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Original research article

Service Life of Reinforced Concrete Structural Members

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ABSTRACT

Estimating the remaining service life of a structure is an essential part of bridge management systems (BMS). This involves investigating multiple deterioration mechanisms in concrete via chemical attacks due to chlorides, sulphates, acids, carbonation and other external effects. The influence of materials used in construction, exposure conditions, and maintenance history of the bridge are normally studied for estimating the remaining life. In the present case, an analytical study was performed to understand the deterioration in concrete due to carbonation. Carbonation occurs when carbon dioxide (CO_2) enters into concrete through interconnected pores under humid environmental conditions. The effect of carbonation on the initiation time of corrosion in bridges can be determined based on IRC: SP 60-2002. In the current work, the effect of carbonation on different types of cement -Ordinary Portland Cement (OPC) (Type-1), OPC + fly ash (Type-2), OPC+ silica fume (Type-3), with varied grades (M20 to M50) and types of concrete of different dosage (air entrained and non-air entrained) and rate of carbonation is compared for (sheltered and non-sheltered) and structures with different exposure conditions. It was found that the effect of carbonation on service life is less in the presence of supplementary cementitious materials, while air-entrained concrete is less susceptible to the impact of carbonation than non-air-entrained concrete.

Keywords: Bridge; Carbonation; Concrete; Deterioration; Exposed structures; Service life

1. Introduction

In transportation infrastructure, bridges and culverts are commonly considered key elements with structural and economic significance and high vulnerability [1]. Bridges deteriorate over time due to a combined effect of mechanical action, environment, and extreme events like earthquakes, etc., rendering loss of performance [2, 3]. Also, while dealing with the service life of existing bridges, infrastructure inspectors often face issues

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related to design and construction done with a limited set of rules, variation in quality of materials workmanship, inadequate maintenance, etc. [4]. Increasing the service life of infrastructure is considered to be essential to reduce the life cycle costs and to generally improve sustainability [5, 6]. As of 2021, Indian Railways has a total number of 1,55,278 bridges out of which 729 bridges are important, 12,493 bridges are major and 1,42,056 bridges are minor. During the year 2020-21, 1,114 bridges were strengthened/ rehabilitated/rebuilt to enhance the safety of train operations [7].

Deterioration of civil infrastructure results in a significant apportionment of the budget being allocated to repair, rehabilitation and reconstruction of existing facilities. To effectively allocate resources, it is important to diagnose the cause of deterioration and determine cost-effective and appropriate methods of restoration. Deterioration in bridge decks may be primarily caused by chlorides from de-icing salts, alkali-silica reaction (ASR), frost damage, shrinkage, and carbonation of concrete [8]. Deterioration can also be due to poor design and detailing, use of inappropriate materials, poor construction quality and inadequate maintenance. Due to a variety of such reasons, diagnosis of deteriorated structures is not always a simple task [9]. Some of the mechanisms of deterioration are not fully understood and are complicated as more than one mechanism is generally involved in the process.

Carbonation can become a primary reason for deterioration in reinforced concrete, more than chloride attack. Carbonation is due to carbon dioxide presence in the environment that ingresses into the concrete through interconnected porosity, under humid conditions and the formation of $CaCO_3$. It then decreases the pH of the capillary pore solution and thus, the passive layer on steel gets broken and becomes active for corrosion. This in turn decreases the service life of concrete structures. These changes in mechanical properties due to rebar corrosion reduce the cross-section area and result in the deterioration of the bond between the rebar and concrete, leading to a decrease in the service life of the concrete structure. Using supplementary cementitious materials based on high-performance concrete [11], slag blended concrete has a higher carbonation resistance than control concrete [12]. Further, climate changes, such as an increase in CO_2 concentration temperature and humidity, will accelerate the rate of CO_2 penetration and steel corrosion [13]. Consequently, the service life of concrete will vary based on the degree of saturation of concrete. The rate of carbonation in the structure also depends on the thickness of the cover and the permeability of the concrete surface cover. If the water-cement (w/c) ratio of concrete is more than 0.6, the permeability will be high, also the compaction will be improper. Due to this, higher amounts of air voids are formed and these air voids are the main reason for carbonation. One more reason can be due to improper gradation of aggregates (gravel) causing poor compaction, and air voids in concrete, leading to an increase in permeability and a decrease in the service life of a concrete structure [14]. The evaluation of service life, considering the effect of changes in temperature and humidity is hence, crucial for carbonation-based durability design of OPC concrete.

