but the strength of concrete specimens was more that of control mix concrete indicating the beneficiary role of flyash in strength property. The reason for the enhancement of strength of concrete specimens with flyash is due to the pozzolanic reactivity of along with its mineralogical composition. The testing of concrete specimens was performed as per IS: 516-1956 [31]. The compressive strength and workability of the binary mix consisting of cement and fly ash has shown better compared to control mix for all the three grades considered in the study as shown in Tables 3, 4 and 5.

3.1.2 Effect of silica fume on workability and strength

With the optimized fly ash content as constant silica fume was varied from 0, 4, 6, 8 and 10% in cement, fly ash and silica fume concrete as shown in Tables 6, 7 and 8. The workability of the blended concrete mix was marginally increased with the increase in silica fume proportion in the total binder content of cement concrete composite may be due to the effect of the combination of fly ash content along with particle characteristics of silica fume having spherical shape which provides the reduction of water by its ball bearing effect by dispersing the cement and silica fume particles through its adsorption and repulsion mechanism. The optimum content of silica fume was achieved at 8% based on the compressive strength. The ultra-fine particle size distribution of silica fume provides the micro filler effect by densifying the interfacial transition zone is the main reason for the substantial enhancement in the strength aspect. The pozzolanic reaction between the silica fume particles and calcium hydroxide to provide additional C–S–H gel is also another

Table 3 Optimization of Fly ash in 30 MPa

Cement replacement by fly ash (%)	Quantity of cement (kg/m^3)	Quantity of fly ash (kg/m^3)	Slump (mm)	Compressive strength (MPa)
0	394	0	105	30.5
5	374.3	19.7	109	32.2
10	354.6	39.4	114	33.8
15	334.9	59.1	118	36.1
20	315.2	78.8	122	34.4
25	295.5	98.5	126	33.5

Table 4 Optimization of fly ash in 50 MPa

Cement replacement by fly ash (%)	Quantity of cement (kg/m^3)	Quantity of fly ash (kg/m^3)	Slump (mm)	Compressive strength (MPa)
0	418	0	101	50.8
5	397.1	20.9	104	53.2
10	376.2	41.8	109	55.4
15	355.3	62.7	113	58.1
20	334.4	83.6	117	56.7
25	313.5	104.5	121	54.6

Table 5 Optimization of fly ash in 70 MPa

Cement replacement by fly ash (%)	Quantity of cement (kg/m^3)	Quantity of fly ash (kg/m^3)	Slump (mm)	Compressive strength (MPa)
0	440	0	96	70.2
5	418	22	99	73.8
10	396	44	103	76.2
15	374	66	107	78.5
20	354	88	110	76.8
25	330	110	114	74.3

Table 6 Optimization of silica fume in 30 MPa

Quantity of fly ash (kg/m^3)	Cement replacement by silica fume (%)	Quantity of cement (kg/m^3)	Quantity of silica fume (kg/m^3)	Slump (mm)	Compressive strength (MPa)
59.1	0	334.9	0	120	30.5
59.1	4	321.5	13.4	124	37.9
59.1	6	314.8	20.1	127	39.2
59.1	8	308.1	26.8	129	41.2
59.1	10	301.4	33.5	130	40.1

Table 7 Optimization of silica fume in 50 MPa

Quantity of fly ash (kg/m^3)	Cement replacement by silica fume (%)	Quantity of cement (kg/m^3)	The quantity of silica fume (kg/m^3)	Slump (mm)	Compressive strength (MPa)
62.7	0	355.3	0	111	50.8
62.7	4	341	14.2	115	60.2
62.7	6	334	21.3	118	62.5
62.7	8	326.8	28.4	121	64.8
62.7	10	319.7	35.5	122	63.1

Table 8 Optimization of Silica fume in 70 MPa

Quantity of fly ash (kg/m^3)	Cement replacement by silica fume (%)	Quantity of cement (kg/m^3)	Quantity of silica fume (kg/m^3)	Slump (mm)	Compressive strength (MPa)
66	0	374	0	108	70.2
66	4	359.1	14.9	111	80.3
66	6	351.6	22.4	115	82.2
66	8	344.1	29.9	118	84.5
66	10	336.6	37.4	120	82.5

reason for the enhancement of strength. The compressive strength and workability of the blended concrete mix consisting of cement, flyash and silica fume shown better compared to control mix for all the three grades considered in the study as shown in Tables 6, 7 and 8.

