Improvement of Durability and Service Life of Concrete Using Class F Fly Ash

Pradip Nath[1] and Prabir Sarker[2]
[1]Postgraduate Student, Department of Civil Engineering, Curtin University, Perth, Western Australia
[2]Senior Lecturer, Department of Civil Engineering, Curtin University, Perth, Western Australia

Synopsis: Durability is one of the primary considerations in designing concrete structures, especially when used in aggressive environment. Various supplementary cementitious materials (SCM) can be used to improve durability properties of concrete. However, the degree of improvement is dependent on the type of SCM and the mixture proportions of the concrete. In this study, Class F fly ash sourced from Western Australia was used as 30% and 40% of the total binder. The chloride diffusion properties of concrete containing fly ash were compared with those of control concrete. Fly ash concretes that were designed with adjusted water to binder ratio and total binder content to achieve similar 28-day compressive strength of the control concrete showed less chloride diffusion as compared to the control concrete. Simple deterministic service life estimation technique using the well known Fick's law was applied to assess the service life of concrete mixes against the corrosion due to chloride diffusion. Early age properties were used along with certain selected parameters to predict the service life of concrete. Fly ash concretes resulted in higher service life than the control concrete when chloride diffusion was considered as the dominant form of attack.

Keywords: Chloride diffusion, durability, fly ash, service life.

1. Introduction

Being a non-homogeneous material, concrete is vulnerable to various forms of aggressive attack that affects its durability and service life. Inclusion of supplementary cementitious materials such as fly ash, blast furnace slag and silica fume as partial replacement of cement can enhance the durability properties of concrete. These materials can produce additional binder and act as microfiller; hence improve the microstructure of concrete (1). It also promotes the sustainability in concrete production by using by-product materials in place of cement which in turn reduce green house gas contribution from cement production. Yet, huge amount of cementitious by-product material remains unused worldwide. In Australasia, only 12% of total coal combustion product (CCP) was used in cementitiuos application in 2008 while approximately 69% CCP was waiting for future potential use (2). These materials can be effectively used to improve sustainability of concrete production.

Chloride-induced corrosion of reinforcement is one of the major causes of deterioration that affects the service life of reinforced concrete structures. Concrete exposed to marine environment is susceptible to chloride attack. Chloride ion finds its way through concrete by slowly absorbing capillary water and then starts to diffuse in the deeper zone. It attacks the protective passive layer on the reinforcement even at high pH level and initiates corrosion. Once corrosion is initiated in reinforcement, its volume expands and causes cracking and spalling of concrete cover which affects the serviceability of concrete structure. Since the acceptable service life after corrosion initiation is uncertain and shorter than the initiation period, age at corrosion initiation may be conservatively taken as the service life (3). The chloride diffusion in concrete depends on many factors: the mix proportions, curing period, maturity, w/b ratio, presence of supplementary cementitious materials etc (4). Fly ash concretes, due to its dense pore structure, possess high resistance to chloride penetration (4, 5). Despite the numerous reports on the effects of fly ash on concrete durability (4-6), no common design approach is available to achieve optimum performance in the corrosive environment. It is mostly due to variation of materials, geographic location and climatic factors.

In this study, the performance of concrete incorporating local fly ash (Class F) was evaluated for exposure to chloride environment. Fly ash was included as 30% and 40% replacement of the total binder. The service life of the concrete mixtures was estimated using 28-day properties. As the service life of concrete structure is stochastic in nature, estimation with respect to all likely variables leads to random results (7). Hence a simple deterministic approach was applied to assess the service life taking some variables as constant. It was assumed that, concrete was subjected to only chloride attack.

2. Experimental details

2.1 *Materials*

Concrete mixtures were prepared using locally available materials in Western Australia. A General Purpose (GP) Portland cement conforming to Australian standard (8) and Class F fly ash (9) available in Western Australia were used. The compositions of these materials are shown in Table 1. Aggregates included natural sand with a nominal maximum size of 1.18 mm and crushed granite with nominal maximum size of 7, 10 and 20 mm that met the Australian standard (10). A high range water reducer (superplasticiser) was used to enhance workability and it was added to the normal tap water during mixing.

