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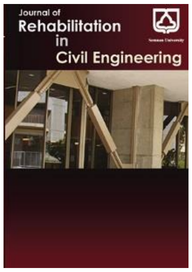

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Influence of Supplementary Cementitious Material on Estimated Service Life of Structure in Chloride Environment

Modi Monika[1], **Thakkar Sonal**[2*]

1. M. Tech, Civil Engineering Department, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India.
2. Assistant Professor, Civil Engineering Department, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India.

Corresponding author: sonal.thakkar@nirmauni.ac.in

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ABSTRACT

Chloride ingress in concrete leads to deterioration of reinforcement and subsequent distress in concrete. The focus of the present study was to determine the amount of chloride ingress in concrete with and without supplementary cementitious materials (SCM) using Rapid Chloride Penetration Test (RCPT) and Rapid Chloride Migration Test (RCMT). A comparison of chloride ingress was made of Control concrete with six other mixtures having varying percentages of fly ash (20% & 30%), ground granulated blast furnace slag (GGBFS) (30% & 40%), silica fume (5%) as replacement of cement. Compressive strength, RCPT and RCMT tests were evaluated for all the mixtures after 28 and 90 days respectively. A correlation between RCPT and RCMT tests was established. Mixtures containing fly ash as SCM had lesser initial compressive strength compared to mixtures with GGBFS and silica fume. Chloride permeability of concrete mixture with silica fume as SCM has a significant decrease in chloride permeability in both RCPT and RCMT tests at both ages compared to concrete without SCM. Estimation of service life was carried out using Life-365TM software. It was observed that the service life of concrete without SCM was estimated to be 14.8 years while in the concrete with 5% silica fume expected service life was 24.9 years. Thus, the incorporation of supplementary cementitious material in concrete enhances the service life and is a boon to the construction industry.

1. Introduction

In the construction industry, reinforced cement concrete (RCC) is the most popular building material. However, the durability of the RCC structure in an adverse environment is a major concern to civil engineers. Structures generally do not function for their

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intended design life mainly due to distress either in concrete or in reinforcement. Ingress of chloride ions in concrete can be considered as one of the main causes for corrosion of reinforcement. The high pH of concrete helps in the formation of a passive film on the surface of the reinforcement which normally prevents the steel from corrosion. Due to the ingress of chloride ions from the cover concrete of an element, lowering of the pH value of concrete occurs which results in corrosion. The situation gets worsened if the structure has exposure to marine environments, de-icing salts or alternate wetting and drying conditions. Therefore, the durability of the structure is mainly dependent on chloride diffusivity [1].

Chloride ions can ingress in the concrete through either diffusion, permeation or migration mechanism. Hence various test procedures are developed to measure the chloride ions presence in the concrete. AASHTO T259, ASTM C1202 (RCPT) determines chloride diffusion in concrete by exposure to salt solutions using ponding or immersion test [2]. Rapid Chloride Migration Test (RCMT) is another method that has shown a good correlation with other long-duration tests, which is now standardized by AASHTO TP64 and NT Build 492 [3].