The preparation of concrete cubes while casting and testing are shown in Figs. 1, 2, 3, 4, 5 and 6.

Fig. 1 Concrete preparation

3.1.3 Effect of lime sludge on workability and strength

Later with the optimized fly ash and silica fume content as constant, lime sludge was varied from 0, 5, 10, 15 and 20% in cement as shown in Tables 9, 10 and 11. The workability of the blended concrete mix was increased in ternary blended cement concrete mix due to combined effect of the presence of flyash, silica fume and lime sludge along with cement content. The fine particle size of lime sludge has resulted in the enhancement of blended cement concrete slump. Lime sludge is the by-product from paper industry available locally possessing high amount of calcium content

Fig. 2 Prepared concrete specimens

Fig. 3 Concrete specimens in curing

Fig. 4 Specimens for testing after curing

Fig. 5 Testing of specimen under compression

which can be efficiently utilized as a partial replacement of cement. Certain combinations of materials, consisting of pozzolana along with cement can produce greater strength compared to control mix. These cementitious materials sieved from 90 μm sieve and fineness has resulted in the superior performance in the strength point of view. The particle size and surface area played a vital role in the rate of reactivity and produced better strength. Moreover, the formation of additional C–S–H gel with the presence of lime sludge in blended cement concrete mix is the reason for the enhanced strength of concrete specimens. The optimum content of lime sludge was achieved at 10% based on the compressive strength. The compressive strength of ternary blended cement concrete mix has also shown better compared to control mix for all the three grades considered in study. The compressive strength of mix has also shown better compared to control mix for all the three grades considered in the study as shown in Tables 9, 10 and 11.

Taking the optimized contents of flyash, silica fume and lime sludge, a ternary blended concrete was established. Mechanical properties mixes were evaluated for all grades of

Fig. 6 Testing of the specimen under flexure

concrete by compressive strength, split tensile strength and flexural strength as shown in Table 12. There was a significant improvement in strength characteristics of concrete with the inclusion of mineral admixtures. Increase in compressive strength was about 42.5% in 30 MPa, 32.48% in 50 MPa and 22.79% in 70 MPa concrete respectively, whereas the increase in split tensile strength was about 19.54, 12.46 and 13.35% in 30 MPa, 50 MPa, and 70 MPa respectively. The increase in flexural strength was about 20.48, 14.56 and 11.22% in 30 MPa, 50 MPa, and 70 MPa concrete. From these results, it is evident that the mineral admixtures attributes for the increase in strength properties of ternary blended cement concrete significantly.

Fly ash and silica fume possess pozzolanic property rich in silica and alumina. Lime sludge is possessing high calcium content. These mineral oxides react with lime in the presence of water in blended concrete mixes and results in the formation of C–S–H gel similar to the compounds formed in hydrated Portland cement. Particle size distribution of these materials plays a dominant role in the improvement of cement paste-aggregate interfacial transition zone,

Table 9 Optimization of lime sludge in 30 MPa

Quantity of fly ash (kg/m^3)	Quantity of silica fume (kg/m^3)	Cement replacement by lime sludge (%)	Quantity of cement (kg/m^3)	Quantity of lime sludge (kg/m^3)	Slump (mm)	Compressive strength (MPa)
59.1	26.8	0	308.1	0	129	30.5
59.1	26.8	5	292.7	15.4	134	42.7
59.1	26.8	10	277.3	30.8	138	44.5
59.1	26.8	15	261.8	46.2	143	43.6
59.1	26.8	20	246.5	61.6	147	42.5