Table 1: Composition of cement and fly ash

Parameter	SiO_2	Al_2O_3	Fe_2O_3	SiO_2+Al_2O_3 +Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	Chloride	Loss on ignition
Cement (%)	21.10	4.70	2.70	28.50	63.60	2.60	2.50	-	0.50	-	0.01	2.00
Fly ash (%)	50.50	26.57	13.77	90.84	2.13	1.54	0.41	0.77	0.45	1.00	-	0.60
Class F fly ash (%) (9)	-	-	-	70.00 min	10.00 max	-	5.00 max	-	-	-	-	6.00 max

2.2 *Mix design and casting of specimens*

The mix design was done using the ACI 211.4R-08 guidelines (11). Two series of concrete mixes were designed, each series comprising of one control mixture and two mixtures with fly ash as 30% and 40% of the total binder (cement + fly ash). The mixture series A was designed with varying total binder content and varying water-binder ratio (w/b) to achieve similar 28-day compressive strength of the control concrete. The other mixture series B was designed with a constant w/b ratio and a total binder content. Superplasticiser was added to the mixture and its amount was adjusted to achieve sufficient workability with slump around 150 mm.

The concrete mixtures were proportioned and mixed in a laboratory pan mixer. The mixture proportions and the measured slumps of the different batches of concrete are shown in Table 2. It can be seen from the slump values that inclusion of fly ash improved the workability of concrete. Increase in fly ash content generally allowed reducing w/b ratio to achieve the similar workability. Concrete cylinders of 100 mm diameter and 200 mm height were cast for compressive strength and chloride diffusion test. Moulds were filled in two equal layers and compacted on a vibrating table. The cylinders were demoulded after 24 hours of casting and then cured in water at 23^{o}C for up to 28 days.

Table 2: Concrete mixture proportions

Series	Mix ID	Binder			Aggregate		Water (kg/m^3)	Superplasticiser (kg/m^3)	w/b	Slump (mm)
		Fly ash (%)	Fly ash (kg/m^3)	Cement (kg/m^3)	Granite (kg/m^3)	Sand (kg/m^3)				
A	A-00	0	0	355	1185	740	145.5	5.11	0.41	140
	A-30	30	132	308	1185	661	141.0	4.77	0.32	170
	A-40	40	176	264	1185	665	136.5	4.75	0.31	185
B	B-00	0	0	517	1185	594	150	6.77	0.29	150
	B-30	30	155	362	1185	570	150	4.80	0.29	175
	B-40	40	207	311	1185	561	150	4.24	0.29	160

2.3 Test methods

2.3.1 Compressive strength test

The compressive strength was evaluated by tests performed on cylindrical specimens (100 X 200 mm) with a Controls MCC8 machine at a loading rate of 0.33 MPa/sec at the ages of 3, 7, 28, 56, 91 and 210 days.

2.3.2 Chloride diffusion test

Chloride diffusion test was carried out in accordance with the NT Build 443 (12). Three slices of the 28 days cured sample were used for the test and one other slice was used to determine the initial chloride content. The samples were about 50 mm thick and 100 mm in diameter. The test specimens were epoxy-coated on every face leaving only one surface open to be exposed to the sodium chloride solution (165 ± 1 gm/L). The exposure period was extended up to 56 days considering the presence of fly ash, low water to binder ratio and the maturity of the mix. After that, eight layers were grinded from each sample at an interval of 2 mm from the exposed surface and dried in the oven. A potentiometric titration method was used to determine the acid soluble chloride content of oven-dried ground samples. The chloride content in each layer was calculated as the average of test results of three samples. The values of surface chloride concentration (C_s) and apparent chloride diffusion coefficient (D_a) were determined by fitting Eq. 1 to the measured chloride contents by means of a non-linear regression analysis in accordance with the method of least squares fit.

$$C(x,t) = C_s - (C_s - C_i).erf\left(\frac{x}{\sqrt{4.D_a.t}}\right) \tag{1}$$

Where, $C(x, t)$ = chloride concentration measured at depth x and exposure time t (mass %), C_s = projected chloride concentration at the interface between the exposure liquid and test surface (mass %), C_i = initial chloride concentration in concrete prior to submersion in the exposure solution (mass %), x = depth below the exposed surface (m), D_a = apparent chloride diffusion coefficient (m^2/s), t = the exposure time (seconds) and erf = error function.

