Chloride-Ion Impermeability of Self-Compacting High-Volume Fly Ash Concrete Mixes

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***Abstract*--** **This paper presents the results of an experimental study on the durability properties of self compacting, high-volume fly ash concrete mixes (SCC-HVFC) mixes. Five self-compacting concrete mixes with a higher cement replacement at 60% of cement with fly-ash, are designed and their performance is compared with two normally-vibrated concrete mixes (NCs) of equivalent M30 strength grade. The durability properties are evaluated in terms of chloride-ion penetrability as measured by RCPT tests . The results indicate that the SCC-HVFC mixes would have lesser permeable voids than the normally-vibrated concrete mixes of comparable strengths. The experimental results also show that large improvements against chloride penetration can be realized with self- compacting high-volume fly-ash concrete mixes additionally admixed with GGBFS, silics fume, metakaolin and rice husk ash.**

***Index Term*--** **Self compacting concrete; large-volume fly ash replacement; chloride permeability,**

I. Introduction

One major challenge facing the civil engineering community is to execute projects in harmony with nature using the concept of sustainable development. This calls for use of high performance, environment-friendly and economical construction materials. In the context of concrete, which is the most predominant building material, it is necessary to identify less expensive cement-substitutes. In recent years, many researchers have established that the use of supplementary cementitious materials (SCMs) like fly ash, blast furnace slag, silica fume, metakaolin and rice husk ash etc. can, not only improve the various properties of concrete - both in its fresh and hardened states, but also can contribute to economy in construction costs. However the strength and durability characteristics of concrete mixes with such SCMs have to be ascertained before using them in large infrastructural projects. Permeability of concrete is believed to be the most important characteristic of concrete that affects its durability[1],[2]. Poor impermeability of concrete may lead to the ingress of Chloride ions into concrete resulting in the corrosion of the steel rebars embedded in it. Once this occurs, the structure will no longer maintain its structural integrity; the lifespan is reduced, and the general safety of the public amenity is severely degraded. It is thus apparent that for many reinforced concrete members, the ability of the concrete to resist chloride penetration is an essential factor in determining its successful performance over an extended period.

At micro-level, the chloride permeability of a concrete mix is related to the pore structure of the cement-paste matrix. As pore volume increases, the apparent chloride diffusion coefficients increases [3-[5]. Pore-structure of concrete varies with age and depth from the exposed surface[6]-[9]. The water-cement ratio has a profound effect on several characteristics of concrete; Mixes with low water/ cement ratios, though less workable, are of high strength, low permeability and high durability [10],[11]. The resistance to chloride penetration of concrete is significantly increased with the incorporation of finer fly ash particles [12],[13] Such an increase in chloride-ion penetration results from the reduced water-to-binder ratio, the reduced average pore-size of the paste and the improved interfacial zone. The incorporation of fly ash may also enhance the workability of the mixes due to the smooth spherical surfaces of the fine fly ash particles. Hence the use of higher volumes of fly ash in concrete is advantageous in reducing the permeability of concrete due to their filler as well as pozzolanic effects[14]. In the present study, an attempt is made to investigate the chloride permeability resistance characteristics of a few candidate self-compacting, high-volume fly ash concrete mixes. Further, effect of blending other mineral admixtures like GGBFS silics fume, metakaolin and rice husk ash concrete mixes are also examined.

II. Experimental Investigations

Materials

Ordinary Portland cement conforming to the requirements of 43 grade OPC [15] [16]was used. Fly ash meeting the requirements of ASTM C 618 (Class F) was used. The characteristics of cement, fly ash and other pozzolanic materials used herein are evaluated and are presented in **Table I**. Two fractions of crushed granite metal, with MAS of 12.5 and 20 mm, and good quality well graded river sand were used as coarse and fine aggregates, respectively. The coarse and fine aggregates had specific gravities of 2.68 and 2.61, respectively. A commercially available poly-carboxylic-based

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high-range water reducing admixture has been used as a hyper-plasticizer in the present investigation.

Mix design

In the present investigation two conventional normally-vibrated concrete mixes were initially designed. These base designs were later modified, based on a series of trials, to develop five different self compacting fly ash concrete mixes, all with a constant, high-volume fly ash dosage of 60% and again admixed with other superpozzolanas. **EFNARC-** guidelines were used to design the SCC mixes. The details of the mix proportions for the various mixes are given in **Table II**. Thorough mixing and adequate curing are most essential for achieving a good self compacting concrete. In the laboratory, the concrete was mixed in a special horizontal shaft ribbon mixer of 125L capacity. The total mixing time was kept at about 3–4 min for normal concretes. It was increased to about 5–6 min for self compacting concretes made with hyper-plasticizers for realizing the complete potential of the hyper-plasticizer. All the mixes were tested for their flow properties satisfying the EFNARC guidelines . Generally, the demoulding was done between 12 and 24 h of casting.

