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Influence of supplementary cementitious materials on strength and durability characteristics of concrete

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Abstract. The present study is focused on the mechanical and durability properties of ternary blended cement concrete mix of different grades 30 MPa, 50 MPa and 70 MPa. Three mineral admixtures (fly ash, silica fume and lime sludge) were used as a partial replacement of cement in the preparation of blended concrete mix. The durability of ternary blended cement concrete mix was 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 (ADF) were determined, and the results were compared with the control mix. Chloride ions penetration was investigated by conducting rapid chlorination penetration test and accelerated corrosion penetration test on control mix and ternary blended cement concrete. From the results, it was evident that the usage of these mineral admixtures is having a beneficiary role on the strength as well as durability properties. The results inferred that the utilization of these materials as a partial replacement of cement have significantly enhanced the compressive strength of blended concrete mix in 30 MPa, 50 MPa and 70 MPa by 42.95%, 32.48% and 22.79%. The blended concrete mix shown greater resistance to acid attack compared to control mix concrete. Chloride ion ingress of the blended cement concrete mix was low compared to control mix implying the beneficiary role of mineral admixtures.

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

Concrete is one of the most widely used materials in construction industry all over the world. The increased demand for the manufacture and usage of cement in concrete is associated with environmental pollution and hence leading to huge emission of greenhouse gases (Naik *et al*. 1995). Production of 1 ton of cement releases an equal amount of CO_2 into the atmosphere which is accountable for 5-7% of total man-made carbon dioxide emissions globally. This is extremely hazardous, and there is a definite need to reduce these emissions so as to maintain the sustainability. The production of Portland cement reached 4.1 billion tonnes globally in 2015, which is increasing at very fast rate of 24% since 2010 (U.S. Geological Survey 2016). This figure is likely to increase even more in the coming decades. This is mainly because many developing countries are undergoing swift development in the infrastructure to meet the increased demand for growing population. Hence there is lot of demand for housing and infrastructure development greater than ever before (Schneider *et al*. 2011). To meet the increased demand of infrastructure, necessity of production of concrete using natural materials also increased which is the main reason for carbon footprint.

The use of Supplementary Cementitious Materials (SCMs) in blended concrete can reduce the amount of CO_2 into the atmosphere (Imbabi *et al*. 2012). In Recent times, SCMs and their use in blended concrete receiving great attention all over the world in reducing the carbon emission into atmosphere since the energy use and CO_2 emissions from Portland cement clinker manufacturing significantly outweigh those of other concrete components. Blended concrete using SCMs have economic and performance benefits compared to conventional concrete. The utilization of these materials or the combinations of these materials moreover industrial by products like fly ash, ground granulated blast furnace slag, lime sludge and other waste materials occupies more percentage of local landfill space and leading to pollution problems in those regions. In order to minimize the disposal and pollution problems originating from these industrial by-products, it is the need of the hour to develop profitable building materials out of these wastes (Juenger *et al*. 2015). The replacement of Portland cement with these industrial by-product in concrete can greatly reduce the release of greenhouse gases into the atmosphere also avoids the disposal and pollution problems to some extent (Mullick *et al*. 2007). This point led to research on supplementary cementitious materials, which gives us same strength as that of Portland cement without compromising durability aspects. Supplementary Cementitious materials sometimes referred to as mineral admixtures. They may be used individually or in combination in concrete. They may be added to concrete mixture as a blended cement to improve the properties of concrete in fresh and hardened state. Their use can make concrete easier to work with,