The chloride penetration parameter (k_{cr}) was calculated using the Eq. 2 with the measured D_a (mm^2/yr), C_s, C_i and the reference chloride concentration (C_r) which is taken as 0.05 (% mass of concrete).

$$k_{cr} = 2\sqrt{D_a}.erf^{-1}\left(\frac{C_s - C_r}{C_s - C_i}\right) \tag{2}$$

3. Service life estimation

A deterministic approach based on Fick's 2nd law of diffusion was used for calculation of service life against chloride attack. A practical procedure described by Cao and Bucea (13) for service life estimation of marine structures was followed. All the concrete specimens were subjected to submersed condition and this exposure condition was assumed constant. The estimation requires the value of D_a and C_s at any time t. The value of D_a decreases with time (4) and the value of C_s tend to increase up to a maximum value (13). Equations 3 to 5 (14, 15) were applied in this study to predict D_a at time t using D_a at 28 days from the experiment.

$$D_a(t) = D_{28}\cdot\left(\frac{28}{t}\right)^m + D_{ult}\cdot\left(1-\left(\frac{28}{t}\right)^m\right) \tag{3}$$

$$D_{ult} = D_{28}\cdot\left(\frac{28}{36500}\right)^m \tag{4}$$

$$m = 0.26 + 0.4\left(\frac{FA}{50} + \frac{SG}{70}\right) \tag{5}$$

Where, $D_a(t)$ = chloride diffusion coefficient (m^2/s) at time t (days), D_{28} = chloride diffusion coefficient at 28 days (m^2/s), D_{ult} = ultimate chloride diffusion coefficient (m^2/s) (Eq. 4), m = diffusion decay constant (Eq. 5), FA = percent cement replacement with fly ash and SG = percent cement replacement with slag.

The value of m varies in the range of 0.26 - 0.60 depending on the presence of supplementary cementitious materials in the mix (15). Thomas et al. (15) applied this service life model on 25 year old concrete containing slag up to 65% as cement replacement and found good results. Hence the value of m was taken as 0.26 for control concrete using Eq. 5. However, due to inadequate reliable information about fly ash concretes in literature, a conservative value of m = 0.40 was used considering the variations of cementitious mixes of this study from the original mixes used to develop equations 3 to 5. The value of C_s was used as 0.8% for both fly ash concrete and control concrete which is suggested by Cao and Bucea (13) for the grade 60 concretes. These values of $D_a(t)$ and C_s as well as C_i that obtained from experiments, were put in Eq. 1 to calculate chloride concentration at the cover depth of reinforcement (x). Corrosion of the reinforcing steel is considered to be initiated by the chloride concentration reaching a threshold level (C_{cr}) at the cover depth of reinforcement. There is no universally accepted single value of C_{cr} for corrosion initiation. The value of C_{cr} equal to 0.1% and 0.2% w/w of concrete (13) were used in this study. The calculation was repeated with different set of $D_a(t)$ and t until the concentration at cover depth became equal to the assumed critical chloride level ($C(cover, t) = C_{cr}$). The time at this point is the estimated service life of the concrete. In this study, age at initiation of corrosion of the reinforcing steel is assumed as the service life of the concrete, considering the uncertainty of subsequent corrosion rate and serviceability of structure. Service life was calculated for varying cover depths ranging from 10 to 100 mm.

4. Results and discussions

4.1 Compressive strength

The developments of compressive strength of all the concrete mixes with age are plotted in Fig. 1. The compressive strengths at 28 days are given in Table 3. Fly ash concretes of series A (A-30 and A-40), that were designed with variable w/b ratio and total binder content, gained similar strength which is within ±6% of the control concrete (A-00) at 28 days. Hence, incorporation of fly ash with adjusted w/b helped gain of strength to the similar level of the control concrete at 28 days. The strength of fly ash concretes developed at a higher rate than that of the control concrete until 56 days, when both the fly ash concretes gained more than 110% strength of the control concrete. On the other hand, in the concretes of series B, with constant w/b ratio and total binder content, inclusion of fly ash reduced the strength at early age. Nevertheless, fly ash concretes (B-30 and B-40) achieved more than 80% of the control concrete's (B-00) strength at 28 days. The strength further increased to 96% and 92% of the control concrete's strength at 56 days for 30% and 40% fly ash content respectively.

