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Resistance of Fly ash based High Performance Concrete to acidic environment

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ABSTRACT

Fly ash is one of the residues generated in combustion of coal. Fly ash is generally captured from the chimneys of power generation facilities. Fly ash includes substantial amounts of silica (SiO_2), both amorphous and crystalline, and lime (CaO). Fly ash is commonly used to supplement Portland cement in concrete production, where it can bring both technological and economic benefits. Increased awareness of environmental hazards, steep rising prices of building materials, non-availability of space to stock the fly ash and other such factors have generated interest among the researchers to work on the gainful utilization of fly ash as an alternate building material with potential for replacing cement partially in constructions. Fly ash utilization in concrete not only reduces the cost due to cement savings but also contribute to reduced carbon-dioxide emissions contributing to environmental protection. It is well established by now that the concrete structures exposed to acidic environments deteriorated much faster when compared to their counterparts in non-aggressive environments. High-Performance-Concrete (HPC) is a new generation concrete which has the potential to perform well in aggressive environments. This paper presents the details of an experimental investigation planned to utilize fly ash in production of HPC. Acid attack tests have been conducted to measure the durability of HPC. This investigation is undertaken to study and define a better HPC mix containing locally available fly ash which can sustain in chloride and sulphate environments. The investigation examines the progressive deterioration of concrete mixtures containing various combinations of fly ash based HPC mixes exposed to sulphate and chloride solutions.

INTRODUCTION

The production of one ton of Portland cement produces approximately one ton of CO_2. Since, the worldwide production of Portland cement is expected to reach nearly 2 billion tons by 2010, replacement of 30% of this amount by fly ash could dramatically reduce global carbon emissions. The replacement of Portland cement with fly ash also reduces the greenhouse gas foot print of concrete. Crystalline silica and lime are the major components of exposure concern. The fine crystalline silica present in fly ash has been linked with lung damage, in particular silicosis. The other fly ash component of some concern is lime (CaO). This chemical reacts with water (H_2O) to form calcium hydroxide [$Ca(OH)_2$], giving fly ash a pH somewhere between 10 and 12, a medium to strong base. This can also cause lung damage if present in sufficient quantities. These hazards can be minimized by controlling emissions of fly ash from bulk handling operations via closed pumping systems, and use of storage and handling equipment with approved automated spill containment equipment.

Hassan et al. (2000) presented the influence of two mineral admixtures, silica fume and fly ash on the properties of super-plasticized high-performance concrete. The results indicated that usage of the mineral admixtures improved the properties of high performance concrete and they also concluded that silica fume contributed to both long and short term properties of concrete, whereas fly ash required a relatively longer time to get its beneficial effect. Naik et al. (1994) found that although concrete made with high volumes of class C fly ash passed ASTM C-944 for abrasion resistance, better abrasion resistance was obtained for concrete without the high fly ash content. Zhang et al. (1997) presented the mechanical properties of high performance concrete made with high calcium sulphate fly ash and reported that high calcium fly ash exhibited good performance in both fresh and hardened states. Gopalakrishnan et al. (2001) presented the performance of HPC mixes having different replacement levels of cement with low calcium fly ash (class F) and reported a compressive strength of 80 MPa with 25 % replacement of cement with fly ash and also concluded that fly ash concretes have superior durability properties. Long et al. (2002) presented studies on very high performance concretes with ultra fine powders such as pulverized fly ash (PFA), pulverized granulated blast furnace slag (PS) and silica fume (SF) and reported that the use of ultra fine powders improved the relative density of compound pastes with low w/b ratios. Atis (2003) evaluated the strength and shrinkage properties of concrete containing high volumes of fly ash. His studies revealed that the concrete containing 50% fly ash developed higher strength than OPC concrete at 28 days and beyond. He also reported that inclusion of high volumes of fly ash in concrete with a low water-cement ratio resulted in the reduction of shrinkage values up to 30% when compared to OPC concrete. Doven & Pekrioglu (2005) presented effective utilization of high volume fly ash cement paste as a flowable fill material in the construction of structural fills. Bhatty et al. (2006) presented utilization of discarded fly ash as a raw material in the production of Portland cement. Their studies revealed that using fly ash is beneficial in cement plants and power plants. Jerath & Hanson (2007) presented the effects of fly ash replacement of Portland cement and the use of dense aggregate gradation on the durability of concrete mixtures in terms of permeability. Very little research is available on the behaviour of fly ash based HPC to acidic environments. Hence, the present investigation studies the use of fly ash as a partial replacement to cement in the production of HPC as a natural solution to protect the environment and to achieve durability in construction.