Table 10 Optimization of lime sludge in 50 MPa

Quantity of fly ash (kg/m^3)	Quantity of silica fume (kg/m^3)	Cement replacement by lime sludge (%)	Quantity of cement (kg/m^3)	Quantity of lime sludge (kg/m^3)	Slump (mm)	Compressive strength (MPa)
62.7	28.4	0	326.8	0	121	50.8
62.7	28.4	5	310.4	16.4	125	66.2
62.7	28.4	10	294.1	32.7	130	68.5
62.7	28.4	15	277.8	49	134	67.3
62.7	28.4	20	261.4	65.3	138	65.9

Table 11 Optimization of in lime sludge 70 MPa

Quantity of fly ash (kg/m^3)	Quantity of silica fume (kg/m^3)	Cement replacement by lime sludge (%)	Quantity of cement (kg/m^3)	Quantity of lime sludge (kg/m^3)	Slump (mm)	Compressive strength (MPa)
66	29.9	0	344.1	0	117	70.2
66	29.9	5	326.8	17.2	120	85.2
66	29.9	10	309.7	34.4	124	87.5
66	29.9	15	292.4	51.6	127	86.2
66	29.9	20	275.2	68.8	130	84.6

Table 12 Mechanical properties of control mix and ternary blended cement concrete

Grade (MPa)	Mix	Compressive strength (MPa)	Split tensile strength (MPa)	Flexural strength (MPa)
30	Control mix	30.5	2.61	3.92
	With FA + SF + LS	43.6	3.12	4.72
50	Control mix	50.8	3.45	5.08
	With FA + SF + LS	67.3	3.88	5.82
70	Control mix	70.2	3.97	5.97
	With FA + SF + LS	86.2	4.5	6.64

Fig. 7 Preparation of acid to study acid attack

Fig. 8 Pouring of acid in the tubs

which is the weakest link and therefore most important in concrete. Silica fume's size influence in filling the micro-voids present in concrete is also one of the reasons for its contribution to strength development in ternary blended cement concrete.

This particular aspect is desirable in development of concrete with high strength due to its ability to fill the micro-voids and arresting the microcracks with its fineness. The presence of high silica content in fly ash and silica fume and high calcium content in cement and lime sludge can be attributed to the formation of additional C-S-H gel formation.

3.2 Acid strength loss and mass loss factors

The resistance of control mix and blended concrete specimens was examined by immersing cubes in 5% concentration HCl and 5% H_2SO_4 solutions to assess the chloride and sulfate attack. Samples placed in tubs for acidic exposure are shown in Figs. 7, 8, 9 and 10. Mass and strength of the specimens was initially measured before the immersion of the cubes in acidic solutions and compared to mass and strength