The effect of carbonation is less in non-sheltered conditions compared to sheltered structures [15]. The non-sheltered condition structure has more heat of hydration and gains long-term strength due to exposure to the environment and precipitation [16]. CO_2 levels are high in environments in confined spaces and corners compared to exposed environments, due to the effect of wind and bridge overpass. The physical models, contrary to the statistical models, take into account the damage-causing processes and define deterioration based on the environmental effects and relevant material parameters [17]. Hence, they do not depend on the subjectivity of visual inspection. However, physical models do not consider deterioration as a complete process, rather, they just tend to consider particular phenomena causing deterioration [18]. Several researchers have studied the possibility of implementing physical models into service life prediction and bridge management [19-23]. However, the physical models in the form presented by researchers [24-26] have not yet been implemented in any of the operational Bridge Management Systems (BMS). One more possible reason is that substantial research on durability and benchmarking of properties of concrete have been made, enabling a more accurate application of physical models in service life prediction.

2. Research Significance

The emission of industrial effluents, vehicular emissions and other pollutants from machines lead to an increase in CO_2 in the atmosphere, which is also the reason for carbonation in concrete structures. This study considers the carbonation of bridges over rivers, where the conventional testing method (Rebound hammer, UPV, spraying of phenolphthalein for carbonation) is not practical. There is no direct contact between the water body and the structure, but still, the effect of carbonation is significant, and further, there is no feasibility of inspection in the field. Based on the available data, an analytical study was conducted as per IRC: SP 60-2002 [28], to determine the service life of bridges exposed to rain and subjected to carbonation.

The objective of the present research is to monitor the corrosion rates of reinforcing steel after corrosion has already been initiated due to carbonation in bridge side girders, concrete facades, and balconies subjected to real-time exposure and to evaluate the remaining service life of the structures. Seven grades of concrete [M20 – M50] in steps of 5 MPa, three types of cement from IRC SP60 optimum dosage of supplementary cementitious materials [OPC, OPC + varying dosages of fly ash, OPC + different dosages of silica fume] and two types of concrete [Air-entrained, non-air-entrained] are considered in this study.

3. Deterioration Model for Service Life of Structures

The reduction in service life of a structure due to the carbonation effect from corrosion in reinforcement mainly depends on two phases: initiation time and propagation time. The time required to reach the carbonation front from the surface of the concrete to reinforcement is the initiation time of corrosion and mainly depends on the cover depth in the concrete. Fig.1 shows the influence of carbonation on the lifetime of an RC structural element. During the priming stage, the steel reinforcement is passive and there will be no corrosion. Carbonation begins from the surface of the concrete and infiltrates through the concrete cover. Initiation of corrosion occurs when the carbonation front reaches the steel rebar, even if it does not affect the good serviceability and stability of the structure at this point. Initiation of corrosion is a critical period of the structural life. During the initiation time, the carbonation depth of concrete depends on the cover thickness or cover depth provided. The majority of the service life of reinforced concrete (RC) structures is typically within the initiation time, hence a short amount of time is spent by the structure in the propagation stage. The initiation time is followed by the propagation time during which corrosion will start. In this, at first, cracking of concrete occurs followed by spalling and delamination. The service life of the structure also depends on the moisture content in the concrete cover.

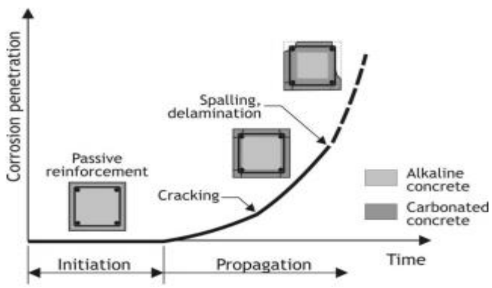


Fig. 1. Degradation of RC structure due to carbonation-induced corrosion [27].