High Performance Concrete (HPC): High performance concrete is a concrete made with appropriate materials combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subjected for its designed life. Aitcin & Neville (1993) stated that in practical application of this type of concrete, the emphasis has in many cases gradually shifted from the compressive strength to other properties of the material, such as a high modulus of elasticity, high density, low permeability, and resistance to some forms of attack. Admixtures play an important role in the production of HPC. Fly ash is one such admixture that has potential for use in the production of durable high-performance-concrete. The present investigation aims to produce high-performance concrete with locally available fly ash. The durability of produced fly ash based HPC will be ascertained by studying the behaviour of fly ash based HPC in resisting acid attack.

MATERIALS AND METHODS

Experimental programme has been planned to consider the durability aspect by studying the resistance of HPC to acid attack and weight loss due to acid attack. The details of various materials used in this investigation are given below.

Cement: Portland cement of 53 grade manufactured by Birla Company conforming to IS: 12269 was used in the investigation. The specific gravity of the cement was 3.06. The initial and final setting times were 40 minutes and 360 minutes respectively.

Fine aggregate: Locally available river sand passing through 4.75 mm IS sieve was used. The specific gravity of the sand was 2.68.

Coarse aggregate: Crushed granite aggregate available from local sources has been used. To obtain a reasonably good grading, 50% of the aggregate passing through 12.5mm IS sieve and retained on 10 mm IS sieve and 50% of the aggregate passing through 10 mm IS sieve and retained on 6 mm IS sieve was used in the production of HPC. In production of M20 grade concrete, 20mm maximum size coarse aggregate has been used. The specific gravity of coarse aggregate was 2.75.

Water: Potable freshwater available from local sources was used for mixing and curing of both HPC mixes and M20 grade concrete.

Super plasticizer: To improve the workability of HPC mixes, a high range water-reducing agent COMPLAST SP-337 has been used in the present work.

Acids: The various acids used in the investigation are HCl, H_2SO_4 and $MgSO_4$ each of 5% concentration.

Fly ash: Fly ash obtained from Rayalaseema Thermal Power Station (RTPS), Muddanuru, A.P. was used in the present investigation. The physical and chemical properties of fly ash are presented in Table 1 (a-c).

Casting of test specimens: To evaluate the resistance of fly ash based high performance concretes to acid attack, a total of 12 mixes have been tried with four plain HPC mixes without fly ash. One plain concrete mix of M20 grade of proportion 1:1.5:3.3 (as per IS Code method) has also been cast and tested in the laboratory as reference mix. As there is no standard method for proportioning HPC mixes, absolute volume method has been used for arriving at the mix proportions in this work. The various mix proportions used are given in Table 2. All the materials were taken by weight as per these mix proportion and mixed thoroughly to obtain a uniform mix. The various parameters studied are given below.

Aggregate-binder ratio (A/B Ratio): 2.0
Water-binder ratio (W/B ratio): 0.3, 0.35, 0.4 and 0.45
Percentage replacement of cement by fly ash: 0, 10, 20, and 30

For each mix, 30 concrete cubes of size 150 × 150 × 150 mm were cast. Out of these, 3 cubes were tested for 28 days compressive strength, and remaining 27 concrete cubes for residual compressive strength after 30, 60 and 90 days of acid immersion. The residual compressive strengths are presented in Table 3.

Twenty seven concrete cubes of size 100 × 100 × 100 mm were cast and tested for weight loss after 30, 60 and 90 days of acid immersion. The test program consisted of finding out residual compressive strength and weight loss of cubes due to immersion in 5 % concentration of acid. The percentage weight loss on acid immersion is presented in Table 4. The concrete cubes are cast in steel moulds of inner dimensions 150 × 150 × 150 mm and 100 × 100 × 100 mm. All materials like cement, fine aggregate, coarse aggregate and mineral admixture are manually mixed thoroughly. Approximately 25% of water required is added along with super plasticizer and mixed thoroughly. After that, the balance of 75% of water is added and mixed thoroughly with a view to obtain uniform mix.