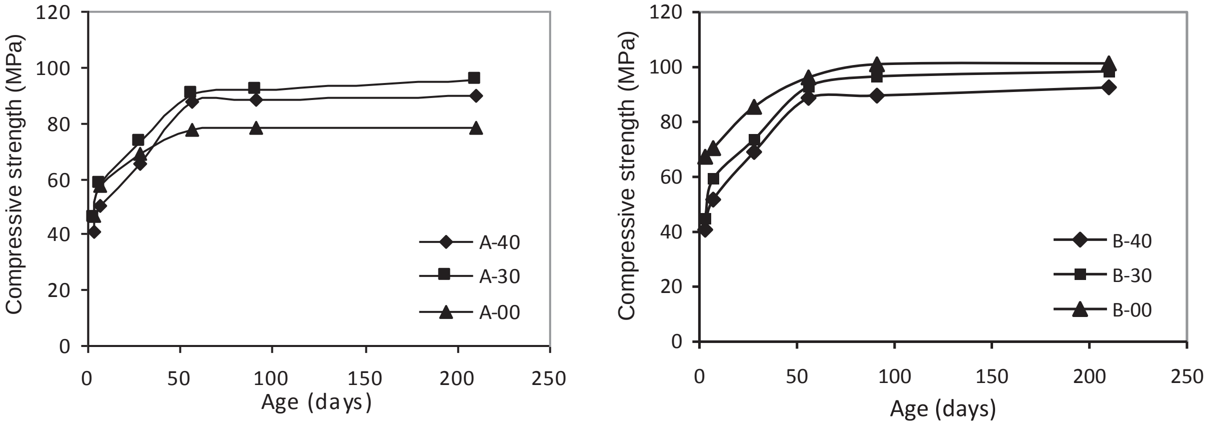


Figure 1. Compressive strength development of concretes of series A (left) and series B (right).

The results indicate that incorporation of fly ash in concrete have different effects on strength development depending on the mix proportions. The compressive strength development at the early age tends to be relatively slow in fly ash concrete as compared to the control concrete (16); however fly ash concrete continues to gain strength and reaches the controls concrete's strength at a later age. It is due to continuing pozzolanic reaction of fly ash after 28 days. The rate of strength development between 28 and 56 days of age is higher for fly ash concretes than the corresponding control concretes, in both series A and B. Concretes with 30% fly ash have shown higher strength gain than that with 40% fly ash.

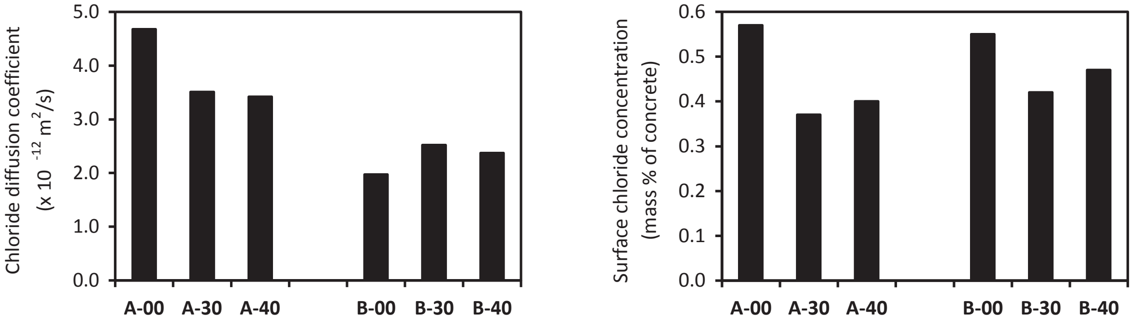
Table 3: Results of test conducted after 28 days of age

Mixture		Strength	Chloride diffusion		
Series	Mix ID	28-day compressive strength (MPa)	Apparent diffusion coefficient, D_a ($\times 10^{-12}$ m^2/s)	Surface chloride, C_s (mass % of concrete)	Penetration parameter, k_{cr} (mm/yr$^{1/2}$)
A	A-00	69.0	4.68	0.57	29.7
	A-30	73.0	3.51	0.37	26.6
	A-40	65.5	3.42	0.40	26.0
B	B-00	85.5	1.97	0.55	19.5
	B-30	73.5	2.52	0.42	22.3
	B-40	69.0	2.37	0.47	21.3

4.2 Chloride diffusion

Concrete samples were exposed to NaCl solution after 28 days of curing. The results of chloride diffusion after 56 days of exposure in submerged condition are shown in Table 3. The variation of diffusion coefficients and surface chloride concentrations of concretes samples of series A and B are shown in Fig. 2. It can be seen from the results that, fly ash concretes of series A (A-30 and A-40) have shown enhanced resistance to chloride diffusion as compared to the control concrete (A-00). The diffusion coefficient of the fly ash concretes reduced by about 25% of the control concrete's value. The diffusion coefficient did not vary significantly with the increase of fly ash from 30% to 40%. Nonetheless, mix A-40 has shown slightly lower diffusion coefficient than mix A-30 during 56 days of exposure.