The corrosion initiation time due to the effect of carbonation can be calculated by using Eq. (3.1) [28]. Depth of carbonation:

$$d = K\sqrt{t}, \quad (3.1)$$

where K is the carbonation rate factor, which depends on the environmental factors and properties of concrete and t is the initiation time of corrosion. t is the age of the concrete structure, while K depends on the grade of concrete, environmental conditions, use of supplementary cementitious material and type of concrete, as shown in (Eq. (3.2)) [28].

$$K = C_{env} C_{air} a\left(f_{ck} + 8\right)^{b}. \quad (3.2)$$

The value of the environmental condition coefficient (C_{env}) depends on whether the structure is sheltered or exposed. If the structure is sheltered, the C_{env} value is 1 and if it is exposed to rain, the C_{env} value is 0.5. The air content coefficient (C_{air}) depends on whether the concrete is air-entrained or non-air-entrained. For the case of air-entrained concrete, the value of C_{air} is 0.7 and for non-air-entrained concrete, it is 1.0. The factors a and b values vary based on the supplementary cementitious material used for concreting. The typical values of a and b for a typical non-conventional cementitious binder material on average are shown in Table 1. f_{ck} is the characteristic compressive strength of concrete at 28 days.

Table 1. Values of a and b for different cements [28].

Binder	a	b
Portland cement (Type 1)	1800	-1.7
Portland cement + fly ash 28% (Type 2)	360	-1.2
Portland cement + silica fume 9% (Type 3)	400	-1.2

The time of carbonation front to reach reinforcement leading to initiation of corrosion is called initiation time (T_i). The initiation time for corrosion due to carbonation can be calculated using (Eq. (3.3)).

$$T_i = \left(\frac{C}{K}\right)^2, \quad (3.3)$$

where T_i is an initiation time of corrosion, C is a cover of concrete structure, and K is a carbonation rate factor.

Carbonation is negligible at fully saturated concrete surfaces which are impermeable to CO_2 as well as fully dry concrete, as, carbonation cannot occur due to a total lack of moisture. It has been observed that at a relative humidity under 50%, carbonation is limited as there will not be enough moisture to initiate the reactions while for values above 70% RH, carbonation is restrained attributed to pore-blockage due to high moisture content [29]. The highest carbonation rate happens at intermediate moisture content. The highest K value is observed at 60% to 70% of relative humidity [32]. The carbonation rate is lower during wetting and drying cycles. As wetting is faster than drying, the wetting period is short, which reduces the penetration of carbonation. Hence, micro-climate is important in the carbonation effect. The carbonation effect varies within parts of a structure due to wetting-drying cycles. The permeability of concrete significantly influences the carbonation effect. Reduction in the water/cement ratio reduces the porosity of the cement paste and adequate curing reduces the carbonation rate. The carbonation rate is also influenced by the cement type. For example in blended cements, the lower $Ca(OH)_2$ content from the hydration of pozzolanic materials in the hardened cement paste may increase the carbonation rate. The carbonation also depends on the concentration of the carbon dioxide present in the atmosphere.

Carbonation is the reaction of CO_2 in the air with hydrated minerals in concrete, leading to a lowering of pH value in the carbonated zone. The protective film on the surface of the steel lying in the carbonated zone is destroyed and the propagation of corrosion starts. The propagation time (Tp) of corrosion as per IRC: SP 60-2002 [28] until cracking of concrete cover is given as

$$T_q = 80\frac{C}{D \times r}, \quad (3.4)$$

where C is the thickness of concrete cover (mm), D is the diameter of the reinforcement bar, and r is the rate of corrosion.

For carbonated concrete, the mean rate of corrosion can be taken as 5-10 mm/year at 90-98% and 2 mm/year less than 85% relative humidity. For the bridge components that are exposed to rain, the average relative humidity can be taken as 95 % [28].

Figs. 2-3 illustrate how the carbonation depth varies based on the concrete grade and different types of binders over a 100-year service life using Eqs. (3.1)-(3.2). Upon comparing Figs. 2-3, it is evident that there is a consistent decreasing trend in carbonation depth as the concrete grade increases. This observed trend remains consistent for both non-air-entrained and air-entrained concrete, regardless of the type of binder used. Also, carbonation depth for similar grades of concrete with air-entrained type binder shows a reduction compared to non-air-entrained type, evident from the figures. For air-entrained concrete and Type 1 binder, for a life of 100 years, there is a decrease in carbonation depth in Type 2 more than in Type 3. Type 2 binder air-entrained concrete is superior to Type 1 and Type 3 for typical lower-grade concrete (M20). For remaining grades i.e., M25 and above grades, Type 1 grade is superior to Type 2 and Type 3 binders. In M20 grade Type 2 binder air-entrained concrete is denser compared to the other 2 types of binders so it is superior to the other 2 types of binders.

