J. Build. Mater. Struct. (2023) 10: 1-15 ***Original Article***
DOI : 10.34118/jbms.v10i1.2864

Performance of High Volume Fly Ash Concrete in Structural Applications

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Received: 30-01-2023 **Accepted: 13-02-2023**

Abstract. Application of high volume fly ash concrete is still not advocated by construction fraternity due to lack of standardisation. In India, fly ash as a pozzolanic material can be used in manufacturing of Portland Pozzolana cement and composite cement with a maximum limit of 35%. Present study had been carried out at various percentages of fly ash and a detailed mechanical and durability study was conducted. In this paper, concrete mixes were designed at two water binder ratio with 30%, 35%, 40% and 50% fly ash content. Mechanical behaviour of concrete was studied through tests like compressive strength (at age of 1, 3, 7, 28, 56 and 90 days) and flexure strength (at an age of 7, 28 and 90 days). Durability aspect of high volume fly ash concrete mixes were determined through various test like RCPT, non-steady state chloride migration, bulk conductivity, accelerated carbonation etc. and comparison is made with control mixes (i.e. concrete made with OPC). Alkali silica reactivity (ASR) study was also carried out at 30%, 35%, 40% and 50% fly ash content using reactive aggregates. It was quite evident from test results that strength characteristics of high volume flyash concrete mix made with 50% flyash content was remarkably lower than that of all other concrete mixtures. High volume flyash concrete mix designed at 40% flyash content had shown exemplarily performance in comparison to other high volume flyash concrete mixes as well as control mixes. Flyash content was found to most significant parameter influencing rate of carbonation.

Key words: High volume fly ash concrete mixes, RCPT, non-steady state chloride migration, bulk conductivity, accelerated carbonation, Alkali Silica Reactivity (ASR)

1. Introduction

In order to achieve sustainability, 21st century has provided momentum to various industry sectors to identify levers to their energy intensive materials and processes (Mehta, 2004). In cement and construction industry, use of Ordinary Portland cement contributes towards high production cost as well as high embodied energy of concrete. Production of one tonne of Portland cement clinker almost generates one tonne of CO_2. In recent years, one approach to reduce carbon footprint of the construction industry that has drawn significant attention is the manufacturing of high volume fly ash concrete mixtures. In such concrete mixes, fly ash substitutes the Portland cement clinker at a level well above the range of 15 % to 25 % as commonly used in the production of the current fly ash based concrete mixtures (Mehta, 2004; Obla et al., 2012). As per various international standards and codes, substitution level of Portland cement clinker by the fly ash is of the order of 20 % to 35 % (CEA, 2022; Ojha et al., 2022). As a by-product of coal based thermal power plants, fly ash is the most abundant of all siliceous materials available throughout the world. However, proportion of fly ash as a part replacement of Portland cement clinker for Reinforced Cement Concrete (RCC) construction is very small and a major proportion of fly ash is disposed off as a backfilling material or dumped at sites. Dumping of fly ash only creates environmental nuisance that requires immediate redressal under the current scenario. In India, use of fly ash has been diversified into various sectors such as cement sector, construction sector, agriculture sector etc (CEA, 2022; Ojha et al., 2022; Jo Jacob et al., 2014). Their still exist a great opportunity to further enhanced the fly ash level in concrete through a comprehensive study that can support the revision of the existing standards or codes. Fly ash improves workability through "ball bearing action" of spherical shaped fly ash particles and decreases internal temperatures. Fly ash leads to improvement in grading of the concrete mix by smoothing out of finer size particle distribution. Fly ash decreases the amount of water needed by about 15 to 20% (Ojha et al., 2022). Mehta (2004) has concluded in his study about mechanisms for reduce in water content in concrete mix with higher than 50% fly ash thereby indicating improvement in workability, reduction in thermal and drying shrinkage and improved durability. Increase of fly ash content from 30% to 45% increases the durability perfromance of concrete without decrease in compressive and flexural tensile strength (Jo Jacob et al., 2014). Malhotra and Mehta (2002) concluded that HVFAC is sustainable, durable and eco-friendly concrete. Poon et al. (2000) studied compressive strength at age of 28 days and found that concrete with 45% fly ash achieved compressive strength of 80 MPa and exhibited lower heat of hydration and chloride diffusivity in comparison to ordinary portland concrete. Siddique (2004) studied mechanical properties of concrete with fly ash and observed that fly ash concrete has lower mechanical properties compared to OPC concrete at early ages but at later ages mechanical properties have been increased continuously. In this research work, a comprehensive study had been carried out on concrete mixes designed at various percentages of fly ash. The study was carried out at two water-binder ratio (0.40 & 0.60) with 30%, 35%, 40% and 50 % fly ash content. For their application in structural concrete, various mechanical and durability studies were conducted at various ages. Alkali silica reactivity (ASR) study was also carried out in line with ASTM C 1567 i.e. accelerated mortar bar test at various replacement percentages of fly ash content using reactive aggregates.

2. Experimental program

In this present research work, concrete mixes have been designed at 30%, 35%, 40% and 50 % fly ash content. Material used in the production of concrete mixes are characterized for basic physical and chemical parameters as mentioned in 2.1. The details of the concrete mix design as well as test conducted are given in 2.2 and 2.3 respectively.

2.1. Used Materials

2.1.1. Cement and fly ash

Cement used in study is OPC-43, conforming to IS 269 (2015) whereas fly ash used in study was siliceous in nature with 25 % reactive silica content, conform to requirement of IS 3182 Part 1 (2017). Some of the physical and chemical properties of cement and fly ash is given in Table 1

Table 1. Physical and Chemical properties of cement (i.e. OPC-43) and fly ash

Sl No.	Properties	OPC-43	Fly ash
(A) Physical Analysis:			
1	Specific Gravity	-	2.22
2	Blain's fineness, m^2/kg	293	329
3	Compressive strength, N/mm^2 3 days, 7 days & 28 days	32.5, 41.50 & 54.00	-
4	Lime Reactivity (MPa)	-	5.2
(B) Chemical analysis%			
1	Loss of Ignition (LOI)	1.86	0.12
2	Silica (SiO_2)	20.22	59.78
3	Iron oxide (Fe_2O_3)	3.57	5.13
4	Aluminum oxide (Al_2O_3)	5.26	29.81
5	Calcium oxide (CaO)	61.87	2.04
6	Total Alkalies as Na_2O Equivalent	1.31	0.76
7	Chlorides	0.049	0.004
8	Insoluble Residue	1.99	-

2.1.2. Aggregate

The coarse aggregates (20 mm & 10 mm) and fine Aggregate (Zone II), conforming to IS 383 (2016) were used in all the concrete mixes. Silt content of the fine aggregate was approximately 5%. Some of physical properties of aggregates so used are mentioned in table 2.