In series B, the concretes incorporating fly ash (B-30 and B-40) have shown higher chloride diffusion than the control concrete (B-00) in 28-day test. This is due to the early age of the Class F fly ash. Hence, replacement of cement with fly ash without adjusting w/b ratio affected concrete's resistance to chloride penetration to some extent in early days. It is usually observed that chloride diffusion depends on the binder type and w/b ratio in the concrete (17). Since the concretes of series B had same w/b ratio in each mix, the fly ash concretes had relatively less hydration product as compared to the control concrete at 28 days.



(a) (b)

Figure 2. Results of chloride diffusion test after 28 days (a) D_a, (b) C_s

Concretes of series B have shown better resistance to chloride diffusion than that of series A. It is because the concretes of series B had higher binder content and lower w/b ratio than the concretes of series A. The values of penetration parameter (k_{cr}) followed the similar trend as chloride diffusion.

The surface chloride concentration (C_s) over the period of exposure is important in explaining chloride diffusion. Usually at maturity, fly ash concretes accrue higher surface chloride concentration than control concrete due to their higher resistance to chloride diffusion (17). From Fig. 2(b), it can be seen that, fly ash concretes in both series A and B have shown less amount of surface chloride concentration as compared to the corresponding control concretes. This is because of the early age effect of Class F fly ash. The test was conducted at 28 days when fly ash concretes continue to develop its mechanical properties through pozzolanic reactions, as also seen in the compressive strength results. However, the surface chloride concentration of the 40% fly ash concrete was higher than that of the 30% fly ash concrete in both series. This may be because of the increased resistance to chloride penetration resulted by the increase of fly ash content in the mixture.

4.3 *Service life estimation results*

The service lives of the concrete mixtures were estimated as examples to understand the effect of fly ash on service life. The estimation was based on the 28-day chloride diffusion test results and some other typical parameters. Despite the fact that, the hydration of fly ash concrete would continue beyond 28 days, it is conservatively assumed that fly ash concretes of series A reached the similar maturity of the corresponding control concrete at 28 days, as it achieved similar 28-day strength. Conversely, the fly ash concretes of series B resulted in reduced compressive strength and higher chloride diffusion as compared to the control concrete at 28 days. These results may not represent the actual behaviour due to the incomplete hydration of fly ash concrete at 28 days. Hence, the service life calculation was kept limited to concretes of series A.