Fig. 9 Concrete specimens in acid

Fig. 10 Concrete specimens after 56 days in acid

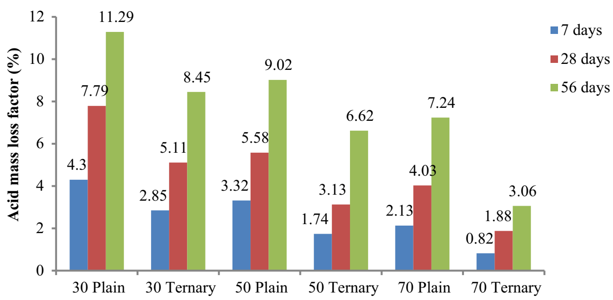

Fig. 11 Variation in acid mass loss factor for specimens in 5% HCl

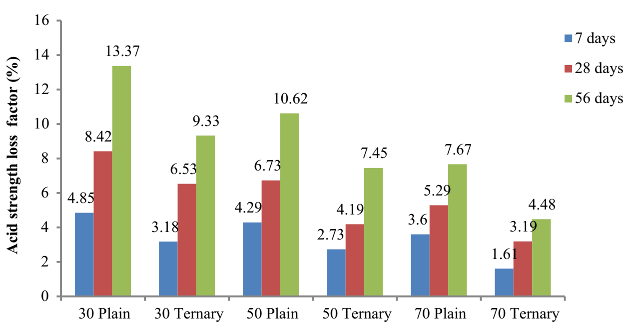

Fig. 12 Variation in acid strength loss factor of specimens 5% HCl

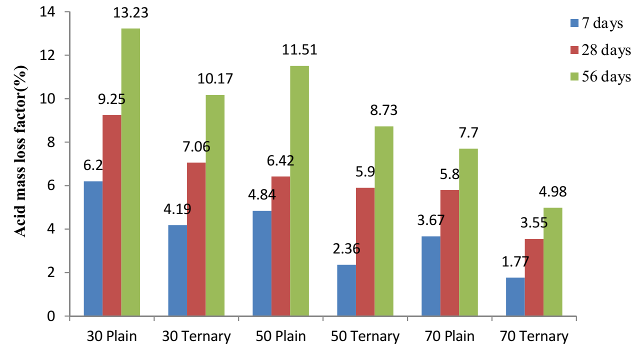

Fig. 13 Variation in acid mass loss factor for specimens in 5% H_2SO_4

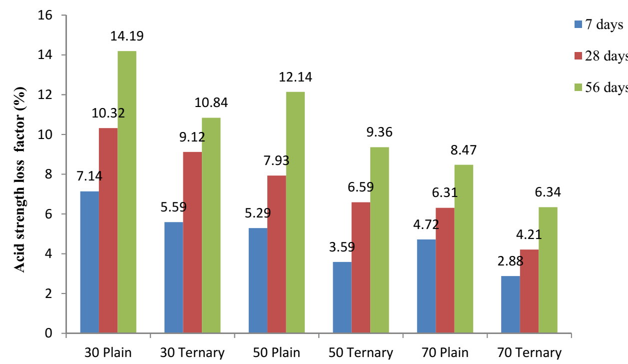

Fig. 14 Variation in acid strength loss factor for specimens in 5% H_2SO_4

of the specimens after the immersion of cubes in acid at 7, 28 and 56 days to determine the acid mass loss factor, acid strength loss factor and are shown in Figs. 11, 12, 13 and 14.

Maximum mass loss factor was found to be as 11.29, 9.02 and 7.24% for 30 MPa, 50 MPa and 70 MPa control mix specimens respectively. Maximum mass loss factor was found to be as 8.45, 6.62 and 3.06% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete mix specimens respectively in 5% HCl acidic environment as shown in Fig. 11.

Maximum strength loss factor was found to be 13.37, 10.62 and 7.67% for 30 MPa, 50 MPa, and 70 MPa control mix in 5% HCl acidic environment. Similarly, maximum strength loss factor was found to be 9.33, 7.45 and 4.48% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete in 5% HCl acidic environment as shown in Fig. 12.

Maximum mass loss factor was found to be as 13.23, 11.51 and 7.7% for 30 MPa, 50 MPa and 70 MPa control mix specimens respectively. Maximum mass loss factor was found to be as 10.17, 8.73 and 4.98% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete mix specimens respectively in 5% HCl acidic environment as shown in Fig. 13.

Maximum strength loss factor was found to be as 14.19, 12.14 and 8.47% for 30 MPa, 50 MPa and 70 MPa control mix specimens respectively. Maximum strength loss factor was found to be as 10.84, 9.36 and 6.34% for 30 MPa, 50 MPa and 70 MPa ternary blended cement concrete mix specimens respectively in 5% H_2SO_4 acidic environment as shown in Fig. 14.

From Figs. 11, 12, 13 and 14 it can be inferred that maximum mass loss factor, and maximum strength loss factor was more in the case of the lower grades compared to higher grades implying lower grade concrete are more susceptible to acid attack and higher resistance was offered by higher grades in both 5% HCl and H_2SO_4 acidic environment.

All grades of control mix specimens have offered less resistance to acid attack showing a pulpy mass in addition to peeling especially at later ages compared to ternary blended specimens at all exposure periods in 5% H_2SO_4 when compared to 5% HCl. The surface and edges of specimens of ternary blended cement concrete specimens were less disintegrated implying a reduced rate of deterioration compared to control mix due to the presence of cement replacement with fine materials improves acid resistance due to the formation of densification of hardened cement paste which fills all the pores and hence paste-aggregate interface zone is enhanced.