Enhancement of durability properties of concrete by incorporation of SCM is well recognized today [4]. The fineness of SCM help in reducing the permeability of concrete and may also bind physically and chemically free chloride ions [5]. As performances of SCM vary depending on their chemical composition, reaction with a binder material and curing conditions, therefore it is essential to evaluate its performance under chloride ion permeability. Yang et al. used an accelerated chloride test to determine the migration coefficient in concrete [6]. Bagheri et al. evaluated chloride penetration in concrete by using RCPT, RCMT and electrical resistance tests for a varying percentage of SCM like silica fume, fly ash, slag and developed a correlation between these tests [7]. Sengul and Tasdemir discussed the effect of the inclusion of pozzolanas in concrete and observed that there was a reduction of chloride ions due to the inclusion of pozzolana in concrete [8]. Farahani and Taghaddos used Element - Free Galerkin (EFG) method to predict the service life of chloride-induced corrosion [9]. Meck and Sirivivatnanon compared results of chloride concentration by colourimetric and RCPT method and observed that poor correlation exists between both the method but better quality concrete had low charge passage [10]. Neithalath and Jain observed that chloride ingress in concrete is greatly influenced by pore connectivity and pore size rather than the porosity of concrete [11]. Sui et al. evaluated the durability performance of SCM using binary and tertiary combinations to find the effect of pore structure, binding capacity and pore solution w.r.t. chloride transportation. It was observed that in SCM samples lower diffusion was observed compared to the OPC sample [5]. Cherif et al. observed that due to the addition of slag in concrete there is a reduction of dissolution of portlandite during the chloride transfer mechanism [12]. Huang and Yang in their work observed that there was a linear relationship between charge passed during the RCPT test and total chloride content on the surface of the specimen [13]. Aggregates type also play a pivotal role in deciding the chloride ingress in concrete. Arabani et al. found that the RCPT performance of Socria as lightweight aggregate was better compared to Leca and Pumice aggregates in Lightweight concrete [14]. Several studies have also been carried out by researchers to predict the service life of structures subjected to chlorides. Andrade et al. developed a mathematical model for service life prediction in the saline environment to evaluate the service life of structure [15]. Jun et al. used Monte Carlo simulation to predict the service life of RC structures that were exposed to chloride penetration and compared the results with the traditional service life prediction method [16]. Bentz also used the Monte Carlo technique and predicted the life cycle of the structure subjected to chlorides [17]. A finite element model for chloride penetration based on convection and diffusion was developed by Nemati et al. It was correlated with short term laboratory tests and it was observed that there was a decrease in chloride concentration when partial replacement of cement with silica fume was carried out [18]. Shahfikhani and Chidiac carried out a critical review of various models used for quantifying the concrete chloride diffusion using various models and found that models which accounted for capillary porosity, pore structure and paste diffusivity gave the best result [19]. Angst predicted the corrosion initiation mechanism using critical chloride content and improvements to be incorporated in chloride ingress models for better predictions [20]. Marchand and Samson discussed the limitations of models based on simplified equations and their effect on the repair and rehabilitation approach [21].

Thus, it can be observed from studies that the concrete having enhanced resistance to chloride attack can be produced by using a low water-cement ratio and incorporating SCM as a replacement for cement. The focus of the present study was to determine the amount of chloride migration in the concrete by conducting RCPT and RCMT tests on concrete with or without SCM. The compressive strength of concrete was evaluated after the incorporation of SCM in varying percentages. A correlation between two methods of measurement of chloride ions was carried out. Estimation of service life was carried out using Life 365 software with different SCM in varying percentages.

2. Experimental program

2.1. Materials

Ordinary Portland cement (OPC) of 53 grade was used in all the mixtures [22]. Coarse aggregate consisted of locally available 10 mm and 20 mm downsize aggregates and river sand was used as fine aggregate and tested according to IS: 383 [23]. Class F fly ash confirmed to IS: 3812 [24] and GGBFS confirming to IS: 12089 [25]. The specific gravity of Class F fly ash, GGBFS and silica fume was 2.2, 2.9 and 2.5 respectively [26]. The specific surface area of Class F fly ash, GGBFS and silica fume was 416.4 m^2/kg, 379 m^2/kg and 15 m^2/gm. Desired workability (100 mm to 150 mm slump) in all the concrete mixtures was obtained by incorporation of Naptha based superplasticizer. The chemical composition of all the SCM used in the mixture is shown in Table 1.

2.2. Mixture design

Control concrete mixture (M 1) was of M 25 grade concrete with a water to cement ratio of 0.44 and cement content of 359 kg/m^3. In the mixtures, M 2 and M 3, fly ash was used as SCM with replacement levels of 20% and 30% while in M 4 and M 5, GGBFS was used as SCM with the replacement levels of 30% and 40% as the replacement of cement. In Mixture M 6, 5% of silica fume was used as SCM as a replacement of cement. All the mixture designs were done according to provisions of IS: 10262 [27]. The mixture constituents of all six mixtures are shown in Table 2.

Table 1. Chemical Compositions of Fly Ash, Slag and Silica Fume.