Table 2: Physical properties of aggregates

Property	Fine Aggregate (Natural)	Coarse Aggregate	
		20 mm	10 mm
Specific gravity	2.59	2.73	2.73
Water absorption (%)	0.8	0.4	0.3

The gradation curve for fine aggregate is given in figure-1 and it meets requirement of Zone-II category fine aggregate as per IS 383 (2016).

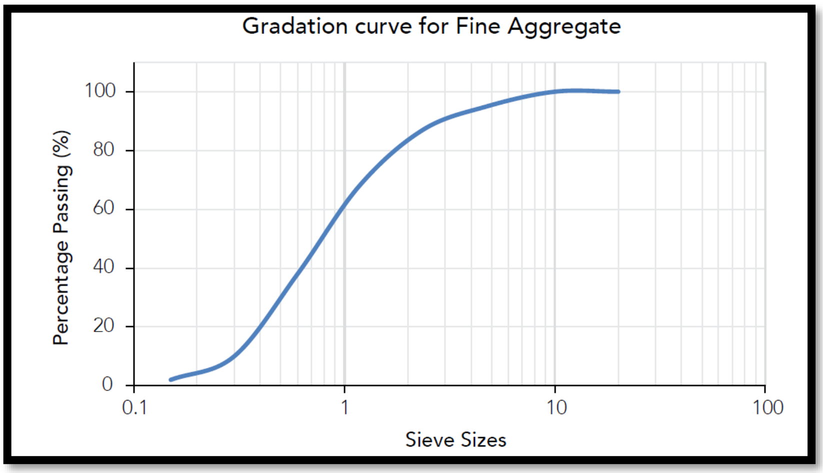

Fig. 1 Gradation curve for fine aggregate

2.1.3. Admixture

Naphthalene based super plasticizer normal type confirming to IS 9103 was used in concrete mix design. The specific gravity and concentration of solid particles in admixture were 1.24 and 28.14 % respectively.

2.2. Concrete mix

The water -binder ratio selected for the present research is 0.60 and 0.40. The details of the mix selected for the study are given in table3. In order to achieve the slump value of the concrete mixes in the range of 50-75 mm, dosage of super-plasticizer has been optimized accordingly. In total 10 concrete mixes including two conventional mixes i.e. control concrete (C1/0.60 and C2/0.40) had been studied. The cement was substituted with fly ash by mass for the mixes at sr.no. 2 to 10 studied and presented in Table-3 below.

2.3. Test conducted

Mechanical properties of the concrete have been evaluated in terms of compressive strength and flexural strength at various ages as mentioned in table 4. The laboratory conditions of temperature and relative humidity were monitored during the ambient curing i.e. 27±2^{o}C and relative humidity 65±5 as per IS: 516. Various durability tests or techniques had been selected on the basis of environmental conditions which determines the aggressiveness of deleterious agents. During the working life, a RCC structure is supposed to be exposed to various type of physical as well as chemical attack such as chloride attack, sulphate attack, acid attack etc. Therefore, it becomes essential to evaluate the behavior of the concrete as well as concrete making materials against the aggressiveness of exposure conditions. Durability test or techniques had been developed to check the performance of concrete and concrete making ingredients against the penetration of aggressive substances (IS-383, 2016; Arora and Kaura, 2014; 2015; 2016; Arora et al., 2017-a; 2017-b; Ojha et al. 2021; 2022). For details of the durability tests, refer to table 4.

Table 3. Typical concrete mix proportions

Sr. No	Mix Identification	water-binder ratio	Total binder content (kg/m³)	OPC-43 (%)	Fly ash (%)	Dose of admixture % by Wt. of Cement
1.	C1/0.60	0.60	300	100	0	0.40
2.	M1/0.60/30%	0.60	300	70	30	0.50
3.	M2/0.60/35%	0.60	300	65	35	0.65
4.	M3/0.60/40%	0.60	300	60	40	0.70
5.	M4/0.60/50%	0.60	300	50	50	0.80
6.	C2/0.40	0.40	400	100	0	0.50
7.	N1/0.40/30%	0.40	400	70	30	0.60
8.	N2/0.40/35%	0.40	400	65	35	0.70
9.	N3/0.40/40%	0.40	400	60	40	0.85
10.	N4/0.40/50%	0.40	400	50	50	0.90

Table 4. Details of test conducted

Sr. No	Test conducted	Test standards/ Guideline	Type of specimen and size of specimen	Age of testing (Days)
1.	Compressive strength	IS 516 (Part1/Sec1)	Cube (150 mm)	1,3,7,28,56 and 90
2.	Flexural strength	IS 516 (Part1/Sec1)	Concrete beam (100x100x500 mm)	7, 28and 90
3.	Rapid chloride Penetration test	ASTM C 1202	Concrete disc (100 mm diameter x50 mm height)	28 and 56
4.	Non steady state chloride migration coefficient	NT Build 492	Concrete disc (100 mm diameter x50 mm height)	28 and 56
5.	Bulk Conductivity	ASTM C 1760	Concrete disc (100 mm diameter x200 mm height)	28 and 56
6.	Electrical Resistivity using four point wenner probe technique	RILEM TC 154	Concrete slab (300mm x300 mm x100mm)	28 , 56 and 90
7.	Porosity i.e. Volume of permeable voids	ASTM C642	Concrete disc (100 mm diameter x50 mm height)	28 and 56
8.	Accelerated carbonation depth	ISO 1920 Part 12	Concrete beam (100 mm x100mm x500 mm)	Exposure period = 70days , 140 days and 210 days
9.	Alkali silica reactivity	ASTM C 1567	Mortar bar (25 mmx 25mm x282 mm)	14 days expansion

3. Results and discussion

Mechanical and durability behaviour of High volume fly ash concrete mixes had been studied and comparison was made with the control mixes i.e. concrete made with OPC-43 at both water-binder ratios. The results shown in the graph are the averaged results of three test specimens.