It was noticed that higher grades in both control mix and blended mix, were less susceptible to deterioration due to the presence of higher paste content, compressive strength, and solid formulation of the concrete matrix which in turn does not allow penetration of acid in concrete specimens and thus enhancing micro filler effect of concrete specimens. It was observed that the specimens irrespective of grade, exposed to sulfate attack were having more mass loss and strength loss, especially at later ages, compared to chloride attack may be due to the reaction of calcium content with sulfate leading to the formation of gypsum ($CaSO_4$). The higher deterioration observed in control mix may be attributed to the formation of ettringite. Hence, the quantity of gypsum formed in the reaction between sulfates and $Ca(OH)_2$, which is responsible for the formation of ettringite, might be less in the case of blended concrete specimens compared to control mix specimens.

3.3 Acid durability factor

Acid durability factor was determined from relative compressive strength at 7, 28 and 56 days shown in Tables 13 and 14 and the result indicates that ternary blended cement concrete is more resistant to control mix. Higher durability factor attributes to better durability. In the case of ternary blended cement concrete, acid durability factor (ADF) was more at longer compared to shorter period exposure to aggressive environment. Durability factor was better in chloride attack when compared to sulfate attack in both control mix and ternary blended concrete due to the presence of mineral admixtures contributing in filling up of micropores present in concrete and hence making denser concrete. The

Table 13 Determination of acid durability factor for specimens immersed in HCl 5% concentration

Concrete mix	Original Strength (MPa)	Strength after acid attack (Mpa)			Relative strength			ADF = S_r (N/M)		
	0 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
30 MPa control mix	30.5	29.02	27.93	26.42	0.951	0.915	0.866	0.118	0.457	0.866
30 MPa blended mix	43.6	42.21	40.75	39.53	0.968	0.934	0.906	0.121	0.467	0.906
50 MPa control mix	50.8	48.62	47.38	45.40	0.957	0.932	0.893	0.119	0.466	0.893
50 MPa blended mix	67.3	65.46	64.48	62.28	0.972	0.958	0.925	0.121	0.479	0.925
70 MPa control mix	70.2	67.67	66.48	64.81	0.963	0.947	0.923	0.120	0.473	0.947
70 MPa blended mix	86.2	84.81	83.45	82.33	0.983	0.968	0.955	0.122	0.484	0.968

Relative strength = strength after acid attack/original strength

N number of days immersed or terminated, *M* total number of days for which the test was conducted

Table 14 Determination of acid durability factor for specimens immersed in H_2SO_4 5% concentration

Concrete mix	Original strength (MPa)	Strength after acid attack (MPa)			Relative strength			ADF = S_r (N/M)		
	0 days	7 days	28 days	56 days	7 days	28 days	56 days	7 days	28 days	56 days
30 MPa control mix	30.5	28.32	27.35	26.17	0.928	0.896	0.858	0.116	0.448	0.868
30 MPa blended mix	43.6	41.16	39.62	38.37	0.944	0.908	0.880	0.118	0.454	0.880
50 MPa control mix	50.8	48.11	46.77	44.63	0.947	0.920	0.878	0.118	0.460	0.878
50 MPa blended mix	67.3	64.88	62.86	61.00	0.964	0.934	0.906	0.120	0.467	0.906
70 MPa control mix	70.2	66.88	65.77	64.25	0.951	0.936	0.915	0.118	0.468	0.915
70 MPa blended mix	86.2	83.71	82.54	80.73	0.971	0.957	0.957	0.121	0.478	0.957

presence of fly ash and silica fume resisted the penetration of acid due to their fine particle size.