Oxide (%)	$SiO_2+Al_2O_3+Fe_2O_3$	SiO_2	Al_2O_3	CaO	Loss of ignition
Fly ash	93.04	61.86	29.05	<0.95	1.05
Slag	-	36.8	17.12	34.4	0.6
Silica fume	96.88	-	-	0.39	0.68

Table 2. Mixture Proportions of Various Concrete

Mixes	M 1	M 2	M 3	M 4	M 5	M 6
Cement (kg/m^3)	359	287.2	251.3	251.3	215.4	341.05
Fly ash (kg/m^3)	-	71.8	107.7	-	-	-
GGBFS (kg/m^3)	-	-	-	107.7	143.6	-
Silica Fume (kg/m^3)	-	-	-	-	-	10.77
Fine Aggregate (kg/m^3)	830.39	820.1	815.52	828.11	826.96	833
Coarse Aggregate (kg/m^3)	1127.41	1117.36	1111.12	1128.27	1126.83	1124
20mm	690.3	684.15	680.33	690.83	689.87	692
10mm	437.11	433.21	430.79	437.44	436.96	432
Water (lit/m^3)	158	158	158	158	158	158
Plasticizer (lit/m^3)	2.15	2.15	2.15	2.15	2.15	2.15
W/C Ratio	0.44	0.44	0.44	0.44	0.44	0.44

2.3. Compressive strength

Evaluation of compressive strength of concrete was carried on 150 mm cube specimens. An average of three specimens was taken after 28 days and 90 days of water curing respectively confirming to IS: 516 [28] specifications.

2.4. Rapid Chloride Permeability Test (RCPT)

ASTM C1202 guidelines were used to perform RCPT for all concrete mixtures [2]. Three cylindrical specimens of 100 mm diameter and 50 mm height were prepared from all the six concrete mixtures with a curing period of 28 days and 90 days respectively. Vacuum saturation was carried out in a vacuum desiccator. The specimen was placed between two acrylic cells, one containing 0.3 N sodium hydroxide solution and the second containing 3.0% sodium chloride solution as shown in Fig. 1. Electrodes immersed in sodium chloride and sodium hydroxide solutions were connected to negative and positive terminals respectively and the current was passed keeping a potential of 60 Volts applied for 6 hours with a recording of results carried out at every 30- minute interval.

Fig. 1. Experimental test setup for RCPT test.

2.5. Rapid Chloride Migration Test (RCMT)

RCMT test was performed to determine the chloride migration coefficient under non-steady-state using Nord Test (NT Build 492) specifications [3]. Cylindrical specimens of diameter 100 mm and a thickness of 50 mm were sliced from cast cylinders. Migration of chloride ions occur due to the application of an external electrical potential. 10% sodium chloride solution by mass was used as catholyte while 0.3 N sodium hydroxide was used as an anolyte solution. The rubber sleeves were fitted on the specimen and secured using two clamps. A silicone sealant lining was applied to stop the leakage if the specimen surface was rough before placing the specimen on a plastic support. After filling the anolyte solution above the specimen and immersion of anode, a 30V voltage was applied to the specimen, as shown in Fig. 2. The specimens were axially split, after the test and sprayed with silver nitrate solution to evaluate the depth of penetration of chloride ions in concrete.

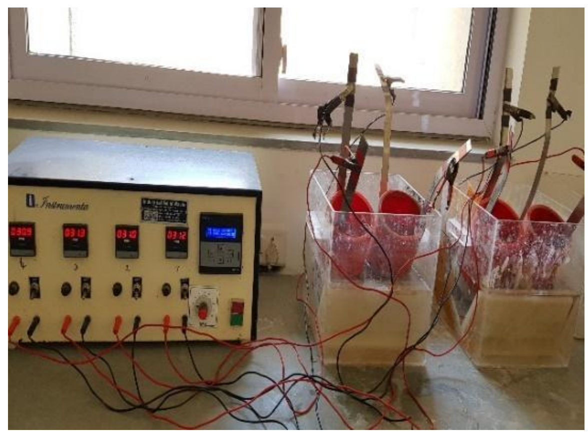

Fig. 2. Experimental test setup for RCMT test.

3. Prediction of service life using life-365^{tm} service life software

The service life of structures exposed to an aggressive environment can be estimated using Life- 365 [23] software. This software helps in the estimation of corrosion in reinforcement in order to devise corrective strategies to mitigate it. Thus, implementing the results obtained from the laboratory for RCMT tests in Life-365^{TM} software will enable the user to devise a protection strategy and prolong the life of the structure and at the same time lower down the repair cost.