Table I
Properties and Chemical Composition of Cementitious Materials

	Cement	FA	SF	MK	GGBFS	RHA
Specific gravity	3.05	2.06	2.20	2.60	2.81	2.43
LimeReactivity, N/mm^2	----	4.73	4.10	4.82	5.16	4.48
LOI	0.28	0.76	--	0.72	0.19	----
Oxides	Percentage contents					
CaO	60.84	1.79	0.68	0.08	23.28	0.51
SiO_2	16.34	58.87	94.89	52.20	43.63	95.96
Al_2O_3	6.95	32.17	2.20	44.50	14.82	0.27
Fe_2O_3	5.38	2.93	0.18	1.11	5.14	0.57
K_2O	2.73	1.14	0.92	--	1.92	1.06
Na_2O	1.5	0.37	0.19	0.41	2.06	0.01
Na_2O_{eq}	---	1.12	0.80	0.41	---	---
MgO	2.32	0.92	0.46	--	3.40	0.21
Mn_2O_3	----	--	0.48	--	----	----
P_2O_5	1.67	0.56	--	0.65	1.60	0.62
SO_3	1.99	0.49	--	0.32	3.97	0.33

Table II
Mix Proportions for various fly ash admixed SCC mixes - M30 Grade

Mix no		**CC1**	**CC2**	**SCFA**	**SCSF**	**SCMK**	**SCGGBS**	**SCRHA**
Cement (Kg/m^3)		410	405	240	222	168	120	198
Fly Ash (Kg/m^3)		---	----	360	360	360	360	360
Silica Fume (Kg/m^3)		---	---	---	18	---	---	---
Metakaolin (Kg/m^3)		---	---	---	---	72	---	---
GGBFS (Kg/m^3)		---	---	---	---	---	120	---
Rice Husk Ash (Kg/m^3)		---	---	---	---	---	---	42
Water (Kg/m^3)		175	172	168	168	168	168	168
Coarse Aggregate(Kg/m^3)		1134	1130	720	720	720	720	720
Fine Aggregate(Kg/m^3)		612	612	765	731	735	754	727
w/p		0.43	0.41	0.28	0.28	0.28	0.28	0.28
HP (kg/m^3)			3.0	3.0	3.0	3.0	3.0	3.0
Slump/Slump flow in mm		90	110	760	700	785	730	735
V funnel in sec		--	---	9	11	9	10.5	10.5
Compressive Strength (N/mm^2)	7days	33.65	36	34.2	21.5	27	34	18
	28days	43.65	45	55.33	38	45	42	37.5

III. Results and Discussions

Cube Compressive Strengths

Five cubes of size 100mm were tested for each mix in a 2000 kN-capacity compression testing machine as per IS: 516-1975 for determining compressive strengths at 7- and 28-days of curing. All the results obtained for cube compressive strengths for the various SCC mixes at the two ages are tabulated in **Table 2.** All the mixes have achieved their target mean strength at the age of 28 days of curing. Among all the mixes, SCSF and SCRHA recorded lowest strength at 28 days , whereas SCFA mix has achieved the maximum strength of 55.33 MPa which may be attributed to higher cement content in this mix. When the cement content in SCFA mix are further replaced by 20 % of GGBS and 12% of metakaolin, the drop in strength is marginal as compared to the binary blends. This may be to the presence of appreciable amount of Calcium oxide in GGBS and to the presence of larger amounts of amorphous, reactive silica in metakaolin.