3.4 Rapid chlorination penetration test

This test consists of monitoring the amount of electrical current passed through a 100 mm diameter × 50 mm thick concrete specimens, where a potential difference of 60 V direct current is maintained across the specimen for a period of 6 h. Chloride ions are forced to migrate out of a sodium chloride solution subjected to a negative charge through the concrete into a sodium hydroxide solution maintained at a positive potential. This test was performed following Indian Standards and ASTM C 1202. The resistance to chloride ions penetration is related by the amount of total charge passed. Amount of current passed in coulombs was 3756, 3584 and 3284 for 30 MPa, 50 MPa, and 70 MPa respectively in control mix concrete and the case of ternary blended cement concrete it was recorded as 1612,1245 and 945 coulombs in 30 MPa, 50 MPa, and 70 MPa respectively.

It is apparent that ternary blended cement concrete of fly ash, silica fume, lime sludge and cement offered higher resistance to chloride ions and implying advantages regarding durability of concrete as shown in Table 15 and such blends are superior to ordinary Portland cement concrete. In the ternary system, the chloride permeability is very low in high strength concrete due to higher paste content and ability to fill the micropores with the available binder content, compared to the concrete of medium and low strength.

3.5 Accelerated penetration corrosion test

This test was conducted on the cylindrical specimens of 100 mm diameter and 200 mm height to assess the amount of current passed maintained at 10 V direct current by forcing chloride ions in 3% concentration sodium chloride to penetrate into the embedded steel reinforcement of 8 mm diameter inserted to a depth of 100 mm in control mix and blended concrete specimens. 3% concentration sodium chloride solution is used. The amount of current passed in milliamperes was noted down once in a day and graph has been plotted milliamperes versus days. The current at which there is a sudden increase in chloride ion penetration is critical corrosion current and the corresponding time is critical corrosion time. The current at which crack is observed in the specimens is the depassivation current and the corresponding time is depassivation time. Amount of current passed was observed to be more in the case of control mix specimens compared to ternary blended cement concrete mix specimens indicating higher durability with the inclusion of mineral admixtures. Lower grades had higher current passed indicating a higher amount of chloride penetration compared to higher grades. There was an increase in post depassivation time about 1-3 days in the case of ternary blended cement concrete specimens showing higher resistance to chloride ion penetration. Figures 15 and 16 show the experimentation of ACPT. The variation of the current passed with time is shown in Fig. 17.

Critical current, time and depassivation current, time of control mix and ternary blended cement concrete is shown in Table 16. The time for required for the sudden increase in chloride ion penetration in the case of control mix was high compared to blended concrete. The increase was even more in lower grades. Critical corrosion current in control mix 30 MPa, 50 MPa, and 70 MPa were 63 milliamperes, 56 milliamperes, and 47 milliamperes respectively. Critical corrosion current in the case ternary blended cement concrete mix was about 72, 55 and 57 milli amperes but the corresponding time for critical corrosion current is more in the case of blended concrete attributing in the increase in critical corrosion time of steel reinforcement and enhanced durability. Further chloride ion penetration leads to the crack, and the depassivation current in control mix 30 MPa, 50 MPa

Table 15 RCPT results on control mix and ternary blended cement concrete

Grade (MPa)	Mix type	Current passed (C)	Remarks
30	Control mix	3756	Medium
	With C + FA + SF + LS	1612	Low
50	Control mix	3584	Medium
	With C + FA + SF + LS	1245	Low
70	Control mix	3248	Medium
	With C + FA + SF + LS	945	Very Low

