THESIS

THE EFFECTS OF DESIGN DECISIONS ON SERVICE LIFE AND LIFE CYCLE COST FOR A CONCRETE SLAB IN A PARKING GARAGE

Submitted by

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ABSTRACT

THE EFFECTS OF DESIGN DECISIONS ON SERVICE LIFE AND LIFE CYCLE COST FOR A CONCRETE SLAB IN A PARKING GARAGE

Parking garages are unique structures that are useful and common as part of the transportation infrastructure system in the US. Large percentage of these structures is open which expose them to ambient environment and in some cases deleterious chloride exposures. Corrosion of embedded steel is the main cause for concrete deterioration and chloride exposure is one of the major causes for corrosion. Therefore, designing these structures for durability is essential to extend their service life and reduce their degradation status and future repair costs. Improving the durability of these structures can be a costly process at the construction phase that might leave owners of parking garages reluctant about increasing the upfront costs. Therefore, Life-365 software has been used in this study to investigate the service life and life cycle cost impacts of different design decisions throughout the lifetime on a reinforced concrete slab element in a parking garage. Life Cycle Cost Analysis "LCCA" is a process that weights the trade-offs of different phases cost including initial construction and subsequent maintenance and repair throughout the design life period and can help understand the long-term value of additional upfront costs. In Life-365, service life is the sum of two periods: the initiation period and the propagation period while LCC is the sum of three cost phases :the construction phase, the barrier phase and the repair phase which starts at the end of the service life period and extends the remainder of design life. The design decisions or design variables that are investigated in this study include varying the concrete cover distance to the embedded steel, varying the w/cm ratio, using different supplementary cementitious materials, using different barriers and reinforcement types. The geographic location of the parking garage was chosen as Denver, Colorado. Corrosion is likely to occur in this city where harsh environmental conditions are present, including snow falling into parking garages' decks or using deicing salts to melt accumulated snow on roads which can be carried by tires or underneath automobiles. Results of this study showed that using supplementary cementitious materials are the best design variables to consider in terms of saving money for the concrete slab during its design life, besides increasing the concrete cover distance. In addition, a combination of SCMs with a low w/cm ratio has proven to be very effective in terms of reducing costs especially when it is used with higher concrete cover. This study can help designers and owners of these structures in managing and allocating the resources they have more effectively.

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1 INTRODUCTION

1.1 Background

Parking garages are an important part of the US transportation system where they facilitate the process of finding temporary parking and they have large capacities to serve in this purpose. Parking garages can be built as independent structures or as a part of multi-use structures, which means their failure can significantly impact peoples' lives. Parking structures are unique and different from other structures in that most garages are open to the environment and have large portions of the parking structure subjected to seasonal and daily variations in ambient weather conditions (VanderMeid et al., 1994). Durable parking garages should serve their design purpose properly by having the capacity to resist different ambient environment and minimize their degradation status over the years.

Parking structures' durability is an essential property that can extend the service life of these structures. Service life can be defined as the period of time between construction and first repair or unacceptable damage (Thomas & Bentz, 2013). Deterioration of parking structures includes but not limited to cracking, spalling and delamination. The reason for these defects can be corrosion of reinforcement steel due to chloride ions penetrating the concrete surface and accumulating in a sufficient quantity at the embedded steel level to initiate corrosion. Deicing salts are the main sources for chloride ions and used to melt snow during winter seasons. Corrosion of embedded reinforcement is the most common cause of concrete deterioration in parking garages (Portland Cement, 2002). Therefore, parking structures' elements require repair and rehabilitation to maintain their serviceability. Billions of dollars are spent to repair and replace degraded concrete infrastructure due to corrosion damage every year in the US (Violetta, 2002). Decisions made by designers and owners of parking garages during the construction phase can affect future cost phases where there is a direct relationship between improving the durability and reducing future maintenance and repair costs. Life Cycle Cost Analysis "LCCA" evaluates the trade-offs between different cost phases during the design life of the structure.

There are three phases in terms of cost when a new parking structure is being built. These phases are construction cost, barrier cost and repair cost. An economical construction cost that provides the necessary durability and functionality is an important factor in building a structural system. However, each of these cost phases add up to the total cost of building a square foot in these structures and evaluating whether a parking structure or an element in it is cost effective or not depends on conducting LCCA. The focus of this study is to investigate many design decisions or design variables for a reinforced concrete slab in a parking garage to evaluate their effects on service life and LCC. These design variables include using different concrete covers to the embedded steel, varying the w/cm ratio, using concrete mixes with various Supplementary Cementitious Materials (SCMs), different barriers and reinforcement types. The design variables have been studied individually and in combination to better understand the effect of changes the variables has on service life predictions and LCC. The intent of this research is to help designers and owners of parking structures to allocate their resources in a better way.