3.1. Mechanical behaviour of the High volume fly ash concrete mixes

Compressive strength and flexural strength are the two basic fundamental engineering properties of the concrete. Mechanical behaviour of the concrete mixer designed with varying percentages of flyash had been evaluated in terms of compressive strength and flexural strength and comparison had been drawn with the control mixes. Compressive strength had been determined using concrete cube specimens (150mm) at an age of 1day, 3 days, 7 days, 28 days, 56 days and 90 days. The result shown in figure 2 and figure 3 are the average of 3 specimens tested as per IS 516 (Part 1/Sec 1). Similarly, flexural strength was determined using concrete beam specimens (100mmx100mmx500mm) tested under three point loading as per IS 516 (Part 1/Sec 1). The flexural strength test was conducted at an age of 7 days, 28 days and 90 days, results are the average of 3 specimens and are shown in figure 4 and figure 5. In the present study, two water-binder ratio i.e. 0.60 and 0.40 had been selected. The selection of the water-binder ratio was to cover different grade of concrete. Generally, concrete mix designed at water cement ratio of 0.60 represent M20 or M25 grade of concrete whereas concrete mix designed at water-cement ratio of 0.40 represent M.35 grade of concrete.

On the perusal of the test results, it was observed that effect of water-binder ratio along with flyash content had a significant influence over strength value. From the figure 2 to 3, it can be observed that early age compressive strength of the concrete mixer designed with flyash had lower strength in comparison to control mixes. This trend of reduced compressive in high volume fly ash concrete mix continued up to an age of 28days. However, at extended ages i.e. 56 days and 90 days, it can be noticed that high volume fly ash concrete mixtures designed at water-binder ratio of 0.40, compressive strength of the concrete mixes designed with flyash content up to 35% is at par with the control mixes. However, at 0.6 water-binder ratio, compressive of high volume flyash concrete mixtures were not found to be encouraging. Concrete mixer designed with 50% fly ash content have significantly lower, compressive strength in comparison to control mixer at all ages. At later ages, gain in the compressive strength in high volume fly ash concrete mixes was observed. This is probably due to the densification of the microstructure resulting from the Pozzolanic Reaction. Pozzalanic reaction in case of fly ash concrete mixes involves reaction between reactive silica and alumina constituent of fly ash with the Portlandite. It is essential to have presence of Portlandite for the continuation of Pozzalanic reaction. Pozzolanic reaction in case of fly ash concrete mixes results in the formation of secondary CSH and sometimes CASH, if alumina is available that contributes towards later age strength (Arora et al., 2017; Ahmed et al., 2019; Du et al., 2021; Park and Choi, 2021, Chen et al., 2019; Kumar et al., 2021, Sun et al., 2021). The test results of flexural strength indicate that at 7days, high volume flyash concrete mixes had lower flexure strength value in comparison to control mixer. At 28days and 56 days, flexural strength of high volume concrete mixer were found to be higher to equivalent w.r.t control mixes. It was also observed that with an increase in fly ash content (limited to 40%) a proportionate increase in the flexural strength value had been noticed.