Life-365^{TM} models chloride transfer through diffusion mechanism assuming there is no crack in the concrete. Chloride content is determined using Fick's second law as stated in equation 1[15].

$$\frac{dC}{dt} = D.\frac{d^2 C}{dx^2} \quad (1)$$

Where, C = chloride content, D = the apparent diffusion coefficient x = the depth from the exposed surface t = time. For the determination of time-dependent changes in diffusion, Life-365 uses the following relationship [23]:

$$D(t) = D_{ref}(\frac{t_{ref}}{t})^m \quad (2)$$

Where, D(t) = diffusion coefficient at time t, D_{ref} = diffusion coefficient at time t_{ref}, m = diffusion decay index. Constant D_{ref} and m values depend upon the composition of the concrete mixture.

4. Results and discussions

4.1. Effect of SCM on compressive strength

A comparison of compressive strength for the concrete mixtures with and without SCM is shown in Fig. 3, for 28 and 90 days of age. Fig. 4, shows a comparison of compressive strength of concrete with SCM with control concrete. Concrete mixtures M 2 and M 3 with fly ash as a replacement had 2.6%, 1.7% lower strength at 28 days while 4.3% and 2.9% at 90 days compared to control concrete M 1. In mixtures M 4 and M 5, with GGBFS as a replacement of cement, the compressive strength increased by 3.8% and 4.5% at 28 days and 4.3% and 5.4% respectively for 90 days compared with M 1. In case of mixture M 6 which had silica fume as a replacement, a higher compressive strength of 7.4 % and 5.7% at 28 days and 90 days respectively compared to M 1 was observed. Thus, replacing cement with 5% silica fume had significant improvement in strength at both, 28 days and 90 days compared to control concrete.

The pozzolanic reactivity of the fly ash is lower during the initial phase of cement hydration and hence compressive strength development was lower as compared to control concrete. In the case of GGBFS, the pozzolanic reactivity is more due to the presence of calcium oxide ions which leads to faster development of strength. Silica fume has particles with a large surface area and as they are finer than cement denser particle packing can be obtained. The presence of SiO_2 ions leads to a faster pozzolanic reaction which contributes to high early compressive strength. Sui et al. in their study have also observed an increase in compressive strength in fly ash after 90 days [5].

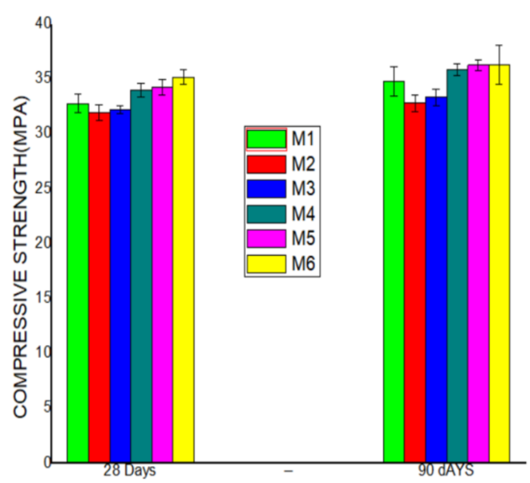

Fig. 3. Comparison of compressive strength with and without SCM.

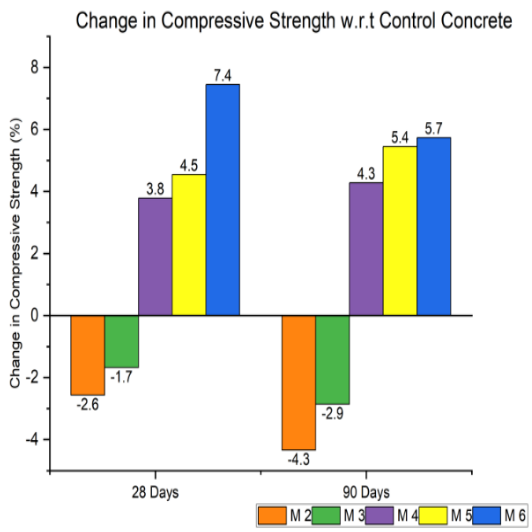

Fig. 4. Percentage change in compressive strength with SCM w.r.t control concrete.