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stronger and more durable (Karthik *et al*. 2017). The most common type of alternative materials that are using to replace the cement in concrete are fly ash, silica fume, ground granulated blast furnace slag, metakaolin, rice husk ash, palm oil fuel ash. Among, all the available supplementary cementitious materials, fly ash is the most available material and enormously used by many researchers (Naik *et al*. 1995). 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. Cement replacement with fly ash in concrete improves the concrete properties in both fresh and harden state due to its pozzolanic property and mineralogical composition for structural applications (Torri *et al*. 1994). The significant enhancement of workability and strength characteristics at later ages compared to conventional concrete is also a property for its incorporation as an alternative material to cement widely. It is generally used to partially replace Portland cement by up to 30% by mass (Hassan *et al*. 2000). Free lime in the presence of water reacts with pozzolanic materials, converted into calcium silicate hydrate (C-S-H). Another supplementary cementitious material silica fume which is a by-product obtained from iron industries enhances the concrete properties in fresh state by improving the workability of the concrete due to the particle characteristics having a spherical shape which provides the water reduction by its ball bearing effect and electrostatic repulsion mechanism (Sata *et al*. 2007). Ultra-fine particles of silica fume enhances the concrete in harden state by acting as a micro filling material in the concrete which fills the presence of micro-voids of concrete. Densification of interfacial transition zone also takes place and further enhancing the matrix aggregate bond (Papadikas *et al.* 2000). The enhancement in the strength due to the additional formation of C-S-H gel due to the pozzolanic reaction between silica fume and calcium hydroxide. Pozzolanic materials substantially improve the durability characteristics of concrete like impermeability, resistance against chlorides and sulphates diffusion into structural members which protects corrosion of reinforcement steel embedded into the concrete in which loss of plasticity of concrete in fresh state and the great sensitivity to plastic shrinkage during the initial curing are utmost important. Other pozzolanic materials such as rice husk ash which is an agricultural by-product formed by the combustion of husk under controlled condition (Zareei *et al*. 2017) which is rich in silica content when used as a partial replacement in cement can achieve high strength concrete and very good chemical resistance to chloride attack compared to conventional concrete. The incorporation of mineral admixture is beneficiary to concrete and performs greatly in aggressive environment and enhancing durability (Zhang *et al*. 1996). Incorporation of mineral admixtures up to certain proportions either individually or blends of such materials as a partial replacement to cement in concrete have advantages such as high strength, enhanced durability, low permeability, corrosion resistance. Blended cement concrete mixtures can be used at various applications such as general construction (residential, commercial, industrial), high performance concrete, pre-cast concrete, masonry units and mass concrete. Properties of these materials in strength and durability are needed to be studied intensively before the incorporation of these materials as partial replacement to cement in concrete. In developing country like India, there is lot of demand for SCMs, particularly where concrete usage is expected to increase and traditional SCMs, such as fly ash and GGBFS, are not available locally. SCMs play a critical role in our ability to provide sufficient quantities of cementitious materials for the anticipated volumes of concrete production. Looking further into the future, the demand for cement in concrete will increase. Globally, extensive research is being done on these materials as a partial replacement of cement. But paper industry by-product is not being used to full extent as a cementitious material which is commonly known as lime sludge. In the present investigation use of paper industry along with other industrial by products as supplementary cementitious materials were addressed.

The pulp and paper industry is one of the key industrial sectors contributing to the Indian economy (Solanki *et al*. 2013). There are 759 paper mills in India with an operating capacity of 12.7 million tonnes and consumption at 11 million tonnes with 9.3 kg per capita consumption of paper. Projected demand for the paper by 2025 is 24 million tonnes. The increase in dumping difficulties of paper industry by-products and construction cost of buildings using cement hints to the research of the materials like lime sludge for partial replacement of cement and its suitability in concrete (Pitroda *et al*. 2013). Significant research is being done all over the globe so as to find new materials as substitute to cement up to certain proportions, attaining same strength to that of concrete. Though the literature gives lot of evidence on extent of materials as a substituent (partially) in concrete like fly ash, now a new material is being tried as a replacement of cement. About 550 mills in India use waste paper (recycling) as primary fibre source for paper, paperboard and newsprint production. Recycling of paper is done only for a limited number of times to make a good quality paper, which produces huge amount of waste in solid form.

The by-product from paper industry waste which is causing severe disposal and land fill problems in that region, to avoid this material can be utilized in profitable manner as a mineral admixture in preparing blended concrete by the construction industry so that sustainability can be maintained. In general, natural materials have a quality control advantage over recycled materials. Since the worldwide production of Portland cement is expected to reach nearly 2.1 billion tons by 2020, replacement of lime sludge along with other materials in certain propositions for making concrete can drastically reduce global carbon emissions without compromising strength and durability aspects of concrete. Utilization of this industrial waste in the construction industry is now one of the serious concerns of present research for sustainable development of any nation. This is also one of the emerging issues to be addressed in regard of global significance for environmental and economic reasons. The incorporation of lime sludge with other mineral admixtures is to be verified in blended concretes. A lot of research is being carried out on supplementary cementitious materials all over the world like fly ash, ground granulated blast furnace slag, silica fume and other materials but less attention is given on the use of Lime Sludge in concrete and its suitability. Keeping these issues in mind the present investigation is carried out on the utilization of lime sludge as one of the supplementary cementitious with other mineral admixtures in blended cement concrete. Blended concrete consists of different materials other than cement as the binder content. Commonly used materials are fly ash, silica fume, GGBS, rice husk ash and other materials are well established materials. These supplementary cementitious materials, when they are utilized as mineral admixtures as a partial replacement to cement in concrete is known as blended concrete. Based on the available literature, blended concrete shows superior performance compared to control mix. This blending of cement with other materials in concrete greatly reduces the amount of cement consumption. Moreover, the literature concludes that the performance characteristics of blended concrete are showing better results compared to conventional mix. The advantageous role of these materials in blended concretes encourages the research on new materials as a partial replacement to cement with the enhanced strength and durability properties. Published literature reveals that a lot of new materials are tried as an alternative to cement in blended concrete. Apart from the regularly utilized materials, this study focuses on the usage of paper industrial waste known as lime sludge.