The geographic location selected for the parking structure in this study is Denver, Colorado. Severe environmental conditions in this city such as temperature fluctuations and using deicing salts to melt accumulated snow on a slab make this location interesting for study. Life-365 software is used as a tool to estimate the service life and calculating LCC for a slab element in a parking structure. Finding the best fit to build a durable parking structure in a cost effective way and without exceeding the specified budget is a big challenge that faces designers and owners.

1.2 Objectives

The objectives of this study include determining the effect of the following design variables on service life and LCC for a reinforced concrete slab in a parking garage:

1- Concrete covers distance to the embedded steel.
2- W/cm ratio.
3- Using SCMs such as silica fume, slag cement and Fly ash “Class F”, within a recommended dosage range, as a partial replacement for Portland cement.
4- Barrier type such as membrane and sealer. Barriers were applied to the slab at the beginning of the project and reapplied once after their failure up to the time of first repair.
5- Using epoxy-coated steel as an embedded steel reinforcement.

In addition, determining the most effective design changes for improving the service life and the most cost effective design choices for lowering LCC for the slab element are examined.

1.3 Thesis organization

Chapter 1 in this thesis presents a brief introduction about the importance of parking structures, explains some essential characteristics for their integrity and talks about the focus of the study. Chapter 2 is a literature review that illustrates built-in and exterior protection systems that can be used in parking structures. In addition, it gives some background information about the most common deterioration mode in reinforced concrete parking structures, chloride induced corrosion. Chapter 3 discusses the tool that is used for the analysis, Life-365 software, and its capabilities that are used in conducting this study such as estimating service life and LCC. In addition, it discusses the design variables and the inputs that were used in the model for all the cases that are analyzed. Chapter 4 presents a sample of results for the estimated service life and LCC for different cases and different design variables that have changed throughout the study. Chapter 5 gives a conclusion about most effective design variables in terms of improving service life and LCC for a slab element in a parking structure. Furthermore, appendix A presents an example of hand calculations for proportioning design of a concrete mixture and estimating its cost. Finally, appendix B presents the complete results for all alternatives in different cases for estimated service life and LCC from Life-365 software through tables and figures plotted by the software.

2 LITERATURE REVIEW

2.1 Background

Concrete has many useful characteristics that are important in designing concrete structures which makes it the most used construction material in the world (Lomborg, 2003). Durability is one of these characteristics and it can be defined as the ability of a structure to withstand the ambient environment for which it was designed and serve its design purpose properly during its design life (Kwan & Wong, 2005). Deterioration of concrete structures occurs for different reasons. The major cause for concrete deterioration is corrosion of embedded steel reinforcement (Portland Cement, 2002). Chloride ions are one of the main deleterious materials that can cause premature corrosion for reinforcement steel (Portland Cement, 2002). The relatively high alkalinity of concrete “high PH” protects embedded steel from corrosion but free chloride ions reduces the PH of concrete and help in depassivating the protection film around the steel which would cause corrosion to start and accelerate in the presence of oxygen and water (P. C. I. P. S. Committee, 1989). Chloride ions are mainly found in deicing salts in North America where these salts are used during winter months to remove ice from highways and roads (Mammoliti, Hansson, & Hope, 1999). Automobiles’ bottom surface or tires carry these deicing salts with ice and snow from the roads and bring them into parking garage decks. After melting, the salty water will fall on the floor and might form ponds which will increase the probability of salty water penetrating into the concrete if it was cracked or highly permeable and brings chloride ions to interact with steel (P. C. I. P. S. Committee, 1989). As a consequence, cracks, spalls and delamination of concrete members such as decks in parking garages and bridges are some effects of reinforcement corrosion where the greater volume of resulting rust applies tensile stresses on surrounding concrete (Mammoliti et al., 1999). Figure 2.1 shows spalling effect due to corrosion of an embedded steel bar.

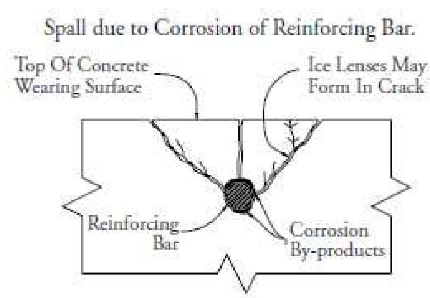

Figure 2.1:Spall in concrete due to corrosion of reinforcing bar (P. C. I. P. S. Committee, 1989)