4.2. Effect of SCM on RCPT results

RCPT test results shown in Fig. 5, were obtained at the age of 28 days and 90 days for all the concrete mixtures. In the mixtures M 2 and M 3 where fly ash was used as SCM with 20% and 30% replacement respectively, the coulomb charge reduced to 2625 and 2415 respectively after 28 days and 2421 and 2235 after 90 days of curing compared 3939 and 3402 values of M 1 at the same age. In the mixtures, M 4 and M 5 with GGBFS as SCM (30% and 40% replacement), the coulomb charge reduced to 2058 and 1905 respectively at 28 days and 1971 and 1875 at 90 days compared to M 1 (control concrete) at the same age. While in the case of M 6 with silica fume, the coulomb charge value reduced to 1269 and 990 compared to 3939 and 3402 at 28 days and 90 days respectively for mixture M 1.

Thus, as shown in Fig. 6, at the same age, M 2 and M 3 had 33.4% and 38.7% reduction in coulomb charge compared to control concrete. In the case of M 4 and M 5 with GGBFS, the reduction in coulomb charge was 47.8% and 51.6%, while when silica fume was used the 67.8% and 70.9% as compared to M 1 at age of 28 and 90 days respectively. This shows that SCM refines the pore structure as it has higher fineness compared due to cement and hence decreases the ingress of chloride ions in concrete. Sengul and Tasdemir also obtained reduced permeability when 50% slag and 50% fly ash was used as a replacement of cement in concrete [8].

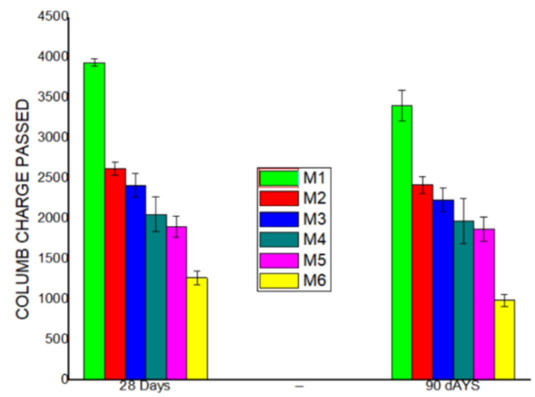

Fig. 5. Comparison of RCPT tests with and without SCM.

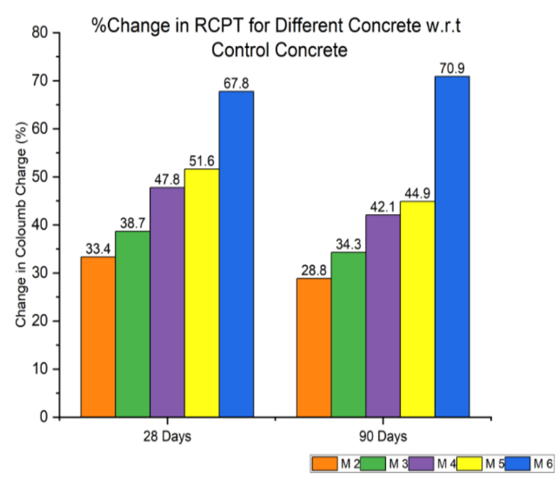

Fig. 6. Percentage change of RCPT values of concrete with SCM w.r.t. control concrete.

4.3. Effect of SCM on RCMT results

RCMT tests of concrete mixtures with and without SCM at 28 and 90 days of age is shown in Fig. 7. In the mixtures M 2 and M 3, RCMT values reduced from 7.7 to 6.1 and 7.25 to 5.9 respectively after 28 days and 90 days compared to 9.5 to 8.45 of mixture M 1 for the same age. In the mixtures M 4 and M 5, the RCMT values reduced from 6.2 and 5.7 respectively at 28 days to 4.6 and 3.5 at 90 days compared to control concrete mixture M 1. While in the case of M 6, for RCMT the change was 4.7 and 3.5 compared to M 1 mixture at the same age. Thus, as shown in Fig. 8, the decrease in RCMT value was 18.9%, 23.7%, 34.8%, 39.6% and 50.1% for mixtures M 2 to M 6 when compared with control concrete M 1 at 28 days. While, RCMT value decreased to 27.9%, 30.1%, 35.3%, 45.1% and 59.1% when compared with M 1 at 90 days.