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 (Maria *et al*. 2015). Experimental investigations by Sata *et al* (2007), Muthadhi and Kothandaraman (2013), Zhang and Mohan Malhotra (1996), Ismail and Waliuddin (1996) 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 (Nehdi *et al*. 2003). Sata *et al*. (2004) investigated in the similar research area of supplementary cementitious materials and concluded that materials like Palm oil fuel ash, when used as partial replacement of 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 alone.

Shannag (2000), Ganesan *et al.* (2008), Duval and Kadri (1998) performed studies on and results inferred that pozzolanic 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 buildings in which loss of plasticity of concrete in fresh state and the high sensitivity to plastic shrinkage during the initial curing are utmost important. 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 (Bai *et al*. 2002). Shi *et al*. (2012) performed research and 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.

Investigation on ternary blended concrete with cement, fly ash and silica fume was done by Sadrmomtazi *et al*. (2017) and concluded that there is a significant increase in strength and enhanced durability compared to control mix. 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 (Ghrici *et al*. 2007). The sulphuric acid attack of 3 % concentration on sulfate resisting Portland cement when compared ordinary Portland cement concrete containing polyvinyl alcohol and pulverized fly ash was almost similar due to the increase in density of concrete in SRPC moreover, it enhanced with an increase in aggregate proportion in concrete (Fattuhi and Hughes 1988). Kazuyuki Torii examined the long-term resistance to sulphate attack, and Mitsunori (1994) 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.

2. Research significance

Currently, the construction industry is focusing on the replacement of cement with locally available eco-friendly materials to cement. The main focus is to reduce the amount of usage of cement content in making concrete which in turn reduces the release of greenhouse gases into the atmosphere. Usage of these materials also avoids the disposal and landfill problems which are causing serious environmental issues. Utilization of these materials as an alternative to cement in profitable way is paramount important in maintaining sustainability. Many researchers focused on supplementary cementitious materials such as fly ash, metakaolin, silica fume, GGBS, rice husk ash, palm oil fuel ash, etc. and inferred that the utilization of these materials have shown enhanced strength and durability characteristics. A thorough review of literature indicated that fly ash and silica fume are the two major materials used as a partial replacement of cement in blended concrete. Very few emphasized on the usage of lime sludge as one of the supplementary cementitious materials along with other materials in producing blended cement concrete mix. The utilization of these three materials is great advantage in terms of environmental and economic (since two of these materials are industrial by-products) point of view. Also this is providing a solution for landfill and global warming problems. To understand the comprehensive behaviour of materials and its applicability in construction industry.

Keeping the above aspects in mind the present investigation is planned to address the following issues.

1) Whether use of lime sludge, a by-product from paper industries can be utilized in the preparation of blended concrete mix or not? How this replacement influences on strength properties?

2) To accept this material along with other materials in preparing blended concrete mix as structural concrete and its performance in aggressive environments needs to be investigated further.

3. Objectives and methodology

The objective of the present 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. 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. 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.

Acid resistance of ternary blended cement concrete and control mix in 5% HCl and H_2SO_4 was conducted by casting a total of 126 cubes of standard size were cast and tested for 7, 28 and 56 days. 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 volts direct current is maintained across the specimen for a period of 6 hours. 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. RCPT was conducted by casting 18 specimens of size 100 mm diameter and 50 mm height. 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 volts 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 mill amperes 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. 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.

4. Materıals used and mix proportions

The different materials used in this investigation are

4.1 Cement

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

4.2 Fine aggregate

The fine aggregate conforming to Zone-2 according to IS: 383- 1970 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.

4.3 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. The specific gravity was 2.8, and the bulk density was 1.50 g/cc.

4.4 Fly ash

For the present investigation, fly ash of low calcium confirming Class F fly ash 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.

4.5 Silica fume

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

4.6 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, 780 min, 1.98 and 32%, respectively.

4.7 Water

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

4.8 Chemical admixtures

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

The chemical composition of the materails used in the present study is shown in Table 1.