Fig. 15 Test setup for ACPT

Fig. 16 Concrete specimens after the test

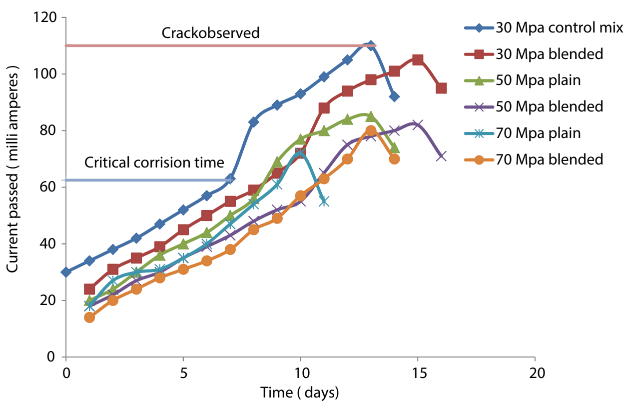

Fig. 17 Variation of current passed with time

and 70 MPa was 110, 85 and 72 milliamperes respectively which is higher than blended concrete 30 MPa, 50 MPa and 70 MPa concrete 105,82 and 80 showing better performance in the aspect of depassivation current. Depassivation time for control mix specimens was 13, 12 and 9 days respectively and for blended concrete specimens was 15, 15 and 13 but the time required for the increase in depassivation time or time at which crack is observed been increased by 2, 3 and 4 days in the blended concrete specimens in 30 MPa, 50 MPa and 70 MPa concrete compared to control mix implies more excellent resistance to chloride ion penetration. From the results, it can be inferred the partial replacement of mineral admixtures have shown in improved durability of concrete. The reason for this better performance is same as in the case of rapid chlorination penetration test.

4 Conclusions

- Significant improvement in mechanical properties of ternary blended cement concrete with the highest strength was obtained at optimized contents of fly ash, silica fume and lime sludge of 15, 8 and 10% based on strength point of view in replacement of cement respectively for all the grades of concrete.
- The influence of the mineral admixtures used fly ash, silica fume and lime sludge as a cement replacement materials in more the case of lower grades (30 MPa) compared to high grades (70 MPa) in the present work.
- Acid mass loss factor and acid strength loss factor of control mix and ternary blended cement concrete was more in lower grades (30 MPa) when compared to higher grades (70 MPa) irrespective of binder, indicating more resistance in durability in higher grade of concrete due to the higher binder content and micro filler effect of mineral admixtures in the concrete.
- Acid mass loss factor and acid strength loss factor was more in the case of H_2SO_4 when compared to HCl at all the ages in all grades of concrete indicating that the concretes are more susceptible to sulfate attack.
- Acid durability factor was determined at 7, 28 and 56 days for both 5% concentration HCl and H_2SO_4 it was noticed that ADF for concrete specimens exposed to HCl was more than H_2SO_4 comparatively at all ages.
- The resistance of chloride ion penetration in rapid chlorination penetration test is more in the case of higher grades compared to lower grades.
- In higher grades, the amount of critical current and corresponding time is delayed due to presence of high binder content compared to lower grades.

Table 16 Critical current, time and depassivation current, time of control mix and ternary blended cement concrete

	Critical corrosion current (mA)	Critical corrosion time (days)	Depassivation current (mA)	Depassivation time (days)
30 control mix	63	7	110	13
30 blended mix	72	10	105	15
50 control mix	56	7	85	12
50 blended mix	55	10	82	15
70 control mix	47	6	72	9
70 blended mix	57	10	80	13

- Ternary blended cement concrete mixes are delaying the amount of current passed into the concrete specimens compared to control mix implying the significance of the combination of these mineral admixtures used.