For all test specimens, moulds were kept on a table vibrator and the concrete is poured into the moulds in three layers by tamping with a tamping rod and the vibration was carried out by means of table vibrator and maintained constant for all the specimens. The moulds were removed after 24 hours and all the specimens were kept immersed in clean water tank. After curing the specimens in water for a period of 28 days, the specimens were removed and allowed to dry under shade. Later, for each mix, 3 cubes of 150 × 150 × 150 mm were tested for 28 days compressive strength by making use of 2000 kN AIMIL-make digital compression testing machine with least count of 1kN. Cube specimens for M20 concrete were also cast for compressive strength test for comparison purposes. The 28-day compressive strength of M20 concrete was also determined and its value is 27.9 MPa. Remaining 27 cubes of 150 × 150 × 150 mm were cured in 5% concentration of HCl, H_2SO_4 and $MgSO_4$ acids in separate tanks. The curing media was replaced with fresh solution at the end of every week to maintain the same concentration (5%) throughout the exposure period, i.e., 30, 60 and 90 days.

Table 1(a): Sieve analysis of fly ash.

Sieve size	% Passing by weight
i. *Dry Sieve Analysis*	
400mm (40 Mesh)	100
250mm (60 Mesh)	99.5
200mm (80 Mesh)	98.5
150mm (200 Mesh)	97.5
75mm (100 Mesh)	89.50
ii. *Wet Sieve Analysis*	
75mm (200 Mesh)	92.0
53mm (100 Mesh)	87.5
45mm (325 Mesh)	85.5
37mm (400 Mesh)	84.0

To determine weight the loss, initial weights of all the cubes of size 100 × 100 × 100 mm were recorded after 28 days curing in freshwater and then they were kept immersed for 30, 60 and 90 days in separate tanks containing solutions of 5% concentrations of HCl, H_2SO_4 and $MgSO_4$. The specimens were again weighed at the end of 30, 60 and 90 days of acid immersion to determine the percentage weight loss.

Table 1 (b): Chemical analysis of fly ash.

Constituent	Test results (% by weight)	IS: 3812 Requirement
Silica as SiO_2	59.16	35.0 min
Alumina as Al_2O_3	30.64	
Iron oxide as Fe_2O_3	4.07	
$SiO_2 + Al_2O_3 + Fe_2O_3$	93.87	70.0 min
Calcium oxide as CaO	2.85	
Magnesium oxide as MgO	0.36	5.0 max
Sulphate as SO_4	0.21	2.75 max
Alkalies	1.38	1.50 max
Loss on ignition	0.21	12.0 max

RESULTS AND DISCUSSION

In the present investigation, the resistance of HPC to the acidic environment has been studied by conducting acid immersion test on HPC cubes. Residual compressive strength and percentage weight loss of HPC after acid immersion have been measured.

Residual compressive strength: The residual compressive strengths on acid immersion in HCl, $MgSO_4$ and H_2SO_4 of all mixes tried in this investigation are presented in Table 3.

Effect of water-binder (W/B) ratio on residual compressive strength: From the results presented in Table 3, it can be observed that the residual compressive strength of HPC at all ages of exposure decreases with in-

Table 1(c): Physical properties of fly ash.

Property	Test results	IS:3812 Requirement	
		Grade 1	Grade 2
Fineness (Blaine), cm^2/g	3989	3200	2500
Lime Reactivity, N/mm^2	8.9	4.0 min	3.0 min
Drying shrinkage, %	0.008	0.15 max	0.10 max
Autoclave Expansion, %	0.012	0.80 max	0.80 max
Specific gravity	2.18	-	-

crease in W/B ratio. The trend is the same for all percentage replacements of cement by the fly ash and for all acids tried in this investigation. The reason for decrease in residual compressive strength with increasing W/B ratio may be attributed to the porous transition zone that develops due to higher water content allowing the acid to penetrate deep and destroy the C-S-H gel. From Table 3, it can be further observed that the residual compressive strengths of all HPC mixes are considerably higher than that of M20 grade reference mix at all ages of acid exposure for all the three acids tried in this investigation. Hence, it can be concluded that fly ash based HPC resists acid attack better than ordinary M20 grade concrete.