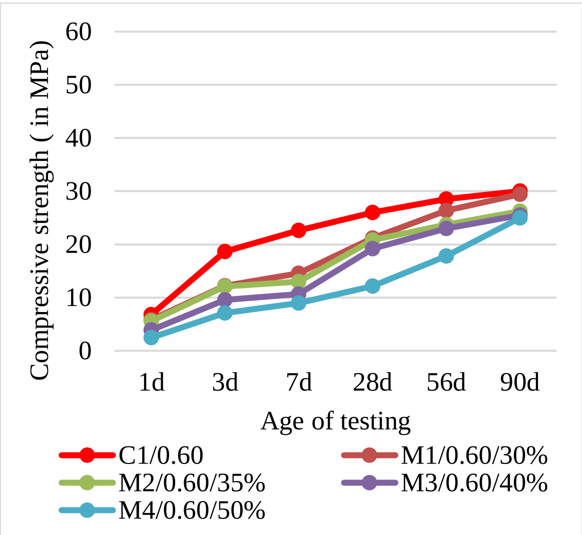

Fig 2. Compressive strength for w/b 0.60

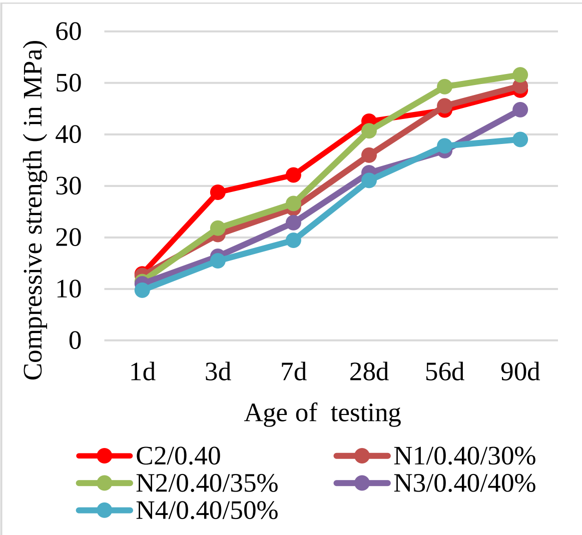

Fig 3. Compressive strength for w/b 0.40

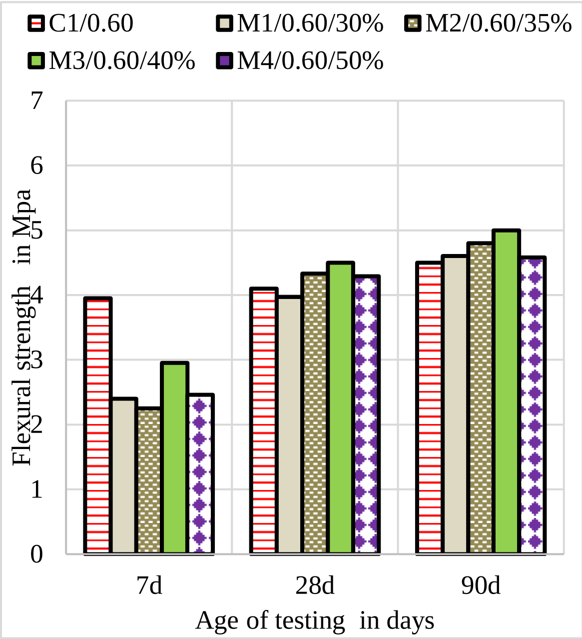

Fig 4. Flexural strength for w/b 0.60

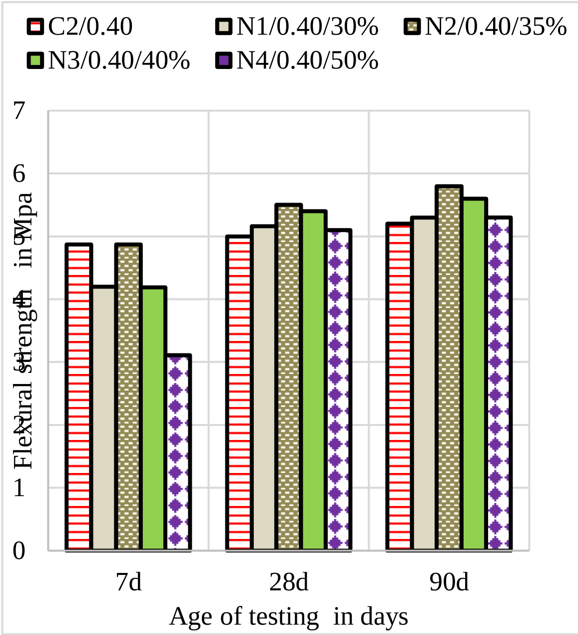

Fig 5. Flexural strength for w/b 0.40

3.2. Durability aspect of High volume fly ash concrete mixes

Durability tests had been developed with an aim to quantity the quality of the concrete as well as concrete making constituents w.r.t aggressiveness of the environmental exposure conditions. Some test provides a qualitative means of judgement whereas some test provides quantitative means of judgement. Durability of concrete is basically defined in terms of permeability characteristics of the material. Generally, a porous concrete is termed to be a less durable concrete. For a designing a RCC structure in coastal environmental, it is important to understand the problems that could affects the performance of the structural concrete. One of the major issue that requires immediate action while designing structure under such climatic condition is related with the attack of chloride ions that results in reinforcement corrosion. This problem can be solved, if performance based testing of concrete or concrete making material had been carried out at the design mix stage. Various tests like rapid ion penetrability test (also known as RCPT), non-steady state chloride migration coefficient test (i.e. NT build N94), bulk conductivity test and electrical resistivity had been developed. In the present study, durability of high volume flyash concrete mixes had been studied through various types of performance based tests.

The test results of RCPT conducted as per ASTM C1202 are shown in figure 6 and figure 7. On the perusal of the RPCT results it was quite evident that water binder ratio, age of concrete and flyash content had significant influence over charge passed value. According to ASTM C1202, chloride ion penetrability classes had been described on the basis of the charge passed. If charge passed is less than 100 coulombs such that of concrete will fall under negligible class whereas if charge passed lie in the range of 100-10000 coulombs, concrete will lie in very low category. Low category had been defined for a charge passed range of 1000-2000 coulombs, moderate category had been defined for a charge passed range of 2000-40000 coulombs whereas a concrete with charge passed value more than 4000 coulombs, it will fall under high chloride ion penetrability class. During the test, it was observed that penetrability class of the control mixes (i.e. C1/0.60 and C2/0.40) lie in moderate category. Whereas penetrability class of the high volume flyash concrete mixtures lie either in very low or low category. High volume flyash concrete mixes designed at 0.40 water- binder ratio had RCPT value in the range of 240 to 540 Coulombs whereas at 0.60 water- binder ratio, RCPT value of these mixes were found in the range of 730 to 1640 coulombs. A decrease in the RCPT value with age had been observed with all concrete mixes. High volume flyash concrete mixes designed with 40% flyash content had the lowest RCPT value in comparison to all other concrete mixtures.

The non-steady state chloride migration coefficient of the concrete mixtures was determined as per nordtest method i.e. NT build492 and results are shows in figure 8 and figure 9. As observed from the test results, water-binder ratio, flyash content and age of concrete were the important parameters influençons the test value. For water -binder ratio of 0.60, at 28 days, non-steady state chloride diffusion value of control mix was found to be $9.0x10^{-12}$ m^2/yr whereas high volume fly ash concrete mixtures had chloride diffusion coefficient in range of 3.0 to 7.7 x 10^{-12} m^2/yr which is approximately 1.2 to 3 times lower than control mix. Similarly, at 56 days, for water binder ratio of 0.60, chloride diffusion coefficient of the control mix was found to be 7.3 x $10^{-12}m^2/yr$, a marginal reduction in comparison to its 28 days' value whereas in case of high volume fly ash concrete mixtures, chloride diffusion coefficient was found to be in the range of 2.0 to 5.6 x $10^{-12}m^2/yr$ which is approximately 1.3 to 3.5 times lower than control mix. For 0.40 water binder ratio, at 28 days, non-steady state chloride diffusion value of control concrete was found to be $7.10x10^{12}m^2/yr$ whereas in case of high volume flyash concrete mixture, chloride diffusion coefficient was found in the range of 1.5 to 2.6 x $10^{-12}m^2/yr$ which is approximately 2.7 to 4.7 times lower than of concrete. Similarly, at 56 days, chloride diffusion coefficient of control mix was found to be $5.20x10^{12}m^2/yr$ which is marginally lower than that of its 28 days' value. In case of high volume flyash concrete mixtures, chloride diffusion rate was found to be in the range of 0.6 to $1.2x10^{-2}m^2/yr$ which is approximately 4.0 to 9.0 times lower than that of control mix. It was quite evident from the test result that addition of flyash had notable influenced over chloride diffusion rate. Flyash addition up to 40% shows better resisting property against ingress of chloride ion at both water -binder ratios in comparison to all other concrete mixtures. Improvement in permeability characteristics of concrete due to addition of flyash is one of primary reason behind lower chloride diffusivity rate in high volume flyash concrete mixtures (Arora and Kaura et al., 2019-b; Andrade and Alonso, 2004; Singh et al., 2020-b).