Rapid chloride penetration test

Accelerated chloride permeability tests were conducted on standard cylindrical specimens (100 mm dia, 50mm thick) of all the candidate large volume fly-ash admixed self-compacting concrete mixes, after different periods of curing, as per **ASTM C1202- 1994**. The RCPT test set-up used for these tests is shown in **Fig.1**. All the results of total charge passed through standard specimens in 6 hours (the RCPT values), taken as a measure of the chloride permeability, are presented in **Fig.2**. It can also be observed that the total charge passed decreases with the increase in the curing period, measured herein up to 90 days, in specimens of all the mix compositions. It is seen that, while the RCPT values (total charge passed in 6 hours) are quite large during the initial periods (3- and 7-days), all self-compacting `fly ash based SCC mixes evaluated herein have RCPT values less than 1000 Coulombs beyond 28-days of curing and can be classified under **very low** chloride permeability concrete mixes as per ASTM C 1202–94 assessment criteria. The corresponding normally-compacted concretes, however, have shown very high values of charge passed, in the range of 1800-2000 Coulombs, even when tested after 90 days of curing, which fall in the range of **low** to **moderate.**

It can be concluded that all the SCC mixes have performed extremely well in an aggressive chloride-rich environment. Comparatively speaking, it is observed that **SCMK** mix has the lowest RCPT values compared to the other SCC mixes. This could be due to the fact that the chloride ion penetration depends on the chloride binding capacity of the constituent materials. Usually chlorides penetrate into concrete by diffusion along water-conveyance paths or open pores. The resistance to such diffusion can be increased by refining the pore-structure of the concrete. Again from the point of view of chemical reactions, some of these chlorides can react with the cement compounds, mainly tricalcium-aluminates (C_3A), forming stable chloro-complexes while the excess of chloride ions are free and may lead to the initiation of the corrosion process. The increased % of fly ash along with Metakaolin may lead to an increase in the amount of alumina present in the mix and to an increase in the content of calcium silicate hydrate that is formed in the pozzolanic reactions. Thus, the chloride-binding capacity of concrete tends to increase with fly ash addition and consequently less free-chloride is available to initiate the corrosion process. This view is well supported by the data in **Fig. 3** where it appears that the alumina content has a significant influence on the chloride ion penetrability into the concrete. As the alumina (Al_2O_3) content increases, the total charge passed decreases indicating increased resistance against chloride ion penetration and hence corrosion. Thus, in aggressive chloride environment, such as sea coast or structures where deicing salts are used, the increased addition of fly ash in SCC mixes will prove beneficial.

The implications of such substantial decreases in chloride ion penetrability should be seriously considered in the design of offshore structures, bridge decks, parking garages and other structures that are vulnerable to corrosion of reinforcing steel under chloride ion attack. Not only would SCC made with high-volume replacement composite cements provide excellent workability at a competitive cost, but the repair, maintenance and overall life cycle costs would make such a material more appealing. The results show that at an early age, chloride permeability is most influenced by the water/binder ratio. However, at later ages the beneficial effects of fly ash is apparent and is the governing parameter in reducing permeability.

IV. Conclusions

The following conclusions drawn based on the results of the present study. Increased of wet curing decreases the chloride penetrability of SCC-HVFA concrete mixes.The high volume fly ash SCC mixes showed significantly lower chloride ion permeability than normal concretes mixes. All the SCC-HVFA mixes were assessed to have ‘‘very low” chloride permeability as per ASTM C 1202–94 assessment criteria, with RCPT values< 1000 coulombs after 28-days of wet curing. Among the mixes tested herein, metakaolin-blended self compacting high volume fly ash concrete mix, SCRHA has exhibited the best performance under chloride attack.As a future scope same mixes can be analysed for corrosion under accelerated curing conditions and life of the structure can be predicted

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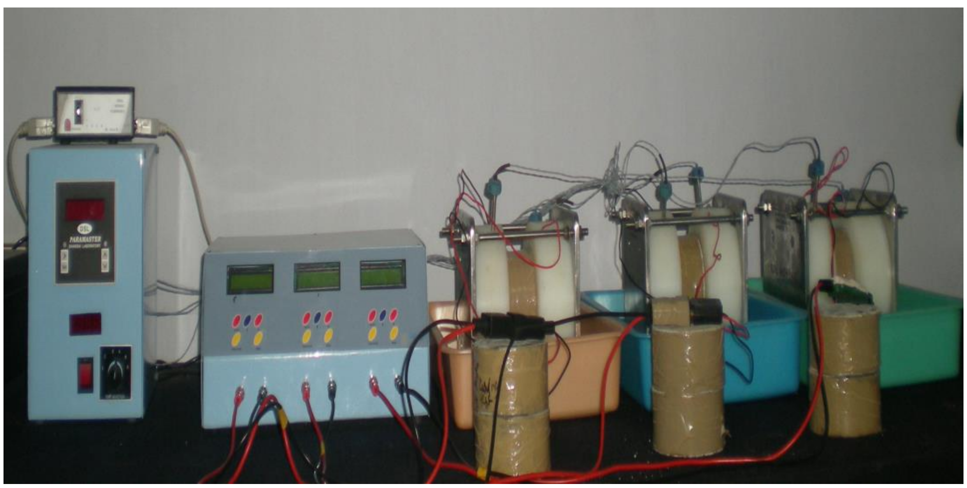