Effect of percentage replacement of cement by fly ash on residual compressive strength: The effect of percentage replacement of cement with fly ash on residual compressive strength after exposure to the three different acids for 30, 60 and 90 days is presented in Figs. 1, 2 and 3 for W/B ratio of 0.3. It can be observed from these figures that the addition of fly ash has directly improved the resistance of HPC to acid attack up to 10% replacement. It can be observed from these figures that for the fly ash based HPC mixes, the residual compressive strength increased up to 10% replacement and then started decreasing at 20 and 30% replacement levels. Maximum residual compressive strengths have been achieved at 10% replacement. Though the plots are shown only for W/B = 0.3, same trend can be noticed for other W/B ratios (Table 3). Hence, it can be concluded that 10% replacement level of cement by fly ash is optimum for the HPC in resisting the acid attack.

Effect of age of acid immersion on residual compressive strength: The effect of age of acid immersion on residual compressive strength for fly ash based HPC mixes for three different acids and for different W/B ratios can be observed in Figs. 1-3. From these figures it can be observed that the residual compressive strength decreases with increase in age of acid immersion. This is true for all the acids tried in the present investigation and for all W/B ratios. Maximum loss of compressive strength is noticed at 90 days of acid immersion. The decrease in residual compressive strength is expected because of formation of more and more ettringite with increase in age of acid immersion.

Table 2: Mix proportions for different HPC mixes (For one cubic metre of concrete).

	Mix designation	W/B ratio	Cement (kg)	Fly Ash (kg)	Coarse aggregate (kg)	Sand (kg)	Water (litres)
0% Fly Ash	A1	0.3	647.1	0	970.6	647.1	194.1
	A2	0.35	626.8	0	940.2	626.8	219.4
	A3	0.4	607.8	0	911.6	607.8	243.1
	A4	0.45	589.8	0	884.8	589.8	265.4
10% Fly Ash	B1	0.3	577.5	64.2	962.4	641.6	192.5
	B2	0.35	559.5	62.2	932.5	621.7	217.6
	B3	0.4	542.6	60.3	904.4	602.9	241.2
	B4	0.45	526.8	58.5	877.9	585.3	263.4
20% Fly Ash	C1	0.3	508.9	127.3	954.3	636.2	190.9
	C2	0.35	493.3	123.3	924.9	616.6	215.8
	C3	0.4	478.5	119.6	897.3	598.2	239.3
	C4	0.45	464.6	116.2	871.2	580.8	261.4
30% Fly Ash	D1	0.3	441.7	189.3	946.4	630.9	189.3
	D2	0.35	428.1	183.5	917.5	611.6	214.1
	D3	0.4	415.4	178.1	890.2	593.5	237.4
	D4	0.45	403.5	172.9	864.6	576.4	259.4

Effect of type of acid on residual compressive strength: In the present investigation HPC mixes have been subjected to 5% concentration of solutions of HCl, $MgSO_4$ and H_2SO_4. The influence of these acids on residual compressive strength after 90 days of acid exposure for HPC mixes containing 10% of fly ash is presented in Fig. 4. It can be observed that maximum loss of compressive strength occurred in case of H_2SO_4 acid immersion when compared to HCl and $MgSO_4$. Out of the three acids the least loss of compressive strength is recorded for HCl acid immersion. Further, it can be seen from this figure that beyond a W/B ratio of 0.4, the influence of acid attack is severe indicated by the steep slope of the line. From the results of the present investigation it can be concluded that the attack of H_2SO_4 is most severe on HPC, and HCl is the mildest one in the ranges tested. The reason for the decrease in compressive strength due to acid attack is the dissolution of calcium hydroxide, which occurs according to the following reaction.

$2HX + Ca(OH)_2 \rightarrow CaX_2 + 2H_2O$ (X is negative ion of the acid.)