Bulk conductivity and electrical resistivity test method are generally adopted to measure the electrical resistance of the hardened concrete. Both test methods depend upon instrinc property of the material and influenced by several factors like pore solution composition and porosity as well pore size distribution. Bulk conductivity test was carried out as per the requirements of ASTM C1760 at 28 days and 56 days. From the results shown in figure 10 and figure 11, it could be seen that effect of age was insignificant whereas factors like water -binder ratio and flyash content were more prominent. The bulk conductivity value of the control mix at 28 days was found to 13.74 mS/m and 7.9 mS/m at 0.60 and 0.40 water binder ratio respectively. In case of high volume flyash concrete mixes, bulk conductivity was found in the range of 3.14 to 6.12 mS/m and 1.14 to 2.53 mS/m at 0.60 and 0.40 water binder ratio respectively. Bulk conductivity value of high volume flyash concrete mixes were found to be 2 to 5 times lower than that of control mixes. It was also observed that as the percentage of flyash increases, there had been exponential decrease in the conductance value provided that flyash content is limited to 40%. Beyond 40%, an increase in the bulk conductivity value was noticed that may be due increase in the porosity of the mixtures as reported in the later part of this paper. Although, this increase in the conductance value was lower than that of control mix. High volume flyash concrete mix designed at 40% flyash content had the lowest conductivity.