Corrosion is an electrochemical process that requires an anode and a cathode connected by an electrolyte in the form of pore water in the hardened cement paste to form rust (A. Neville, 1995). In general, steel parts near the member top surface work as an anode and get rusted while other steel parts near the member bottom surface work as a cathode and don't get rusted (P. C. I. P. S. Committee, 1989). However, corrosion can occur when two locations on a single metal have different energy levels (Portland Cement, 2002). The positively charged ferrous ions Fe^{+2} at the anode pass to the solution while the negatively charged free electrons remain in the steel bar and pass into the cathode. After that, these free electrons will be absorbed by the components of the electrolyte and would combine with water and oxide to form hydroxyl ions OH^-. Then, hydroxyl ions move through the electrolyte and combine with the ferrous ions to form ferric hydroxide which would convert by further oxidation into rust (A. Neville, 1995). The anodic and cathodic chemical reactions are shown below and Figure 2.2 shows the corrosion mechanism for steel embedded in concrete.

- Anode Reaction

  $Fe \rightarrow Fe^{2+} + 2\ e^-$

  $Fe^{2+} + 2\ (OH)^- \rightarrow Fe(OH)_2$ (ferrous hydroxide)

  $4\ Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4\ Fe(OH)_3$ (ferric hydroxide)

- Cathode Reaction

  $4\ e^- + O_2 + 2H_2O \rightarrow 4\ (OH)^-$

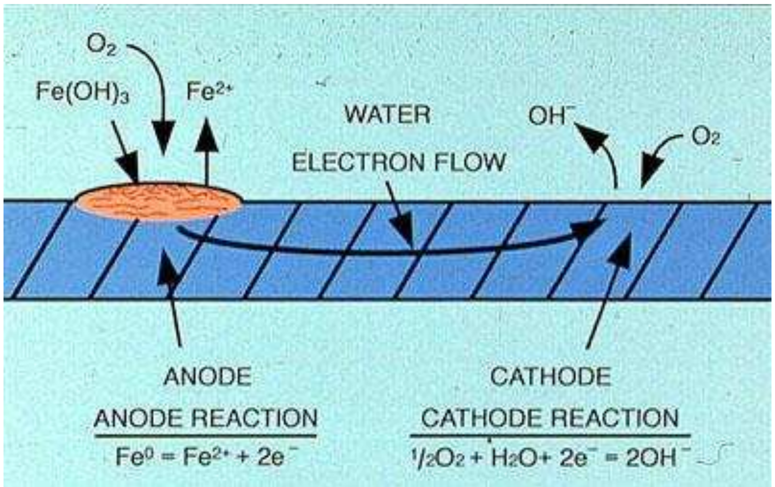

Figure 2.2: Corrosion mechanism for steel embedded in concrete

In conclusion, reinforcement corrosion leads into concrete deterioration where this phenomenon causes loss of concrete cross section, loss in steel cross section and loss of bonding between reinforcement and concrete which will directly weaken the structural member (P. C. I. P. S. Committee, 1989). Therefore, the corrosion of reinforcement embedded in concrete affects the service life for concrete structures that requires them to be repaired in the future for the remainder of their design life. Life Cycle Cost Analysis "LCCA" can be conducted to evaluate different alternatives with different construction, barrier and repair costs and if they are cost effective or not and to evaluate the individual effects of various design decisions on cost. Some built-in and exterior protection systems that are used to reduce corrosion of steel and boost the service life for parking structures are discussed in the coming sections.

2.2 Built-in Protection Systems

2.2.1 Concrete

Concrete components which include cement, water and aggregates are the major factors that affect concrete mix quality (Chrest, 1996). This quality can be measured in terms of concrete properties such as strength and permeability which will directly affect the durability of parking structures or elements in them (VanderMeid et al., 1994). High quality concrete is an essential characteristic for durability in concrete which will give a good concrete performance (P. C. I. P. S. Committee, 1989). It is important to have concrete that satisfies both structural and environmental requirements.

From a strength perspective and in general, concrete durability and strength have a direct relationship (VanderMeid et al., 1994). High strength concrete can be obtained by using high cementitious material content with low water/cement ratio and this might be supported by using fly ash and silica fume (P. C. I. P. S. Committee, 1989).

In terms of permeability, concrete that is produced with low permeability characteristics has many benefits over high permeability concrete. Low permeability concrete is a substantial factor to resist water, chloride and oxygen penetration which is desired to reduce corrosion of reinforcement (VanderMeid et al., 1994). Besides that, the electrical conductivity of low permeability concrete is lower than that for high permeability concrete which decreases the chances to have corrosion in the reinforcement (VanderMeid et al., 1994). Permeability can be reduced by using water/cement ratios between 0.4-0.45 or even less than that ratio in harsh environments that could allow for corrosion rapidly (P. C. I. P. S. Committee, 1989). Figure 2.3 below shows the relationship between coefficient of permeability and water/cement ratio for mature Portland cement pastes (VanderMeid et al., 1994).