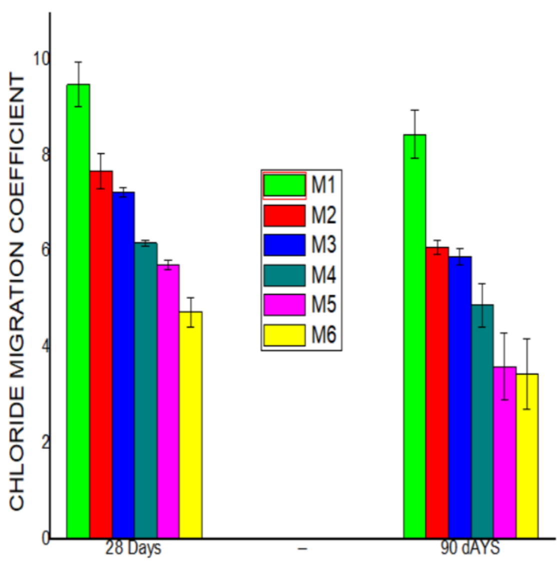

Fig. 7. Chloride migration coefficient results with different concrete mixtures.

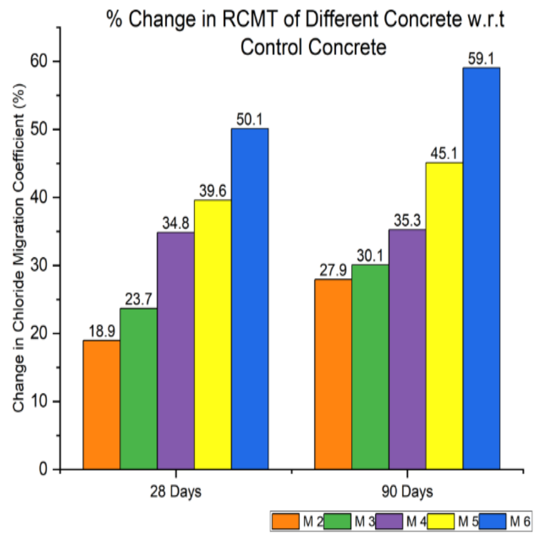

Fig. 8. Percentage change of RCMT values of concrete with SCM w.r.t. control concrete.

RCPT test shows that incorporation of SCM leads to a decrease in coulomb charge. Also, when the replacement level of SCM increased, a consistent decrease in coulomb charge was observed. This was noticeably in both fly ash and slag was used as a replacement. Similarly, there was a decrease in chloride migration co-efficient in the RCMT test with incorporation and increase in SCM materials as compared to concrete made without the inclusion of SCM.

4.4. Correlation between RCPT and RCMT results

Regression analysis was used to check the correlation of the results between RCPT and RCMT tests, after 28 and 90 days, as shown in Fig. 9 and Fig. 10 respectively. Correlation coefficients of 0.943 at 28 days and 0.944 at 90 days was obtained. As the values are greater than 0.9, a good correlation exists between both, RCPT and RCMT test results. Thus, it can be observed that control concrete without SCM was more permeable and allowed higher chloride ingress compared to concrete with SCM.

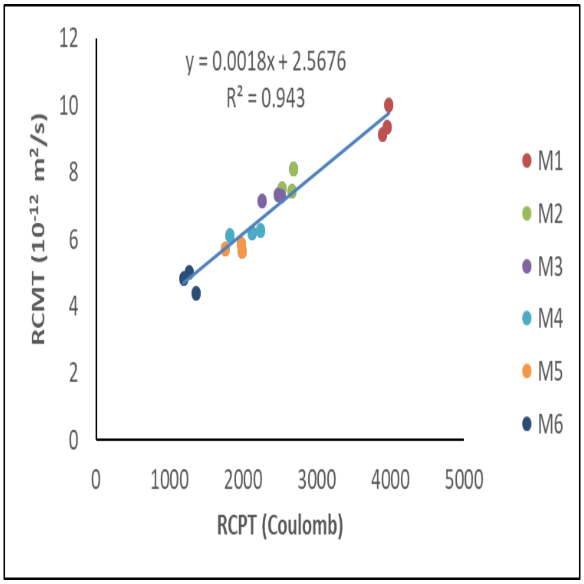

Fig. 9. Relationship between the RCPT and RCMT test at 28 days.