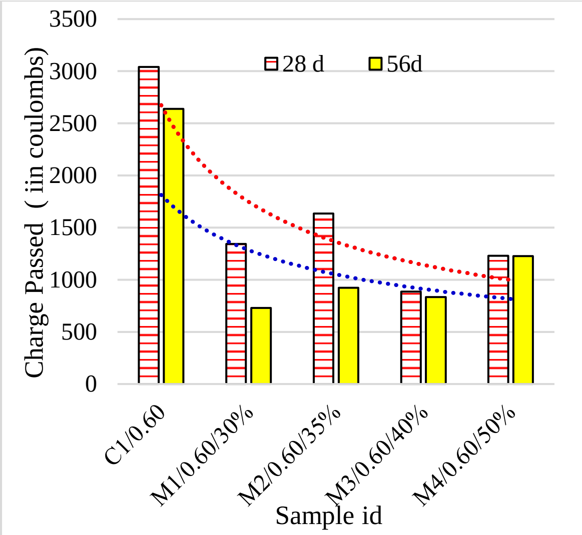

Fig.6. RCPT at w/b 0.60

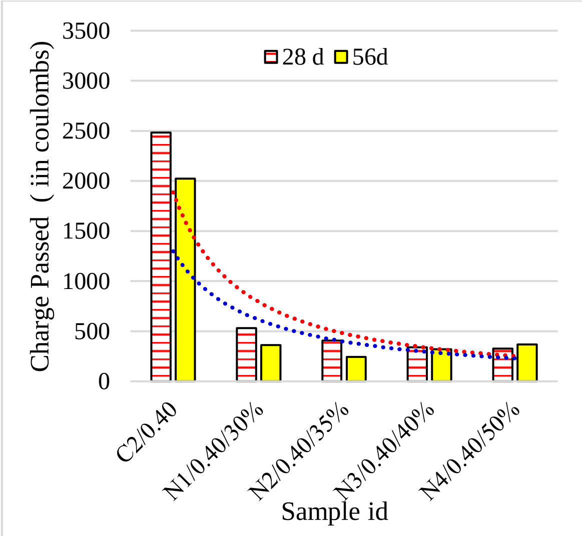

Fig. 7. RCPT at w/b 0.40

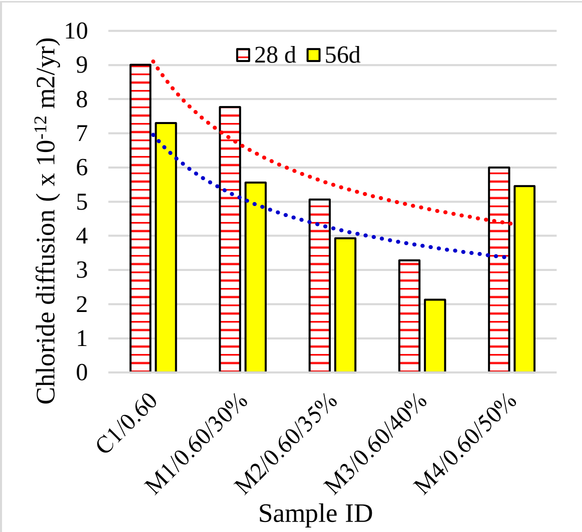

Fig.8. Non- steady state chloride migration coefficient at w/b 0.60

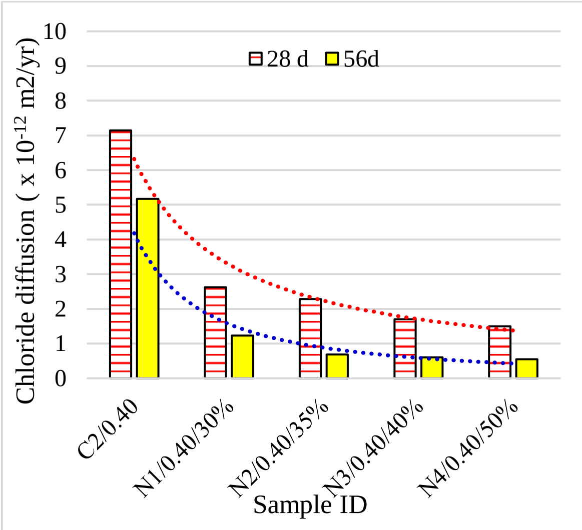

Fig.9. Non- steady state chloride migration at w/b 0.40

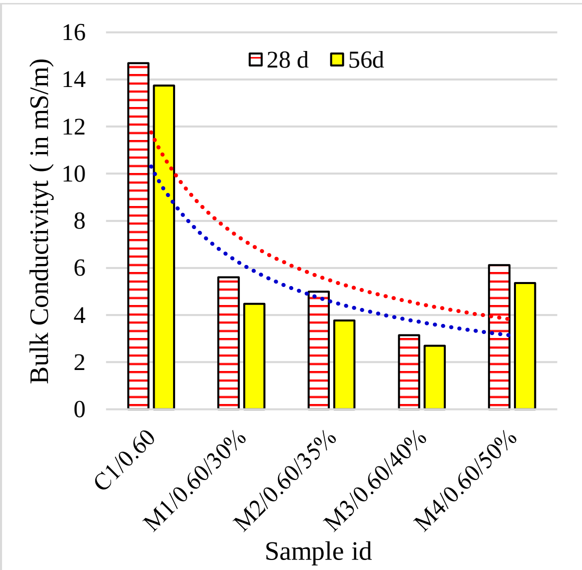

Fig.10. Bulk conductivity at w/b 0.60

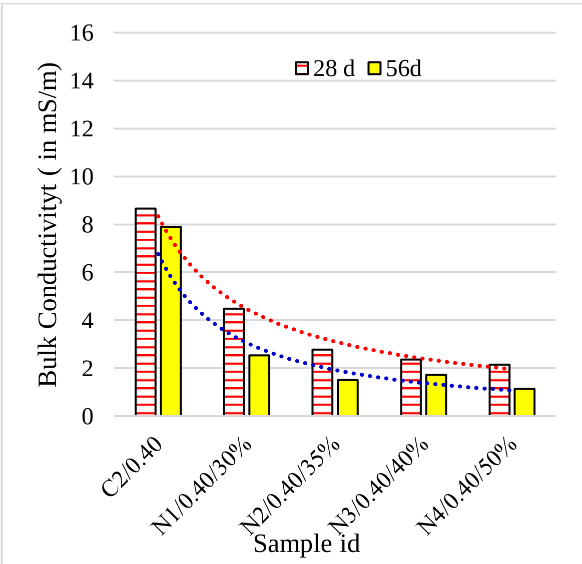

Fig. 11. Bulk conductivity at w/b 0.40

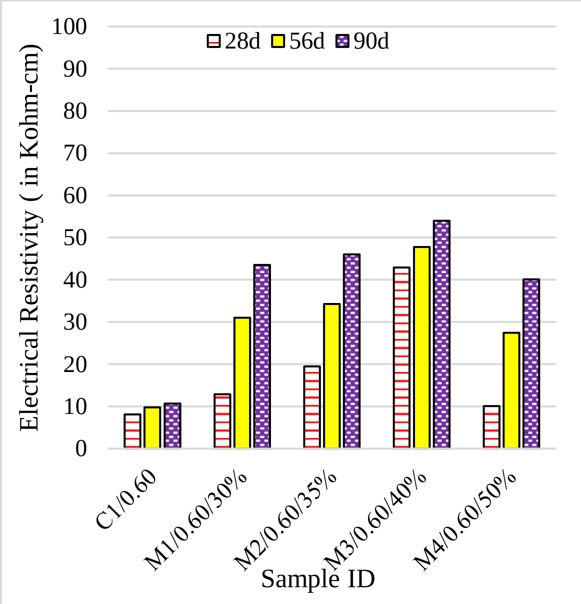

Fig.12. Electrical Resistivity at w/b 0.60

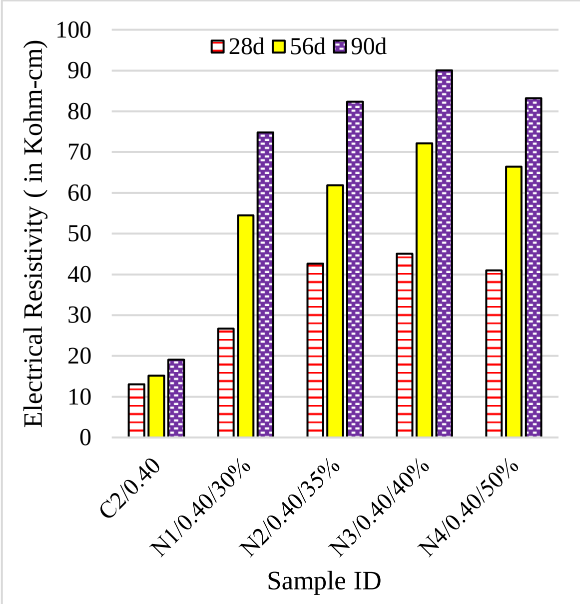

Fig.13. Electrical Resistivity at w/b 0.40

Electrical resistivity test is an indirect way to measure the probability of occurrence of corrosion (Arora et al., 2021; Polder, 2001; Azarsa and Gupta, 2017). According to RILEM TC 154 corrosion risk is high when concrete resistivity is less than 10Kohm-cm whereas when concrete resistivity lies in the range of 10-50 Kohm-cm, risk of corrosion is moderate. However, at concrete resistivity value higher than 100 Kohm-cm changes of occurrence of corrosion is either low or negligible (Polder, 2001; Azarsa and Gupta, 2017; Arora et al., 2017). In present study, the concrete resistivity of the mixes was evaluated at 28 days, 56 days and 90 days. From the graph shown in figure 12 and figure 13, it was quite evident that water- binder ratio, flyash content and concrete age had a significant role to play. Overall, concrete mixes designed with OPC-43 i.e. control mixes fall under the category of high to moderate risk of corrosion.

In case of high volume flyash concrete mixes, electrical resistivity values lie in the range of 18 to 90 Kohm-cm which means risk of corrosion is moderate to low. With the increase in the flyash level up to 40%, a proportionate increased in resistivity value was noticed in high volume flyash concrete. At higher test age, the variation or increase in electrical resistivity values for 30 %, 35 %, 40 % replacement level is lower when results are compared for 56 and 90 days test age for both water-binder ratio. However, with further addition of flyash, decrease in the electrical resistivity value was observed but still resistivity of the concrete made with 50% flyash is significantly higher than that of control mix. Similar type of trend was seen in RCPT, non-steady state chloride migration and bulk conductivity test. At higher test age, the variation or decrease in RCPT, non-steady state chloride migration and bulk conductivity values for 30 %, 35 %, 40 % replacement level is lower when results are compared for 56 days test age for both water-binder ratio. Porosity determination was carried out in accordance to ASTM C642 and results are shown in figure 14 and figure 15 and was defined in terms of percentage of permeable voids. On the analysis of the test results, it was found that high volume flyash concrete mixes designed with flyash content upto 40% had porosity equivalent or at par with the conventional concrete i.e. control concrete. High volume flyash concrete mixes made with 50% flyash had porosity slightly higher than that of control mixes as well as high volume flyash mixture made with flyash content up to 40%. The results show that flyash addition beyond 40% level makes a concrete more porous.