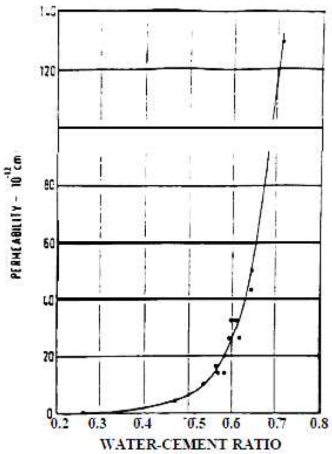

Figure 2.3: The relationship between coefficient of permeability and water/cement ratio for mature Portland cement pastes (VanderMeid et al., 1994)

2.2.1.1 Cement

The selection of cement type depends on the project environmental requirements and should be consistent with standard specifications (Chrest, 1996). One brand of cement should be used during the project construction period to guarantee the best performance by making sure that the results obtained from the specified cement brand are the same (Chrest, 1996).

2.2.1.2 Water

Drinkable-quality water that satisfies ASTM C94 should be used in concrete mixes so that the total chloride content must not exceed the standards limitations (Chrest, 1996).

2.2.1.3 Aggregate

ASTM C33 must be satisfied for both coarse and fine aggregate (Chrest, 1996). Some types of aggregates like chert or lignite might have surface pop-out when they are exposed to freezing and thawing (VanderMeid et al., 1994). Therefore, aggregates properties such as hardness, soundness and low-absorption are recommended to get a good compressive strength and resist abrasion (P. C. I. P. S. Committee, 1989). In addition, cement and aggregates that can produce the harmful alkali-aggregate reaction should not be used in the concrete mixtures in parking structures. Some aggregate characteristics such as abrasion should be investigated to make sure of their resistance (VanderMeid et al., 1994). In addition, chloride ion content in aggregates should be checked so it doesn't exceed the total chloride content. Finally, To get a durable concrete, it is recommended to use well graded aggregate which will make the concrete mix denser (VanderMeid et al., 1994). However, having many small particles will increase the water needed to cover the larger surface area which will require increasing the water/cement ratio and this might cause shrinkage cracking (Chrest, 1996).

2.2.1.4 Mix proportions

This is the most important part that gives concrete it's strength characteristic and makes it perform properly in terms of being impermeable and being durable or not (VanderMeid et al., 1994). Water/cement ratio should not exceed 0.4 to prevent corrosion in areas where concrete is exposed to deicing salts but the ratio can be increased to 0.45 for normal weight concrete if concrete cover is increased by 0.5 inch according to ACI 318 (VanderMeid et al., 1994). Although, ACI 318 recommends keeping the ratio at 0.4 in areas where freezing and deicing salts are common even with the increased concrete cover. Therefore, water/cement ratio is the main factor to reduce chloride permeability according to a recent study that followed and confirmed another corrosion study by the Federal Highway Administration (FHWA) (P. C. I. P. S. Committee, 1989). The study showed a reduction by 80% in chloride at a depth of 1'' after a tough 1-year saltwater exposure and this is only by decreasing water/cement ratio from a range of 0.46-0.51 into 0.37-0.4 as shown in Table 2.1 (P. C. I. P. S. Committee, 1989). Controlling water/cement ratio and following ACI 318 recommendations will produce low permeable and higher durable concrete.

Table 2.1: Reduction in chloride concentration percentage at 1 in. depth with various w/cm ratio

Study	Change in w/c	Reduction in chloride at 1-in (25-mm) depth (%)
1987 FHWA	0.51 to 0.40	80
Present	0.46 to 0.37	80
1987 FHWA	0.51 to 0.28	95
Present	0.46 to 0.32	94

2.2.2 Drainage

Providing an effective drainage is an important construction technique that is used to minimize chloride-carrying water attack on concrete by preventing water accumulation in ponds in the parking structure surfaces (Chrest, 1996). A recommendation for drainage system design is to have a minimum slope of 1.5 percent in parking structure surfaces while 2 percent is preferred to drain excessive water properly (VanderMeid et al., 1994). The drainage system should be designed by considering camber and deflections of slabs and beams (Chrest, 1996). In addition, a bucket as shown in Figure 2.4 that can be removed and cleaned during regular drain maintenance needs to be included in the drainage design to reduce the probability of pipe blockages due to sediments (Chrest, 1996). Therefore, continuous trench drains need to be avoided if possible, otherwise they require periodic cleaning from silt and sediments which will increase the maintenance costs (VanderMeid et al., 1994). Also, a bumper guard should be placed around vertical drain lines to protect them from vehicle bumper damage (P. C. I. P. S. Committee, 1989).