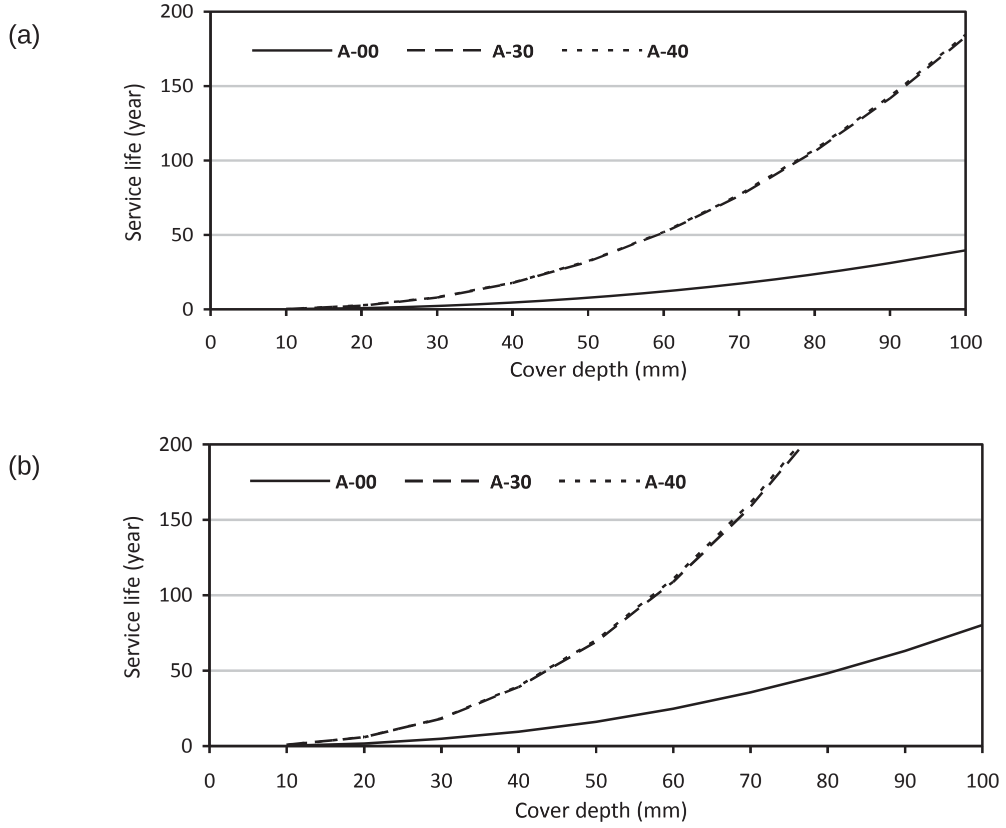


Figure 3: Variation of service life with cover depth when (a) C_{cr} = 0.1% (b) C_{cr} = 0.2%

The service life for various cover depths were estimated and plotted in Fig. 3. The graphs represent the variation of service life of similar grade of concretes having different mixture proportions with the assumptions outlined in section 3. It can be seen from the figures that, fly ash concretes required less cover depth to reach similar service life of control (A-00) concrete. Incorporation of fly ash increased the service life at a higher rate as compared to the control concrete. There is no significant difference between the results of the concretes with 30% and 40% fly ash (A-30 and A-40). This is because the difference between the experimental values of the 28-day diffusion coefficients of the two fly ash concretes was very small and the same value of diffusion decay constant m was used in calculation for both 30% and 40% fly ash concrete.

The effect of critical chloride level (C_{cr}) on the cover depth requirement is compared in Fig. 3 and in Table 4. It is observed that, for any given cover depth, the service life is longer for higher value of C_{cr}. It is predictable; because chloride concentration has to exceed the higher C_{cr} before initiating corrosion. In other words, concrete with higher C_{cr} requires less cover depth for a given service life. When the value of C_{cr} is raised from 0.1% to 0.2% w/w of concrete (100% increase), the required cover depth decreased by 25%. Since there is no universal value of C_{cr}, the lower value can be suggested for design conservatively.

Table 4: Cover depth requirement for the service life of 50 and 100 years

Mixture		Fly ash (%)	Required cover depth (mm) when C_{cr} = 0.1		Required cover depth (mm) when C_{cr} = 0.2	
Series	Mix ID		50 years	100 years	50 years	100 years
A	A-00	0	110	150	82	110
	A-30 / A-40	30 / 40	60	78	44	58

The cover depth requirement for fly ash concretes to achieve expected service life of 50 years and 100 years were estimated and are shown in Table 4. For the assumed conditions, the fly ash concretes required only 52 - 55% of cover depth of control concrete for service life up to 100 years. This indicates that, fly ash concretes having similar 28-day strength of control concrete required less (at least 45%) cover depth to achieve similar service life of control concrete. As illustrated in Table 4, service life can be increased from 50 years to 100 years by adding more cover as much as 30-32% for fly ash concrete and 34-36% for control concretes.

According to the Australian Standard AS 3600-2009 (18), for a design life of 50 years ± 20%, the required cover depth is 35 mm for permanently submerged condition (exposure classification B2) where standard formwork and compaction are used. This value is significantly less than that estimated for 50 years service life of both the fly ash concretes and the control concrete. In this regard, it should be noted that in this study the variation of diffusion coefficient for the presence of fly ash in concrete was considered in terms of diffusion coefficient at 28 days and the diffusion decay constant (m). The variation of service life due to the variation of other variables, such as C_s, C_{cr} and cover depth, over the age (19) was not considered in this estimation. Moreover, the critical chloride content is assumed constant for all the concretes, which can be different for fly ash concretes (20). However, the estimates presented here show the effects of fly ash on service life of reinforced concrete based on the 28-days chloride diffusion values.