Carbonation is one of the major challenge associated with the RCC structures located in the non-coastal environmental. Carbonation induced corrosion is basically a slow process and take years to occur. In case of carbonation, alkalinity of the concrete reduces to a pH level of less than 9.0 due to the formation of calcium carbonate. Calcium carbonate is formed due to the chemical reaction between atmospheric CO2 and hydration product of cement primarily Portlandite, calcium silicate hydrate. As the alkalinity of concrete reduces stability of the passive layer gets jeopardized. Under such circumstances when passive layer gets breakdown, process of corrosion gets initiated. Since, carbonation induced corrosion affects the serviceability of RCC structure. Therefore, it becomes necessary to study the factors that govern the rate of progress of carbonation front and leads to premature determination. As reported in various literature, parameters like grade of concrete, water- cement ratio, type of cement as well as supplementary cementitious material (SCM) used are the same of the instrinc factors influencing the rate of carbonation whereas environmental parameters like relative humidity, temperature, number of raining and sunshine period govern not only the ingress role of carbonation front in the concrete but also play a decisive role in the process of corrosion (Arora and Singh, 2017; Kaura et al., 2019; 2022; Anjos et al., 2020; Ojha et al., 2021; 2022-a; 2022-b; Saouma, 2020; Malvar et al., 2002; IS-456, 2000; Singh et al., 2021; Patel et al., 2020). In the present research work, factors like water binder ratio, role of fly addition had been studied. The study had been carried out at relative humidity level of 65$\pm$ 5%, temperature of 27$\pm$ 2°C and concrete beam specimens were exposed to carbonation (CO_2 level kept as 4$\pm$ 0.5% by vol.) for an exposure period of 70 days, 140 days and 210 days. The test results of accelerated carbonation are shown in figure 16 and figure 17. The carbonation depth of control mixes were 3 to 5 times lower than the high volume flyash concrete mixtures. In case of high volume flyash concrete mixtures, as the flyash content increases there had been increase in the depth of carbonation. Therefore, it can be concluded that high volume flyash concrete mixture had a significant higher rate of carbonation when compared to control mix. This also indicates that resistance offered by the high volume flyash concrete mixtures is low.

There are three possibilities due to which high volume flyash concrete mixtures show higher depth of carbonation. Firstly, flyash substitutes Portland cement clinker (a source of $Ca(OH)_2$) that results into lower alkalinity level. Secondly, during the pozzolanic reaction, flyash consumes the portlandite formed during the hydration process of Portland cement clinker that will further depletes the alkalinity level. It means higher the amount of flyash in concrete lower will the Portlandite content which result into reduced alkalinity. Thirdly, it is quite evident that for flyash to react, availability of portlandite is must and if all the ($Ca(OH)_2$ gets consumed during the pozzolanic reaction, presence of any unreacted flyash will serve only as a filler material. Since, flyash is used as a replacement to Portland cement clinker, under such condition, the microstructure of flyash mix will be more porous.