Figure 2.4: Bucket included in drainage design

2.2.3 Admixtures

There are many types of admixtures that are used to increase workability of concrete without affecting its durability negatively by using the appropriate quantities and combinations. Some admixtures that contains chloride should not be used in parking garages where they might increase chloride content above the acceptable limits (VanderMeid et al., 1994).

2.2.3.1 Air Entraining Agents (AEA)

Air entraining agents are a type of admixtures used to tackle the problem of freeze-thaw damage in concrete in cold climates (Du & Folliard, 2005). Deterioration of concrete due to freeze-thaw happens when water inside the concrete freezes which will increase the water volume after it freezes by 9 % and results in extra stresses on the concrete which might develop to cause ruptures (VanderMeid et al., 1994). The basic idea of AEA's is to have air filled voids that allow adjacent excessive water to easily expand into when it freezes and this action will prevent the freeze water from increasing the volume and damage the concrete (A. M. Neville, 1995).

In conventional concrete mixes, about 1-3% of the volume will be trapped air distributed in non-uniformly large pockets. In contrast, entrained air is distributed uniformly in millions of tiny bubbles that will help to relieve stresses and minimize deterioration (Chrest, 1996). Entrained air bubbles have a diameter of 0.002 in while trapped air bubbles are much larger (A. M. Neville, 1995). Although AEA's improve the durability of concrete, they cannot entirely prevent concrete deterioration in freeze-thaw environments. The recommended percentage of AEA's in concrete is 5-7% air by the volume of concrete (Chatterji, 2003). There are many factors that can affect AEA's content in concrete such as cement chemistry, temperature and additional cement materials (Du & Folliard, 2005). Also, aggregate size might affect the proper air content to resist freezing-thawing phenomena (VanderMeid et al., 1994). Finally, there is an average spacing (0.01 in) between air voids that needs to be established to get the best results of protecting concrete from freezing damage. Figure 2.5 shows the relationship between the durability factor and the spacing between air entrainment bubbles (A. M. Neville, 1995).

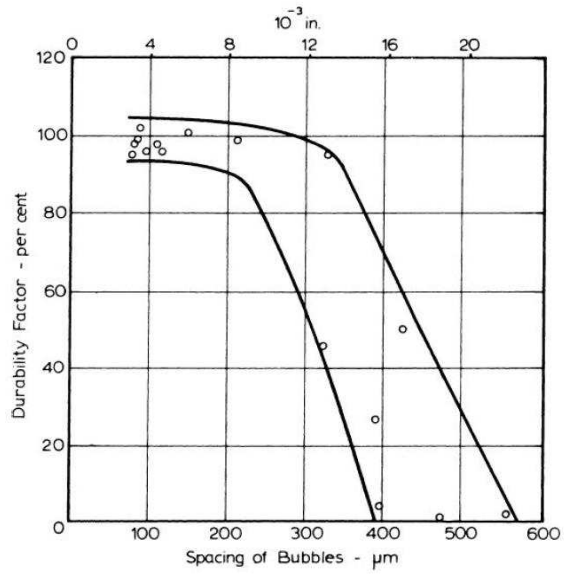

Figure 2.5: The relationship between the durability factor and the spacing between air entrainment bubbles (A. M. Neville, 1995)

2.2.3.2 Water Reducing Admixtures (WRDAs)

Stronger and more durable concrete mix can be achieved by using water reducing admixtures where these admixtures decrease the water/cement ratio in mixtures without increasing the cement content (Chrest, 1996). This action will minimize the concrete permeability which leads to reduce reinforcement corrosion. The water content can be reduced by approximately 5-10% by using WRDA's (Kosmatka, Kerkhoff, & Panarese, 2011).

2.2.3.3 Corrosion inhibitors

A corrosion inhibitor's function is to postpone the initiation of corrosion, minimize the corrosion rate and ideally increase the service life for the structure (P. C. I. P. S. Committee, 1989). The problem of steel corrosion due to the use of deicing salts forms a large percentage and an essential factor for concrete deterioration which might cause structural and financial issues for parking structures (Mammoliti et al., 1999). Corrosion inhibitors are used in concrete to prevent or slow corrosion for unprotected mild steel reinforcement. A comprehensive understanding of the effect of corrosion inhibitors on concrete properties such as strength, workability, air-void content and durability is essential (Hansson, Mammoliti, & Hope, 1998). Corrosion threshold value can be increased by using corrosion inhibitors (Mammoliti et al., 1999). It was suggested that if the chloride/nitrite ratio doesn't exceed 1.5 then Protection from corrosion can be achieved where chloride ions can't dominate the domain and will be suppressed by the existing nitrite supply (Mehta, 1999). Calcium nitrite is an example of corrosion inhibitors that reacts with ferrous ions to protect steel reinforcement (Chrest, 1996). Adding 2% of calcium nitrite by mass can raise the chloride concentration threshold into levels that are high enough to inhibit the corrosion of steel (Mehta, 1999).