Fig. 5. RCPT Test Apparatus

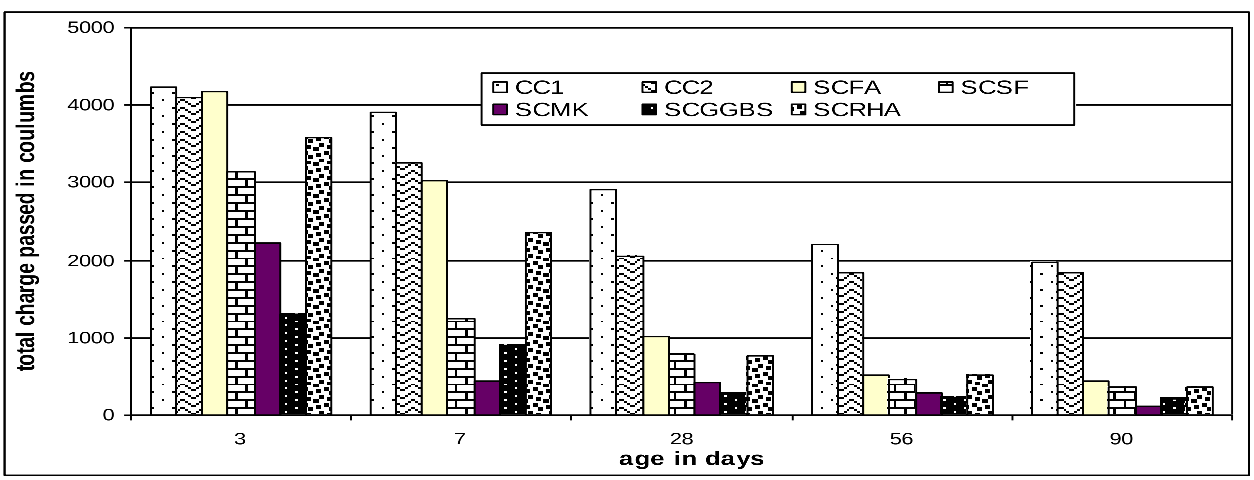

Fig. 2. RCPT-Test Results for Various SCC Mixes

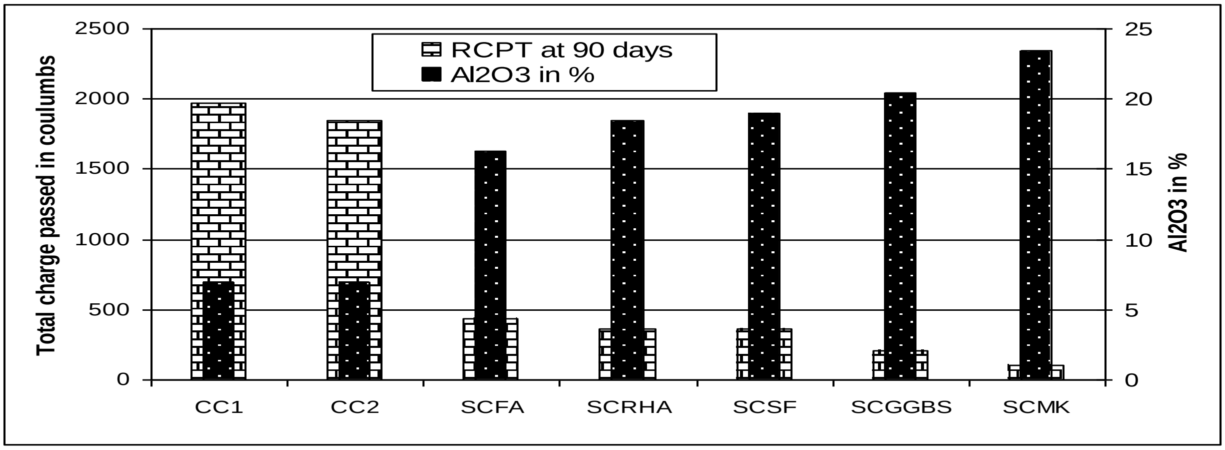

Fig. 3. Graph of Chloride Ion Penetration with Al_2O_3