4.9 Mix proportions

Three mix proportions of target compressive strength of 30 MPa, 50 MPa and 70 MPa concrete designed without any mineral admixtures as per IS 10262: 2009. Various water to binder ratio was attempted ranging from 0.28 to 0.56 for the required target strength of 30 MPa, 50 MPa and 70 MPa strength. They were achieved as 0.5, 0.39 and 0.32 respectively as shown in Table 2.

Table 1 Chemical composition of mineral admixtures was conducted and shown in Table 1

Constituent	Fly ash Composition (%)	Silica Fume Composition (%)	Lime Sludge Composition (%)
CaO	4.32	1.4	48.20
SiO_2	63.13	92.8	9.35
Fe_2O_3	4.18	1.2	2.95
Al_2O_3	24.93	1.6	3.15
MgO	1.38	0.8	2.58
LOI	2.06	2.2	33.77

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

5. Results and discussions

5.1 Effect of mineral admixtures in ternary blended cement concrete

5.1.1 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 as shown in Tables 3-5. 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 (Mullick *et al*. 2007). 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 (Hassan *et al*. 2000, Sata *et al* 2007). The testing of concrete specimens was performed as per IS: 516- 1956. The compressive strength of the binary mix (is the average value of three specimens) has shown better compared to control mix for all the three grades considered in the study as shown in Table 3-5.

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

5.1.2 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 6-8. 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 (Shannag *et al.* 2000). 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 reason for the enhancement of strength (Kumar *et al*. 2014). The compressive strength (is the average value of three specimens) 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 6-8.

5.1.3 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 9-11. 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

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

concrete slump (Ngoc *et al*. 2018). Lime sludge is the by-product from paper industry available locally possessing high amount of calcium content which can be efficiently utilized as a partial replacement of cement (Ngoc *et al*. 2018). Certain combinations of materials, consisting of pozzolana along with cement can produce greater strength compared to control mix. These cementitious materials sieved from 90 micron 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 (Mymrin *et al* 2009). 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 3 grades considered in study. The compressive strength (is the average value of three specimens) of mix has also shown better compared to control mix for all the three grades considered in the study as shown in Tables 9-11.

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

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

of 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 (Jones *et al* 1997, Thomas *et al* 1999, Meghat Johri *et al* 2011). 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 (Audinarayana *et al*. 2013). 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, which is the weakest link and therefore most important in concrete (Pandey *et al*. 2000). Silica fume's size influence in filling the microvoids present in concrete is also one of the reasons for its contribution to strength development in ternary blended cement concrete.

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

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

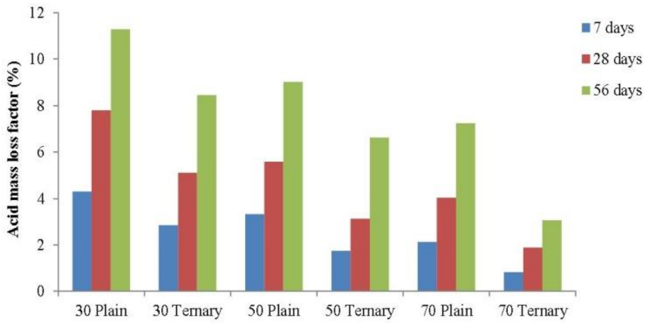

Fig. 1 Variation in acid mass loss factor for specimens in 5% HCl

This particular aspect is desirable in development of concrete with high strength due to its ability to fill the microvoids 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 (Kumar *et al*. 2014).

5.2 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. Mass and strength of the specimens was initially measured before the immersion of the cubes in acidic solutions and compared to mass and strength 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. 1-4.

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. 1.

Maximum strength loss factor was found to be 13.37%,

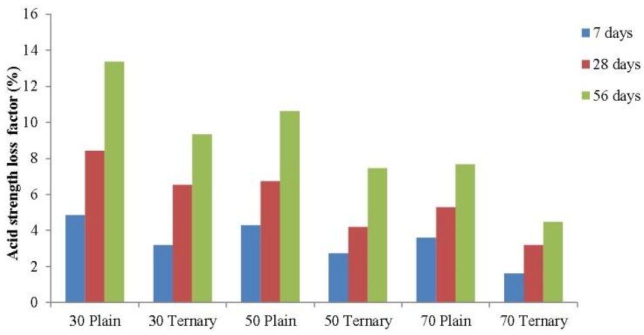

Fig. 2 Variation in acid strength loss factor of specimens 5% HCl

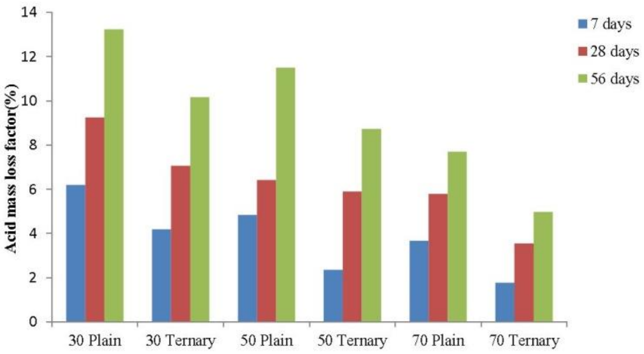

Fig. 3 Variation in acid mass loss factor for specimens in 5% H_2SO_4

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. 2.