2.2.4 Supplementary Cementitious Materials

Environmental concerns of emissions during cement manufacturing besides concrete mixes properties improvement such as strength and durability have led to the use of supplementary cementitious materials such as fly ash, GGBS, HRM, silica fume and other materials (Patil & Kumbhar, 2012).

2.2.4.1 Fly Ash

Fly ash is a very fine material that possess cementitious characteristics and can be used as a partial replacement for cement in concrete mixtures (Chrest, 1996). At early ages, high volume fly ash concrete has strength and durability properties less than Portland cement concrete due to the slow hydration process of fly ash which limits fly ash selection by engineers in concrete mixtures (Li & Zhao, 2003). However, high resistance for water permeation and chloride ion penetration are a remarkable characteristics of high volume fly ash (Mehta, 1999). Using fly ash can enhance some concrete properties such as impermeability and final strength which is desired to increase durability of concrete parking structures (Chrest, 1996). In addition, it can boost the environmental friendliness of concrete where only 6 percent or 25 million tons of fly ash that results as a by-product from the combustion of ground or powdered coal out of a total of 450 million tons has been used in concrete mixtures (Mehta, 1999).

2.2.4.2 Ground Granular Blast Furnace Slag "slag cement" (GGBFS)

GGBS is a byproduct of steel manufacturing which can be used as a concrete admixture (Chrest, 1996). Environmentally friendly is one of the important characteristics of GGBS concrete in comparison with ordinary Portland cement concrete as GGBS requires less energy and produces less greenhouse gases (Teng, Lim, &

Divsholi, 2013). An experimental study has shown that the strength of GGBS concretes at early ages is lower than that for concretes with the same cement content due to the fact of slow pozzolanic reaction and time required for calcium hydroxide to form (Oner & Akyuz, 2007). However, the strength of GGBS concretes will increase over time by extending the curing interval (Oner & Akyuz, 2007). Also, permeability and penetration of chloride ions have been clearly dropped in mortar specimens that contain GGBS as a partial replacement for cement which will decrease corrosion in steel reinforcement and enhance concrete durability (Cheng, Huang, Wu, & Chen, 2005).

2.2.4.3 Silica Fume

Silica fume is a very fine material that improves the concrete mix characteristics such as strength, impermeability and electrical resistivity if added in the right proportions (Chrest,1996). Silica fume is preferable among different supplementary cementitious materials due to its outstanding durability properties (Roy, Arjunan, & Silsbee, 2001). Silica fume works by filling the empty spaces between cement particles that gives low permeability concrete which leads to durability (Chrest, 1996). Silica fume concrete has high density that lower the mix permeability, reduce the chloride penetration and support the durability of the concrete structure (P. C. I. P. S. Committee, 1989). Impermeability of one-year-old silica fume concrete gets to the point where it can give close values of impermeability in comparison with concrete coated with a protective sealer (Chrest, 1996).

2.2.4.4 High Reactivity Metakaolin (HRM)

HRM is a manufactured white powder that has a particle size smaller than cement but larger than silica fume (Chrest, 1996). High compressive strength, low permeability and good workability are some of the properties for concrete made with HRM (Gruber, Ramlochan, Boddy, Hooton, & Thomas, 2001). These properties are major factors that can enhance durability of concrete in parking garages. Experimental tests have showed that replacing 8-12% of cement by mass with HRM reduced the permeability of concrete and increased the concrete resistance for chloride ion penetration (Gruber et al., 2001). Also, increasing HRM content and decreasing w/c ratio for concrete mixes lead to enhance the compressive strength of the mix at all ages and boost the concrete resistance of chloride penetration which will delay reinforcement corrosion (Boddy, Hooton, & Gruber, 2001). In addition, alkali-silica reactivity (ASR) and the risk of its harmful expansion can be reduced by adding 10-20% of HRM into the concrete mixes that contain highly reactive aggregate (Gruber et al., 2001). In comparison, HRM concrete has similar properties to silica fume concrete with less cost (Chrest, 1996).