The decomposition of HPC depends on the porosity of the cement paste, on the concentration of acid, the solubility of the acid calcium salts (CaX_2) and on the fluid transport through the concrete. Insoluble calcium salts may precipitate in the voids and can slow down the attack. Sulphuric acid is very aggressive as its calcium salts are readily soluble and removed from the acid front. As a result of this, the binding capacity of the hardened cement is destroyed leading to loss of compressive strength. Hydrochloric acid is less harmful as its calcium salts, due to its low solubility, inhibit the attack by blocking pathways within the concrete such as interconnected cracks, voids and porosity. Sulphuric acid is very damaging to HPC as it combines an acid attack and a sulphate attack. Sulphate ions combine with free calcium ions to form gypsum. Sulphate ions also combine with hydrated calcium aluminate to form calcium sulfoaluminate (ettringite). Gypsum and calcium sulfoaluminate have higher volume than the reactants leading to the development of internal stresses in concrete. These

Table 3: Residual compressive strengths on acid immersion.

S. No	Mix designation	28 days compressive strength (MPa)	Residual compressive strength on acid immersion(MPa)								
			HCl			$MgSO_4$			H_2SO_4		
			30days	60days	90days	30days	60days	90days	30days	60days	90days
1	R	27.9	24.4	21.9	19.5	24.2	21.7	18.9	23.8	20.8	16.9
2	A1	83.4	76.7	71.7	65.9	76.2	70.7	64.7	75.7	69.9	63.3
3	A2	81.1	74.4	69.6	63.2	73.9	68.4	62.5	73.3	67.8	61.1
4	A3	80.2	73.1	68.1	61.9	72.9	67.6	61.7	72.3	66.8	59.9
5	A4	75.9	68.8	63.9	58.2	68.8	63.7	57.9	68.0	62.9	56.3
6	B1	85.7	79.3	75.8	71.0	79.0	75.3	69.2	78.2	73.9	68.3
7	B2	83.8	77.2	73.6	67.9	76.7	73.2	66.9	76.0	72.2	64.7
8	B3	79.2	72.5	68.7	63.7	72.2	67.9	62.9	71.6	67.0	60.7
9	B4	78.9	72.1	67.6	62.5	71.7	67.2	61.9	70.9	66.1	60.7
10	C1	72.4	66.4	62.1	57.3	65.9	61.3	55.9	65.4	60.9	55.2
11	C2	71.3	65.4	60.7	55.5	64.9	59.7	54.6	64.1	59.4	53.8
12	C3	69.9	63.6	58.8	53.5	63.5	58.6	53.3	62.8	58.1	52.5
13	C4	66.7	60.2	55.7	51.1	59.9	55.5	50.8	59.2	54.8	49.2
14	D1	60.1	54.8	50.9	46.5	54.5	50.1	45.6	53.9	49.8	44.8
15	D2	56.9	51.7	47.6	43.1	51.3	46.8	42.8	50.9	46.7	42.2
16	D3	55.7	50.3	46.2	41.9	50.0	46.1	41.7	49.5	45.5	40.6
17	D4	54.4	48.9	45.0	40.4	48.6	44.7	40.4	48.0	44.2	39.5

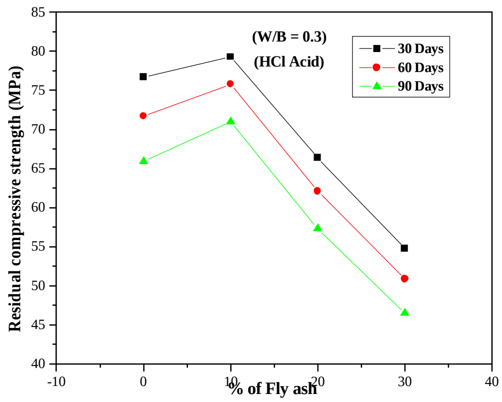

Fig. 1 Effect of % fly ash on residual compressive strength after immersion in HCL acid