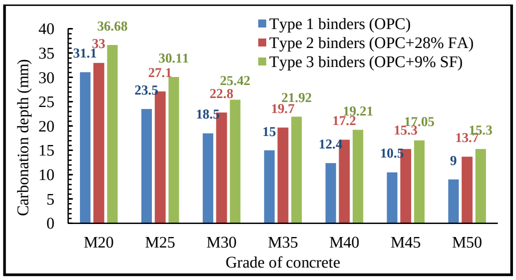


Fig. 2. Carbonation Depth Vs Grades of concrete (Non air-entrained for a service life of 100 years).

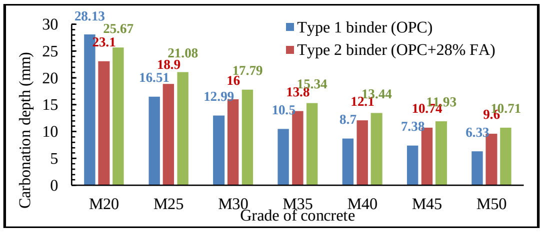


Fig. 3. Carbonation Depth Vs Grades of concrete (Air entrained for service life 100 years).

As compared to conventional OPC binders, the carbonation depth shows a 23% increase with the addition of optimum dosages of fly ash (28%) and 37% increase with the addition of optimum (9%) dosage of silica fume as a binder, for similar exposure time, in case of M30 grade non-air entrained concretes (Fig. 4). The increase in carbonation can be due to both pozzolanic and hydration reactions. Pozzolanic materials enhance the formation of additional cementitious products, and the hydration of cement produces calcium hydroxide, both of which contribute to the alkalinity and chemical stability of the concrete initially. However, over time, carbonation affects the concrete, consuming the calcium hydroxide and reducing alkalinity, making the concrete more vulnerable to carbon dioxide penetration and subsequent carbonation. The carbonation depth in air-entrained concrete exhibits a similar trend as in non-air-entrained concrete. In this case, also, M30 grade with fly ash as binder shows a 23% increase in carbonation depth, while with silica fume; it shows a 37% increase in depth of carbonation compared to a similar M30 grade concrete with OPC. There is a significant effect of cement-replacing materials on carbonation depth. The addition of binders hence increases the carbonation depth, which is not good for the service life of the concrete. The air-entrained concrete shows 30% less carbonation depth compared to non-air-entrained concrete for all grades of concrete and cement replacing materials also due to air entrainment causing a longer percolation path.

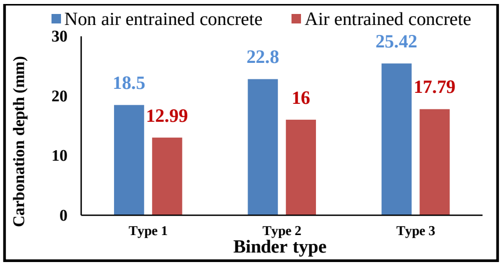


Fig. 4. Comparison of Carbonation depth for M30 grade for different binders.

The percentage variation in carbonation depth for non-air-entrained and air-entrained concretes of different grades with various binders is shown in Fig. 4. The OPC shows a minimum reduction of 10% in carbonation depth for M20 grade and a maximum of 30% reduction for all other grade mixes considered in the study. The use of fly ash and slag can lead to a reduction in carbonation resistance with increased replacement levels. In addition to clinker reduction, the pozzolanic reactions in concretes with SCMs consume a significant amount of the available Ca $(OH)_2$ and can reduce the upper limit of the initial pH of hardened concrete to ≈12.5, as compared to ≈13.5 in OPC [14]. When type 2 binder is used, the air-entrained concrete shows an invariable reduction of 30% in the carbonation depth for all concrete mixes. Concrete with Type 3 binder also shows a uniform reduction of 30% with air entrainment compared to non-air entrained concrete mixes.

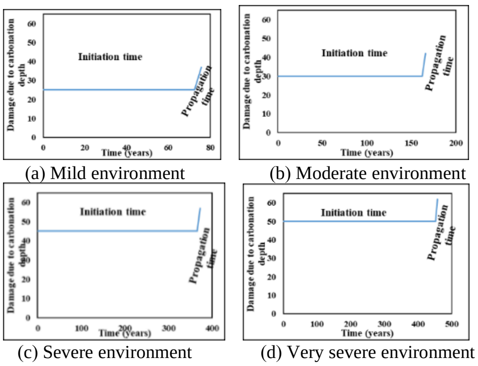


Fig. 5. Service life of column-M25, Type-1 concrete binder (non-air entrained).