2.2.4.5 Latex

Latex is an additive that reduces water required to achieve the appropriate viscosity for placement of the mix and produces Latex-Modified Concrete (LMC) (Chrest, 1996). In comparison with conventional concrete, LMC has a denser microstructure which reduces water penetration and improves durability performance of concrete structures as shown in Table 2.2. In addition, LMC prevents corrosion in reinforcement better than conventional concrete and this increase with age where LMC corrosion time increased about 23.9% from 28 days to 90 days test age. However, the increment in corrosion time for conventional concrete was only 4.2% from 28 days to 90 days test age and this is shown below in Table 2.3 (Shaker et al., 1997). From a cost perspective, initial cost of latex-modified concrete is higher than conventional concrete or silica fume concrete but the total cost during the lifetime of the structure should be considered where less repairs are required for LMC structures (Chrest, 1996).

Table 2.2: Test results of water penetration, absorption and sorptivity at different test ages for LMC and conventional concrete (Shaker et al., 1997)

	Test Age (days)	Water Penetration (mm)	Absorption %	Sorptivity (mm/min$^{1/2}$)
LMC	28	12	0.8	0.023
	56	8	0.6	0.014
	90	3	0.4	0.008
Conventional Concrete	28	26	4.3	0.284
	56	22	4.0	0.273
	90	20	3.8	0.239

Table 2.3: Corrosion time at different test ages for LMC and conventional concrete (Shaker et al., 1997)

	Test Age (days)		
	28	56	90
LMC	230	245	285
Conventional Concrete	48	48	50

2.2.5 Reinforcement

2.2.5.1 Cover

Concrete cover in parking garages slabs' is a substantial part of protecting reinforcement from corrosion which boosts the durability of the structure (VanderMeid et al., 1994). According to ACI 318, extra cover above the minimum requirements might be needed to preserve reinforcement in harsh corrosive environments (Chrest, 1996). Recommendations for concrete structures subjected to deicing salts include using a 2-inch cover for cast in place concrete and 1.5-inches for precast concrete (P. C. I. P. S. Committee, 1989). In conclusion, concrete cover increase doesn't guarantee corrosion free reinforcement but it delays the corrosion initiation which extends the service life of the structure (VanderMeid et al., 1994).

2.2.5.2 Epoxy-Coated Reinforcement (ECR)

ECR is used to isolate reinforcement from coming into direct contact with migrated chloride ions carried by water which will reduce the probability of corrosion and increase concrete durability (P. C. I. P. S. Committee, 1989). A disadvantage of epoxy coated prestressed strands is that epoxy don't have a good fire resistance where epoxy melts in relatively low temperatures which can cause bonding problems between concrete and the pre-tensioning strand (VanderMeid et al., 1994). This deterioration in bonding starts for temperatures in the range of 160-180 F. The use of epoxy coated steel in parking garages can add 10-15 years of protection before corrosion starts according to the Concrete Reinforcing Steel Institute and industry users (Mehta, 1999). In contrast, some state departments of transportation don't allow the use of epoxy coated steel due to the fact that they found severely corroded epoxy coated steel in some structures that weren't too old (Chrest, 1996).

2.2.5.3 Galvanized reinforcement steel

Steel coated with metals such as zinc, copper and nickel in order to protect it from corrosion is called galvanizing (S. Yeomans, 2004). Galvanized steel tolerates levels of chloride in concrete 2.5 times the levels that cause corrosion in uncoated steel or black steel (S. R. Yeomans, 1994). Field application supported by experimental data showed that galvanization protects steel from corrosion and therefore cracking of the concrete which improves the durability of the concrete (S. Yeomans, 2004). In addition, galvanized steel has postponed the time taken to initiate corrosion 4 to 5 times in comparison with black steel subjected to the same environmental conditions and in the same concrete (S. R. Yeomans, 1994).

2.2.5.4 Prestressed reinforcement

Prestressed reinforcement is used in concrete to boost the concrete structural and serviceability characteristics. This use increases load capacity and improves cracking control in concrete which will enhance the structure durability (Smith & Virmani, 2000). In pretensioned elements with simple span construction, the main reinforcement will be placed under the centroid of the section which gives the reinforcement a cover of concrete protection of a foot or more (Chrest, 1996). According to ACI, chloride content in prestressed concrete members is limited to be half of that for conventional concrete members to minimize the probability of fracture or failure due to loss of reinforcement cross section in those highly stressed strands in prestressed members (S. Yeomans, 2004).

2.2.5.5 Fiber reinforcement

Synthetic and steel fibers are two types of fiber reinforcement that are used in concrete where each one of them has its own functionality (VanderMeid et al., 1994). In general, fiber reinforcement supports the concrete ability to resist cracks during finishing and curing (Chrest, 1996). Table 2.4 below shows the functionality of each fiber reinforcement.