References

1. Adorno CD, De Medeiros MH, Hoppe Filho J, Réus GC (2018) Effects of the addition of red ceramic, limestone filler and rice husk ash in alkali silica reaction. J Build Rehabil 3:1–11
2. Imbabi MS, Carrigan C, McKenna S (2012) Trends and developments in green cement and concrete technology. Int J Sustain Built Environ 1:194–216
3. Schneider M, Romer M, Tschudin M, Bolio H (2011) Sustainable cement production—present and future. Cem Concr Res 41:642–650
4. Naik TR, Singh SS, Hossain MM (1995) Properties of high performance concrete systems incorporating large amounts of high-lime fly ash. Constr Build Mater 9:195–204
5. Karthik S, Rao PR, Awoyera PO (2017) Strength properties of bamboo and steel reinforced concrete containing manufactured sand and mineral admixtures. J King Saudi Univ Eng Sci 29:400–406
6. Juenger MC, Siddique R (2015) Recent advances in understanding the role of supplementary cementitious materials in concrete. Cem Concr Res 78:71–80
7. Sata V, Jaturapitakkul C, Kiattikomol K (2007) Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. Constr Build Mater 21:1589–1598
8. Muthadhi A, Kothandaraman S (2013) Experimental investigations of performance characteristics of rice husk ash–blended concrete. J Mater Civ Eng 25:1115–1118
9. Zhang MH, Malhotra VM (1996) High-performance concrete incorporating rice husk ash as a supplementary cementing material. ACI Mater J 93:629–636
10. Ismail MS, Waliuddin AM (1996) Effect of rice husk ash on high strength concrete. Constr Build Mater 10:521–526
11. Al-Kutti W, Islam AS, Nasir M (2017) Potential use of date palm ash in cement-based materials. J King Saudi Univ Eng, Sci
12. Nehdi M, Duquette J, El Damatty A (2003) Performance of rice husk ash produced using a new technology as a mineral admixture in concrete. Cem Concr Res 33:1203–1210
13. Sata V, Jaturapitakkul C, Kiattikomol K (2004) Utilization of palm oil fuel ash in high-strength concrete. J Mater Civ Eng 16:623–628
14. Duval R, Kadri EH (1998) Influence of silica fume on the workability and the compressive strength of high-performance concretes. Cem Concr Res 28:533–547
15. Shannag MJ (2000) High strength concrete containing natural pozzolan and silica fume. Cem Concr Compos 22:399–406
16. Ganesan K, Rajagopal K, Thangavel K (2008) Rice husk ash blended cement: assessment of optimal level of replacement for strength and permeability properties of concrete. Constr Build Mater 22:1675–1683
17. Joshaghani A, Moeini MA, Balapour M (2017) Evaluation of incorporating metakaolin to evaluate durability and mechanical properties of concrete. Adv Concr Constr 5:241–255
18. Bai J, Wild S, Sabir BB (2002) Sorptivity and strength of air-cured and water-cured PC–PFA–MK concrete and the influence of binder composition on carbonation depth. Cem Concr Res 32:1813–1821
19. Shi X, Xie N, Fortune K, Gong J (2012) Durability of steel reinforced concrete in chloride environments: an overview. Constr Build Mater 30:125–138
20. Sadrmomtazi A, Tahmouresi B, Amooie M (2017) Permeability and mechanical properties of binary and ternary cementitious mixtures. Adv Concr Constr 5:423–436
21. Ghrici M, Kenai S, Said-Mansour M (2007) Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements. Cem Concr Compos 29:542–549
22. Torii K, Kawamura M (1994) Effects of fly ash and silica fume on the resistance of mortar to sulfuric acid and sulfate attack. Cem Concr Res 24:361–370
23. Medeiros-Junior RA, Júnior JR, Monteiro AJ, Bill GH, Kawanami IY (2018) Accelerated carbonation effect on electrical resistivity and sorptivity of concrete. J Build Rehabil 3:1–7
24. BIS (Bureau of Indian Standards) (1987) IS 12269-1987: Specifications for 53 grade ordinary Portland cement. BIS, New Delhi
25. BIS (1970) IS 383-1970: specification for coarse and fine aggregates from natural sources for concrete. BIS, New Delhi
26. BIS (2003) IS 3812–1: Specification for pulverized fuel ash, Part 1: for use as Pozzolana in cement, cement mortar and concrete. BIS, New Delhi
27. BIS (2003) IS 15388–2003 Silica fume—Specifications. BIS, New Delhi
28. BIS (2000) IS: 456-2000 Plain and reinforced concrete - code of practice
29. ASTM (2005) ASTM C494: Standard specification for chemical admixtures for concrete, C494/C494M-05a. ASTM International, West Conshohocken, PA
30. BIS (2009) IS: 10262-2009 Concrete mix proportioning—Guidelines
31. BIS (1956) IS: 516-1956, (reaffirmed 1999): Indian standard methods of tests for strength of concrete. BIS, New Delhi