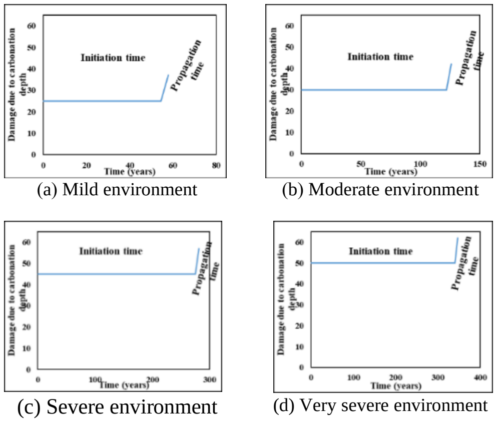


Fig. 6. Service life of M25 Grade concrete, Type -2 concrete binder (non-air entrained).

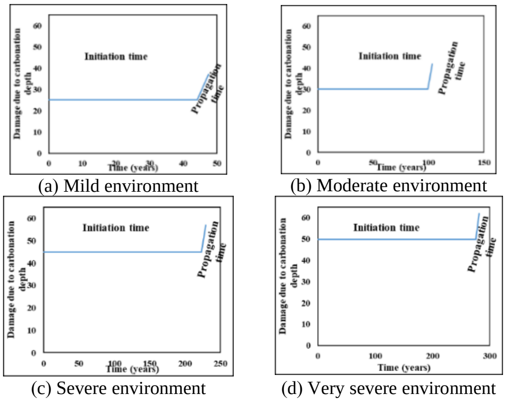


Fig. 7. Service life of M25 Grade concrete, Type -3 concrete binder (non-air entrained).

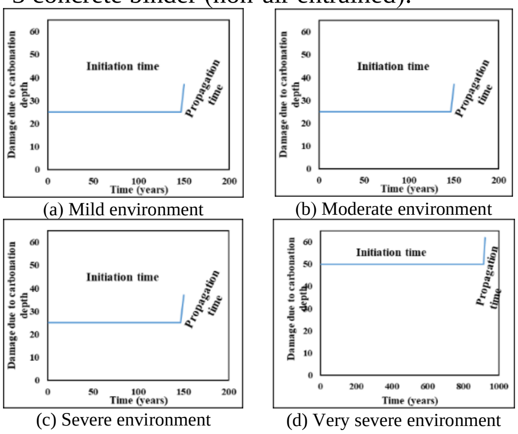
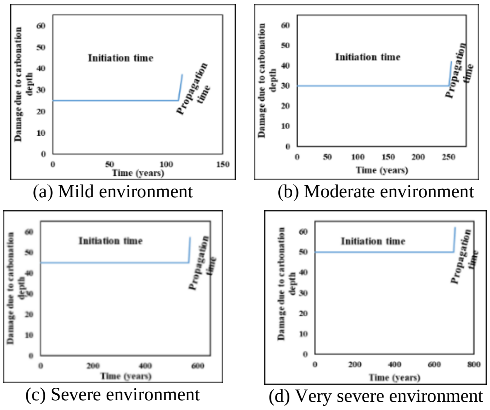


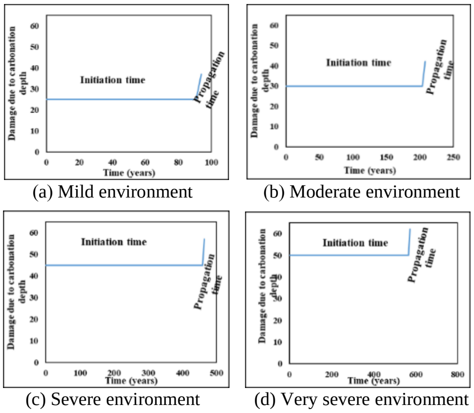
Fig. 8. Service life of M25 Grade concrete, Type-1 concrete binder (air entrained).



(a) Mild environment (b) Moderate environment

(c) Severe environment (d) Very severe environment

Fig. 9. Service life of M25 Grade concrete, Type -2 concrete binder (air entrained).



(a) Mild environment (b) Moderate environment

(c) Severe environment (d) Very severe environment

Fig. 10. Service life of M25 Grade concrete, Type -3 concrete binder (air entrained).