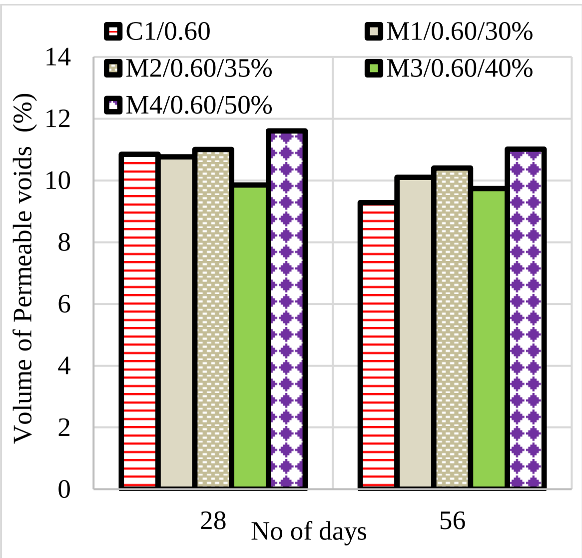

Fig.14. Volume of Permeable voids at w/b 0.60

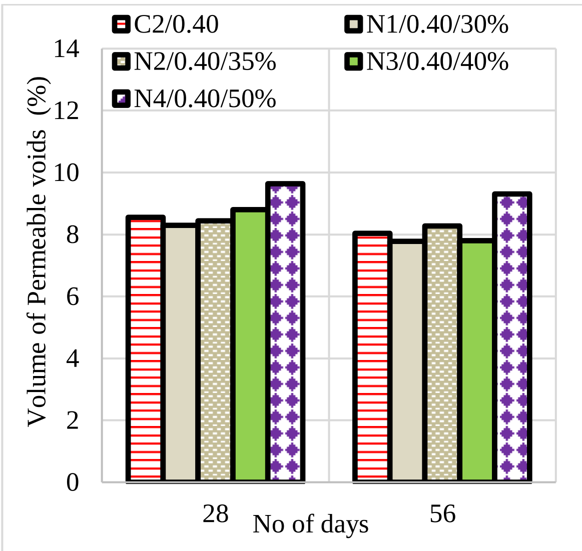

Fig. 15. Volume of Permeable voids at w/b 0.40

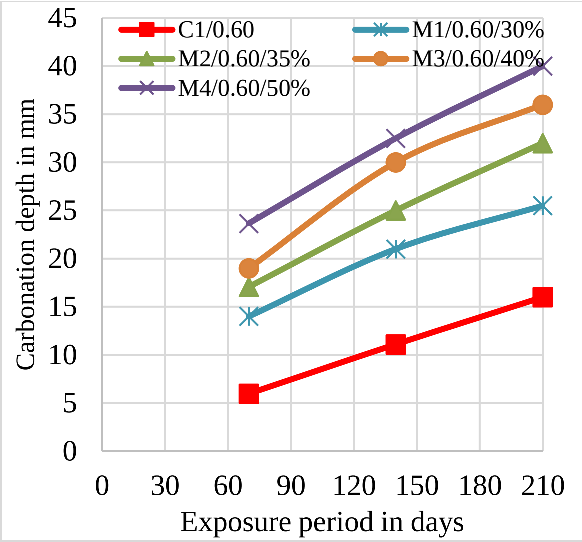

Fig. 16. Accelerated carbonation depth at w/b 0.60

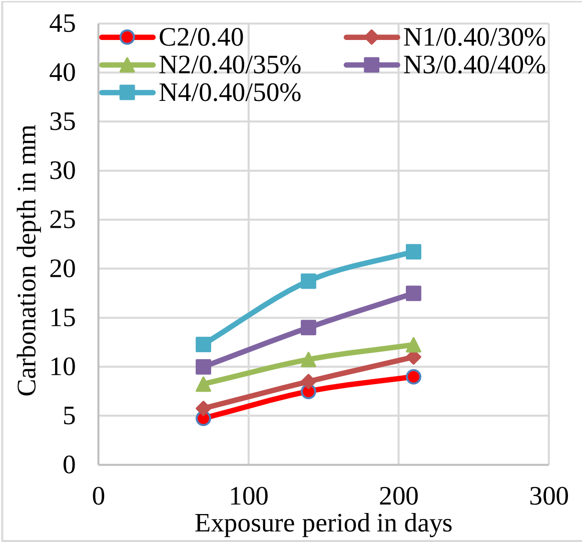

Fig. 17. Accelerated carbonation depth at w/b 0.40

Alkali silica reaction involves chemical reaction between alkali (source generally cement) and reactive silica (source, generally aggregate) in the presence of moisture results in to the formation of a gel that swells or shrinks depending upon the availability of moisture. Such type of chemical form of attack is quite common in hydraulic structures (Ojha et al., 2021-a; 2021-b; 2021-c; Malvar et al., 2002; IS -456, 2000; Singh et al., 2021, Patel et al., 2020, Singh et al., 2020-a; Arora and Singh, 2016, Arora et al., 2019-a; 2019-b; Ojha et al., 2020; Ojha et al., 2022, Arora et al., 2016). In order to avoid ASR, it had been advised to restrict the limit of cement alkalis to 0.60% (by mass). Further, certain standards like IS: 456 (2020) suggests that to mitigate ASR, addition of flyash up to 25% is advantageous when used along with low alkali Portland cement (Na_2O equivalent ≤0.60 %). Generally, use of low Portland cement is not a cost effective solution to manage the ASR problem. The present study had been carried out at 30%, 35%, 40% and 50% flyash content as per ASTM C1567.

The test results are shown in figure 18. From the study, it can be concluded that addition of flyash is beneficial for controlling ASR. As the flyash content increases, maximum up to 40%, there had been decreased in the value of % expansion. Indeed, with further increase in flyash content i.e. at 50% replacement level, a sudden increase in the % expansion has been observed. This may be attributed to the increase in the porosity which had resulted into a less dense microstructure in comparison to other flyash blends. However, % expansion at 50% flyash content is still significantly lower than that of control mix.

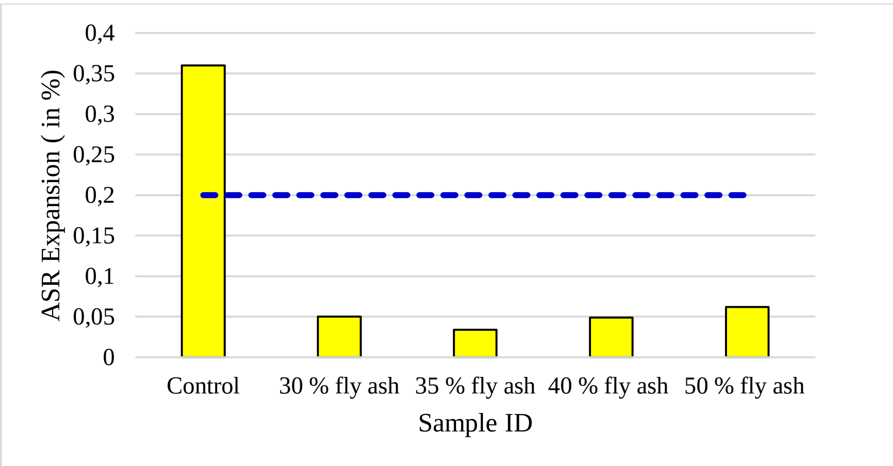

Fig. 18. ASR expansion

4. Conclusions

The outcome of the study are as follows:

i. Parameters like water -binder ratio, flyash content and age of testing/ maturity age had a significant influence over test value.

ii. In terms of mechanical behaviour, high volume flyash concrete mixes had shown promising results at later ages. High volume flyash concrete mixes designed at water-binder of 0.40 with flyash content up to 40 % had shown strength characteristics comparable to that control mix. However, high volume flyash concrete mixes designed at higher water-binder i.e. 0.60 did not yield encouraging results. It was quite evident from the test results that strength characteristics of high volume flyash concrete mix made with 50% flyash content was remarkably lower than that of all other concrete mixtures.

iii. For a chloride rich environment, durability aspect of high volume flyash concrete mixes, when evaluated through tests like rapid chloride penetrability test (RCPT), non-steady state chloride migration test, bulk conductivity test, electrical resistivity test was far superior than that of control mixes. High volume flyash concrete mix designed at 40% flyash content had shown exemplarily performance in comparison to other high volume flyash concrete mixes as well as control mixes.

iv. Durability aspect of high volume flyash concrete mixes when subjected to carbonation was not found encouraging. From the test results, it was quite apparent that carbonation front in high volume fly ash concrete mixtures were progressing at a very faster pace in comparison to the control mix. Flyash content was found to the most significant parameter influencing the rate of carbonation.

v. ASR study had been carried out using reactive aggregates. The test results show that high volume flyash concretes mixes had better resisting ability to mitigate problem of ASR. Mortar bar expansion test carried out in accordance to ASTM C1567 indicates that 40% flyash content is an optimum amount.

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