5. Conclusions

Concrete samples prepared with 30% and 40% Class F fly ash were tested to evaluate chloride diffusion and compared with control mixtures. Service life of the concrete mixtures was estimated as an example using 28 days properties in a simple deterministic method. The following conclusions are drawn from the test results and the service life estimation:

- Inclusion of fly ash improved the workability of concrete and thus allowed reducing w/b ratio to achieve similar workability. The 28-day strength of more than 60 MPa could be achieved by inclusion of up to 40% local Class F fly ash. Strength development of fly ash concretes continued noticeably up to 56 days.
- The partial replacement of cement by fly ash keeping the same w/b ratio and the total binder content reduced the compressive strength of concrete and its resistance to chloride penetration at 28 days. Adjustments of the w/b ratio and the total binder content to take into account the inclusion of fly ash in concrete resulted in increased strength development and reduced chloride diffusion at 28 days.
- Fly ash concretes of similar 28-day strength as control concrete subjected to chloride attack showed longer service life than the control concrete for any given cover depth.

6. Acknowledgement

The authors wish to acknowledge the support from the Centre for Sustainable Resource Processing (CSRP) and the assistance in carrying out some tests from SGS Australia Pty. Ltd. The help of the concrete laboratory staff of Curtin University is gratefully acknowledged.

7. References

1. Poon, C. S., Lam, L., & Wong, Y. L., “A study on high strength concrete prepared with large volumes low calcium fly ash”, Cement and Concrete Research, 30, 2000. pp 447-455.
2. Ash Development Association of Australia (ADAA), “Annual Membership Survey Results”, January - December 2008, 2010.
3. Bhargava, A. & Banthia, N., “Permeability of concrete with fiber reinforcement and service life predictions”, Materials and Structures, 41, 2008, pp 363–372.
4. Thomas, M. D. A., Matthews, J. D., “Performance of pfa concrete in a marine environment–10-year results”, Cement and Concrete Composites, 26, 2004, pp 5-20.
5. Papadakis, V. G., “Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress”, Cement and Concrete Research, 30, 2000, pp 291–299.
6. Bucea, L., Cao, H. T., & Sirivivatnanon, V., “Durability Properties of High Volume Fly Ash Concretes”, National Symposium on the Use of Recycled Materials in Engineering Construction: Programme & Proceedings, Barton, ACT, Institution of Engineers, Australia, 1996, pp 141-146.
7. Clifton, J. R., “Predicting the service life of concrete”, ACI Materials Journal, 90(6), 1993, pp 611-617.
8. Standards Australia, “Portland and blended cements (AS 3972)”, 1997.
9. ASTM Standards, “Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (ASTM C 618 – 08a)”, 2008.
10. Standards Australia, “Aggregates and rock for engineering purposes Part 1: Concrete aggregates (AS 2758.1-1998)”, 1998.
11. American Concrete Institute, “Guide for selecting proportions for high-strength concrete using Portland cement and other cementitious materials (ACI 211.4R-08)”, ACI Committee 211, 2008, MI, USA.
12. Nordtest Method, “Concrete, Hardened: Accelerated Chloride penetration (NT Build 443, 1995-11)”, 1995.
13. Cao, H. T., & Bucea, L., “Guidelines for the Use of Fly Ash Concrete in Marine Environments”, CSIRO Research Report BRE 062, 2000.
14. Riding, K. A., “Early age concrete thermal stress measurement and modeling”, PhD Thesis, The University of Texas at Austin, 2007.
15. Thomas, M. D. A., Scott, A., Bremner, T., Bilodeau, A., & Day, D., “Performance of slag concrete in marine environment”, ACI Materials Journal, 105 (6), 2008, pp 628-634.
16. Siddique, R., “Performance characteristics of high-volume Class F fly ash concrete”, Cement and Concrete Research, 34, 2004, pp 487-493.
17. Song, H. W., Lee, C. H., & Ann, K. Y., “Factors influencing chloride transport in concrete structures exposed to marine environments”, Cement & Concrete Composites, 30, 2008, pp 113–121.
18. Standards Australia, “Concrete Structures (AS 3600-2009)”, 2009.
19. Khatri, R. P. & Sirivivatnanon, V., “Characteristic service life for concrete exposed to marine environments”, Cement and Concrete Research, 34, 2004, pp 745–752.
20. Thomas, M., “Chloride thresholds in marine concrete”, Cement and Concrete Research, 26 (4), 1996, pp 513–520.