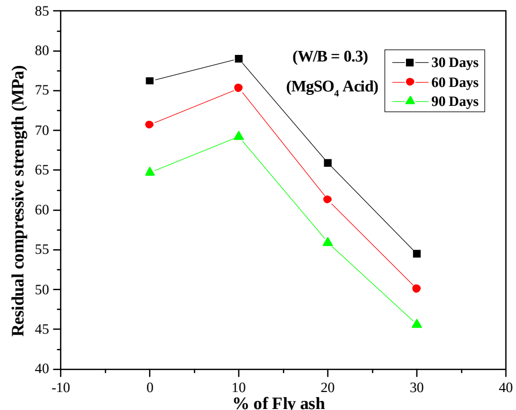

Fig.2 Effect of % of fly ash on residual compressive strength after immersion in $MgSO_4$ acid

internal stresses lead to cracking and spalling of concrete which in turn lead to the deterioration of the concrete and loss of strength. Thus, the sulphuric acid combines both acid attack and sulphate attack, and hence, causes greatest loss of strength.

Percentage weight loss on acid immersion: In the present work, percentage weight loss of HPC due to acid immersion has been determined as a parameter of durability. The original weight of cubes after 28 days water curing was measured and then these cubes were immersed in 5% acid solution for 30, 60 and 90 days. After the specified period, the cubes were removed from acid solution and allowed to dry under shade. Then their weight was measured and percentage weight loss computed. The percentage weight loss due to acid immersion in acids HCl, $MgSO_4$ and H_2SO_4 of all HPC mixes tried in this investigation is presented in Table 4.

Effect of W/B ratio on percentage weight loss: From the results presented in Table 4, it can be observed that the percentage weight loss increases with increase in W/B ratio for all the percentage replacements of cement by fly ash. This trend is similar for all the three acids, i.e., HCl, H_2SO_4 and $MgSO_4$ tried in this investigation. The reason for this phenomenon to happen is that the increase in the water content makes the transition zone porous. The porous transition zone allows more acid to penetrate through resulting in higher "ettringite" formation. This causes volume increase in concrete resulting in spalling and weight loss. It can be further observed that the percentage weight loss of all HPC mixes is considerably lower when compared to that of reference M20 mix. Hence, it can be concluded that HPC mixes very well resist the acid attack as compared to ordinary M20 concrete.

Effect of percentage replacement of cement by fly ash on percentage weight loss: The effect of percentage replacement of cement by fly ash on percentage weight loss of HPC is presented in Figs. 5, 6 and 7 for W/B = 0.3. It can be observed from these figures that up to 10% replacement of cement, the percentage weight loss has decreased and then started increasing at 20 and 30% replacement levels. It is also observed that the percentage weight loss is least at 10% replacement levels for all acids at all exposure durations. Though, the graphs are presented only for W/B = 0.3, same trend can be noticed from the table for other W/B ratios. Hence, it can be concluded that 10% replacement of cement by fly ash is optimum in resisting acid attack.

Effect of age of acid immersion on percentage weight loss: The effect of age of acid immersion on percentage weight loss can be observed from Figs. 5, 6 and 7. It can be observed from these figures

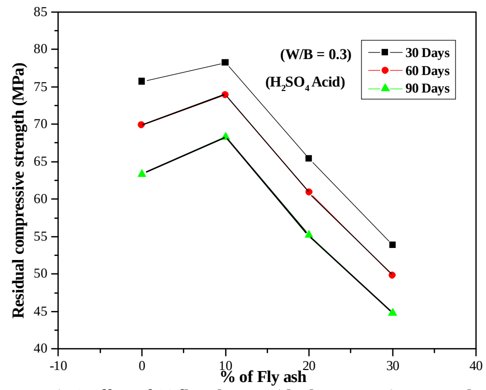

Fig.3 Effect of % fly ash on residual compressive strength after immersion in H_2SO_4 acid

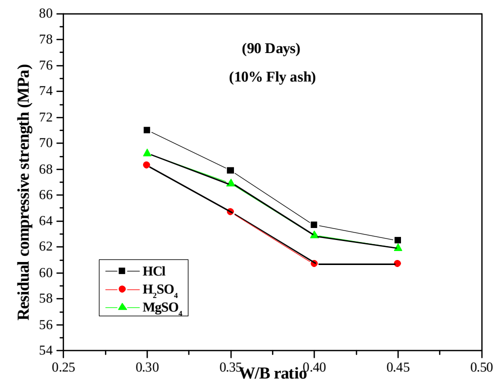

Fig.4 Effect of type of acid on residual compressive strength for fly ash based HPC mixes