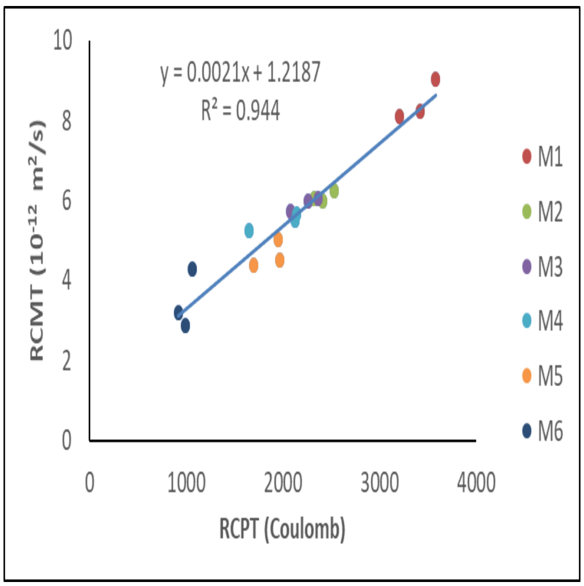

Fig. 10. Relationship between the RCPT and RCMT test at 90 days.

4.5. Service life prediction by LIFE-365 software with various SCM

In the present case, the service life of the slab element was estimated using Life-365 software. The concrete hydration period was assumed to be 25 years while the corrosion propagation period was assumed to be 6 years. On analysis in Life-365 software, estimated service life using different concrete mixtures is shown in Table 3.

It can be observed that concrete without SCM has a service life of 14.8 years. With the incorporation of fly ash service life increased by 4 years to 18.8 years, with the incorporation of GGBFS it increased to 20.8 years and with silica fume to 24.9 years. Bentz used the Monte Carlo method to predict the service life of a structure and found that values of predicted time of corrosion initiation with the Monte Carlo method and Life 365 model were nearly equal if mean values were used in both the models. When 40% of fly ash is used as a replacement for cement, Life 365 gave a service life of 31.1 years while with the Monte Carlo method service life was found to be 33 years. Thus there was a small difference in the results obtained by both methods which may be due to the non-linear nature of basic equations [17].

Table 3. Estimated Service Life of Structure.

Mixture	RCMT co-efficient Values	Initiation Period in years	Propagation Period	Estimated Service Life in years
M 1	9.5	8.8	6	14.8
M 2	7.7	13.8	6	19.8
M 3	7.25	12.8	6	18.8
M 4	5.74	13.9	6	19.9
M 5	6.2	14.8	6	20.8
M 6	4.7	18.9	6	24.9

5. Conclusions

Following conclusions can be drawn from the study:

- The compressive strength of concrete incorporated with fly ash as supplementary material was lesser compared to OPC concrete at 28 days compared to that GGBFS and silica fume. With the increase in age, at 90 days, there is an increase in compressive strength for all the mixtures incorporated with SCM, which is due to the availability of more products of hydration available for reaction. Higher replacement of clinker with GGBFS gave higher compressive strength due to the presence of calcium oxide in it while the inclusion of silica fume as replacement of cement gave high early strength due to its chemical constituents and high fineness.
- The chloride permeability value from RCPT decreases with the inclusion of SCM in concrete due to better particle size distribution and refinement in pore shape. RCPT values of chloride ion permeability for OPC and fly ash was moderate at both ages while with slag (30%) it decreased from moderate to low and slag (40%) it was low at both ages. With the inclusion of silica fume as SCM, RCPT value decreased from low to very low. Control concrete indicated that chlorides were in acceptable limits after 28 and 90 days in the RCMT test. While with the incorporation of SCM resistance to chloride migration increases.
- A good correlation was observed between RCPT and RCMT test results, indicating a good potential for field application.
- The service life of the structure as evaluated using Life 365 software is observed to have increased by 4 years, 6 years and 10 years when fly ash, GGBFS and silica fume are used as SCM.

Thus, it can be observed that the inclusion of supplementary cementitious material in the concrete leads to a reduction of chloride penetration and migration in the concrete. This will lead to a change in the pore structure of concrete and increase the durability of the structure. It will also increase the service life of the structure as validated in Life 365 software.

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