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. 3.

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. 4.

From Figs. 1-4 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

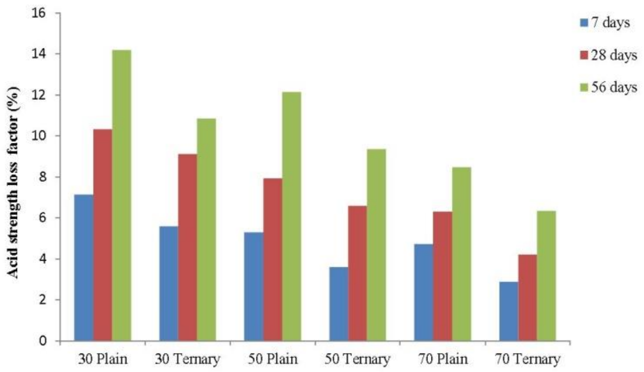

Fig. 4 Variation in acid strength loss factor for specimens in 5% H_2SO_4

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.

5.3 Acid durability factor

Acid durability factor was determined from relative compressive strength at 7, 28 and 56 days shown in Tables 13-14 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 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 presence of fly ash and silica fume resisted the penetration of acid due to their fine particle size.

Relative strength = Strength after acid attack/ original strength

N- Number of days immersed or terminated

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

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

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

Grade	Mix Type	Current passed [coulombs]	Remarks
30 MPa	Control Mix	3756	Medium
	With FA+SF+LS	1612	Low
50 MPa	Control Mix	3584	Medium
	With FA+SF+LS	1245	Low
70 MPa	Control Mix	3248	Medium
	with FA+SF+LS	945	Very Low

M- Total number of days for which the test was conducted

5.4 Rapid chlorination penetration test

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.

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 micro pores with the available binder content, compared to the concrete of medium and low strength.

5.5 Accelerated penetration corrosion test

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. 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 mill amperes, 56 mill amperes, and 47 mill amperes 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

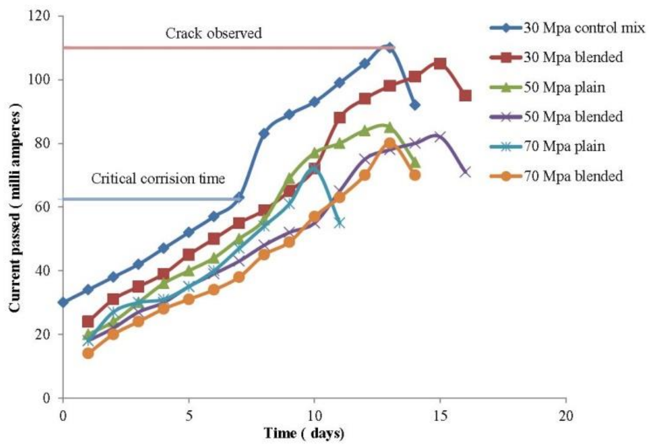

Fig. 5 Variation of current passed with time

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 and 70 MPa was 110, 85 and 72 mill amperes 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. The variation of current passed with time is shown in Fig. 5. The critical corrosion current, corresponding time and depassivation current and time are shown in Table 16.

6. Conclusions

- Substantial improvement in the strength properties of blended concrete mix was developed using fly ash, silica fume and lime sludge of 15%, 8% and 10% respectively as cement replacement.
- The influence of mineral admixtures in the strength point of view was more in lower grades (30 MPa) compared to higher grades (70 MPa).
- Workability of concrete mixes increases with the inclusion of mineral admixtures compared to control mix for all the grades of 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 sulphate attack.
- Acid mass loss factor and acid strength loss factor of both control mix and ternary blended cement concrete were more in the lower grade (30 MPa) when compared to higher grades (70 MPa) indicating more resistance in durability are due to the higher binder content and micro filler effect of mineral admixtures.
- 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.
- In higher grades, the amount of critical current and corresponding time is delayed due to presence of high binder content compared to lower grades.
- 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.

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

	Critical corrosion current (milli amperes)	Critical corrosion time (days)	Depassivation current (milli amperes)	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

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