The service life is calculated using Eqs. (3.3)-(3.4) for the initiation and propagation times under various exposures, cover to reinforcement, type of concrete and binder combinations. Figs. 5-10 present the results of the same for M25 grade concrete with 12mm rebar. The IS 456: 2000 [33] prescribes a nominal cover to the reinforcement of 20, 30, 40 and 50 mm, which is based on environmental exposure conditions - mild, moderate, severe & extremely severe, respectively, from a durability perspective. The service life values of each binder are presented in Table 2.

Table 2. Service life of M25 Grade concrete for different environments.

Type of concrete	Type of binder	Cover (mm)	Initiation time (years)	Propagation time (years)	Service life (years)
Non-Air entrained	Type 1	25	72.43	3.3	75.73
		30	162.00	4.0	166.00
		45	366.00	6.0	372.00
		50	452.00	6.0	458.00
	Type 2	25	54.46	3.3	57.76
		30	122.00	4.0	126.00
		45	275.00	6.0	281.00
		50	340.00	6.0	346.00
	Type 3	25	44.14	3.3	47.44
		30	99.33	4.0	103.33
		45	223.00	6.0	229.00
		50	275.00	6.0	281.00
Air entrained	Type 1	25	146.00	3.3	149.30
		30	330.00	4.0	334.00
		45	742.00	6.0	748.00
		50	916.00	6.0	922.00
	Type 2	25	111.00	3.3	114.30
		30	251.00	4.0	255.00
		45	566.00	6.0	572.00
		50	699.00	6.0	705.00
	Type 3	25	90.70	3.3	94.00
		30	204.00	4.0	208.00
		45	459.00	6.0	465.00
		50	566.00	6.0	572.00

It is evident in general that air-entrained concretes have higher service life compared to non-air-entrained concretes for the same binder type, and identical exposure conditions. Within the same type of concrete, the service life varies with the type of binder as - Type 1>Type 2 > Type 3, wherein, Type 1 concrete always has a maximum service life. This is based on time up to propagation of corrosion in reinforcing steel. Hence, air-entrained concrete with Type 1 binder (OPC) provides maximum service life for bridges under all exposure conditions.

As per IRC-SP-60: 2002 provisions for durability, the bridges are to be designed for a service life of 100 years. This enables the determination of specific combinations of concrete and binder types, with minimum cover-to-reinforcement and maximum size of aggregate (as per IS 456: 2000). It is apparent that the reinforcement cover of 30 mm for non-air entrained concrete and 25 mm for air-entrained concrete is sufficient from a (100 years) service life point of view; however, IRC-SP-60: 2002 prescribes a nominal cover to reinforcement of 40 mm for all bridges.

5. Conclusions

A parametric study is conducted by the IRC-SP-60: 2000 methodology to determine the extent of carbonation-induced corrosion in RC structures. Further, an attempt is made to predict the service life under various exposure conditions and binder types. The following conclusions are drawn for the carbonation effect on concrete:

1) There is a 23% increase in carbonation depth with fly ash addition and a 37% increase with the addition of silica fume in a typical M30 grade concrete with OPC.
2) The percentage drop in the carbonation depth is 30% in air-entrained concrete compared to non-air-entrained Type 1, Type 2 and Type 3 binders except for M20 grade type 1 binder, where it is only 10%.
3) The lower carbonation observed in exposed structures, compared to sheltered structures, is due to the higher saturation achieved in exposed structures. The higher rate of saturation hinders the CO_2 penetration of $Ca(OH)_2$, and thus lowers the rate of carbonation with cover depth.
4) The effect of carbon dioxide reactivity with the moisture in concrete decreases with an increase in the grade of concrete for both air/non-air entrained concrete as well as in Type 2 and Type 3 binders. This confirms the positive effect of reduced surface and volumetric porosity attained in higher grades of concrete which helps in resisting the permeation of carbon dioxide from the environment.
5) The addition of supplementary cementitious materials such as fly ash, blast furnace slag, and silica fume in concrete leads to the initiation of carbonation at a faster rate compared to conventional concrete. This will affect the service life of the structure.
6) Air-entrained concrete indicates lower carbonation compared to non-air-entrained concrete for all grades and types of binders. This may be due to longer percolation pathways in the carbonation processes with increased volumetric porosity of air-entrained concrete. The carbonation impact is in the order – Type 1< Type 2< Type 3.
7) The reduction of cover thickness to 30 mm for non-air-entrained concrete and to 25 mm for air-entrained concrete results in acceptable durability, in terms of time required for the initiation of carbonation and serviceable life (100 years).

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