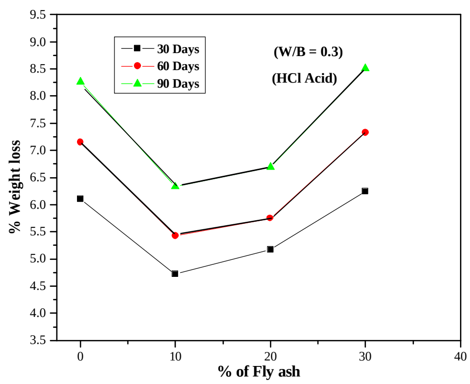

Fig.5 Effect of % of fly ash on % weight loss

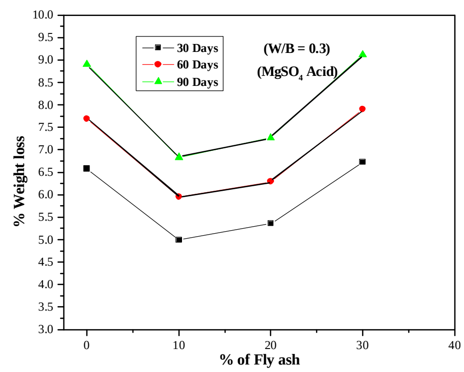

Fig.6 Effect of % of fly ash on % weight loss

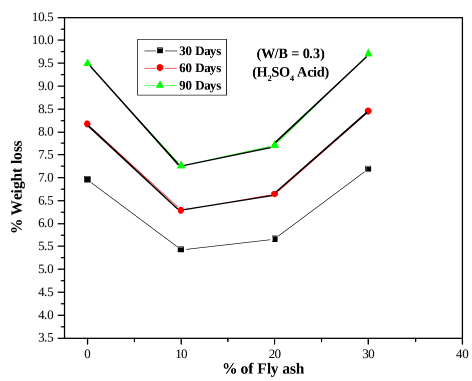

Fig.7 Effect of % of fly ash on % weight loss

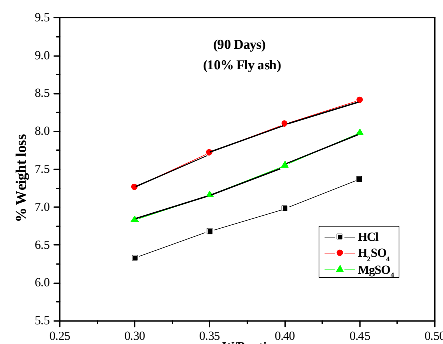

Fig.8 Effect of type of acid on % weight loss for fly ash based HPC mixes

that the percentage weight loss increases with increase in age of acid immersion. This is true for all the acids tried in this investigation. The percentage weight loss is higher at 90 days of immersion in acid. This may be due to more and more formation of ettringite with increase in age of acid immersion. From visual observation of the specimens on 90 days of immersion in acids, it was observed that the edges of the cubes were worn out indicating maximum deterioration.

Table 4: Percentage weight loss on acid immersion.

S.No	Mix design	% weight loss on acid immersion								
		HCl			$MgSO_4$			H_2SO_4		
		30days	60days	90days	30days	60days	90days	30days	60days	90days
1	R	8.9	11.2	13.4	10.2	13.8	16.7	12.3	15.7	18.3
2	A1	6.1	7.2	8.3	6.6	7.7	8.9	6.9	8.2	9.5
3	A2	6.4	7.5	8.6	6.9	8.1	9.3	7.3	8.6	9.8
4	A3	6.7	7.9	9.0	7.2	8.5	9.8	7.6	9.0	10.4
5	A4	6.9	8.2	9.4	7.6	8.9	10.2	8.0	9.5	10.9
6	B1	4.7	5.4	6.3	5.0	5.9	6.8	5.4	6.3	7.3
7	B2	4.9	5.7	6.7	5.3	6.3	7.2	5.7	6.7	7.7
8	B3	5.2	6.0	6.9	5.6	6.5	7.6	5.9	6.9	8.1
9	B4	5.4	6.3	7.4	5.8	6.8	7.9	6.2	7.2	8.4
10	C1	5.2	5.8	6.7	5.4	6.3	7.3	5.7	6.6	7.7
11	C2	5.3	6.1	7.1	5.6	6.6	7.5	5.9	7.0	8.1
12	C3	5.6	6.3	7.3	5.8	6.8	7.9	6.3	7.3	8.4
13	C4	5.7	6.7	7.7	6.1	7.3	8.3	6.5	7.6	8.8
14	D1	6.3	7.3	8.5	6.7	7.9	9.1	7.2	8.5	9.7
15	D2	6.6	7.7	8.9	7.1	8.3	9.5	7.6	8.8	10.2
16	D3	6.9	8.1	9.3	7.5	8.6	10.0	7.9	9.3	10.5
17	D4	7.2	8.4	9.7	7.7	9.1	10.5	8.7	9.8	11.3

Effect of type of acid on percentage weight loss: In the present investigation all the HPC mixes have been subjected to 5% concentration of acids HCl, H_2SO_4 and $MgSO_4$. The influence of these acids on percentage weight loss after 90 days of exposure for the HPC mix containing 10% of fly ash is presented in Fig. 8. It can be observed that maximum percentage weight loss has occurred in case of H_2SO_4 acid immersion and minimum percentage weight loss in HCl acid immersion. The trend is same at all replacement levels, and it can be observed that $MgSO_4$ attack is severe when compared with that of HCl acid. From the results, it can be concluded that the attack of H_2SO_4 is most severe on HPC. On visual observation of cubes, it was noticed that the corners of the cubes on immersion in H_2SO_4 were worn out indicating the severity of acid. The corners were the first to spall of because near the corners the intrusion will be from the two adjacent faces of the cube. The severity of the sulphuric acid is due to its combined action of acid attack and sulphate attack.

CONCLUSIONS

Structures constructed 30-40 years back got deteriorated well before their expected life span, particularly in marine environments. HPC produced with partial replacement of cement by fly ash can provide a wonderful solution and can stand well even in aggressive acidic environments. This fact has been established in the present investigation. The major conclusions of the work are as below.

- Fly ash based HPC mixes resisted acid attack in a better way as compared to conventional M20 concrete at all ages of exposure to HCl, $MgSO_4$ and H_2SO_4.
- It is observed that the residual compressive strength of all HPC mixes are considerably higher than that of M20 grade reference mix at all ages of acid exposure for all the three acids tried in this investigation.
- The loss of compressive strength of HPC mixes due to acid attack is least at 10% replacement of cement by fly ash. Hence, 10% replacement is considered as optimum.
- The loss of compressive strength is 20.3% for fly ash based HPC mixes after 90 days immersion

in H_2SO_4 acid while similar exposure resulted in a loss of 39.5% for reference M20 concrete. This confirms the superior performance of fly ash based HPC in resisting acid attack.

- The residual compressive strength of HPC mixes subjected to acid attack decreases with the increase in water-binder ratio. The trend is observed to be the same for all the three acids and at all percentage replacements of cement by fly ash.
- The residual compressive strength of HPC decreases with increase in age of acid immersion. Maximum loss of compressive strength has occurred at 90 days of acid immersion.
- Maximum loss of compressive strength and weight of HPC occurs in case of H_2SO_4 acid immersion as compared to HCl and $MgSO_4$ acids. Out of the three acids the least loss of compressive strength is recorded for HCl acid immersion.
- The percentage weight loss due to acid attack increases with increase in W/B ratio for all the percentage replacements of cement by fly ash and also for all the three acids tried in this investigation.
- The percentage weight loss decreased up to 10% replacement then it started increasing at 20 and 30% replacement levels. The percentage weight loss is least at 10% replacement levels, for all acids at all exposure durations.
- The percentage weight loss increases with increase in age of acid immersion. This is true for all the acids tried in this investigation.

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