Table 2.4: Synthetic and steel fibers functionality

Synthetic fiber reinforcement	Steel fiber reinforcement
Adding synthetic fibers to concrete helps in reducing the plastic shrinkage cracks by 80% which will increase the durability of concrete (VanderMeid et al., 1994).	Adding steel fibers to concrete helps in controlling the width of the formed cracks (VanderMeid et al., 1994).
Synthetic fibers can't replace structural welded wire fabric or bars for shear reinforcement (Chrest, 1996).	Steel fibers are used to support flexural strength and impact resistance of concrete (VanderMeid et al., 1994).
Synthetic fibers best performance is gotten at early ages after concrete placing by controlling shrinkage cracks (VanderMeid et al., 1994).	Steel fibers best performance is gotten at both early ages and after concrete sets (VanderMeid et al., 1994).

2.2.6 Construction practices

2.2.6.1 Mixing, Transporting and Placing concrete

Mixing, Transporting and Placing concrete are three practices that can improve the concrete mix strength and durability when they are done correctly. Mixing of concrete by using mixers should be done properly to get the desired mix characteristics that has a uniform distribution for all the components that form the mix (Kosmatka et al., 2011). Mixers should not be overloaded and the mixing speed should follow the manufacturer recommendations. On site, one minute plus 15 seconds of mixing time for each cubic meter of concrete is the minimum requirement for many specifications (Kosmatka et al., 2011). Good mixing process leads to good concrete mixes that is necessary for durability of the structure.

Transporting the concrete mix should be planned in advance to minimize the factors that might affect the quality of the concrete such as delaying, early stiffening, drying out and segregation (Kosmatka et al., 2011). All these factors have a bad effect on the concrete mix durability and strength. Placing of concrete should be preceded by moistening the subgrade in hot weather to reduce the water drawn from the concrete mix that can cause cracks in the future and affects the concrete durability. In contrast, concrete will be placed on frozen subgrade in cold weather and the site should be cleaned from debris before placing concrete (Kosmatka et al., 2011).

2.2.6.2 Formwork for Concrete

Concrete formwork should prevent paste loss from the hardened concrete which will require repairs (Chrest, 1996). This can be done by building the formwork to be tight enough. For wood formwork, it is recommended to be oiled to easily release the formwork without causing damage into concrete (Kosmatka et al., 2011). Concrete formwork should be cleaned from cigarette butts, papers and other dirt before pouring the concrete because they might affect the concrete mix properties and durability (Chrest, 1996). In addition, concrete formwork will absorb some of the moisture of the concrete mix if the formwork wasn't moistened which affects w/c ratio, hydration process completion and might cause cracks in the structure (Kosmatka et al., 2011).

2.2.6.3 Consolidation

Consolidation is the process of compacting fresh concrete that is used to reduce the quantity and size of trapped air voids (Kosmatka et al., 2011). This operation can increase the durability of the concrete mix if it is done properly where under vibrating and over vibrating are common mistakes with consolidation that make the concrete less durable (Chrest, 1996). Consequences of improper consolidation include honeycomb which is shown in Figure 2.6 , sand streaking which is shown in Figure 2.6, cold joints and other defects depending on the situation of under vibrating or over vibrating that give poor durability concrete (A. C. I. Committee).

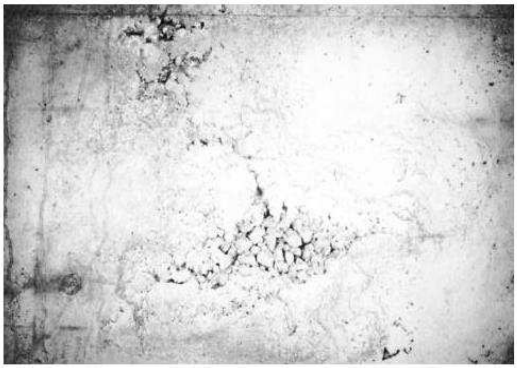

Figure 2.6: Honeycomb (A. C. I. Committee)

Figure 2.7: Sand streaking (A. C. I. Committee)

2.2.6.4 Finishing

Finishing shouldn't be overdone because this practice will force entrained air to leave the concrete surface and be replaced with paste and fine (Chrest, 1996). This practice negatively affects the durability of the concrete mix. In addition, finishing shouldn't drive out all the water on the concrete surface where it is needed in hydrating the cement on the surface (P. C. I. P. S. Committee, 1989).

2.2.6.5 Curing

Permeability and the possibility for shrinkage cracking can be reduced by using proper curing techniques that increase the durability of the structure. Burlap for cast in place concrete and heat curing for precast concrete had shown good results in minimizing chloride penetration into the concrete (VanderMeid et al., 1994). According to AASHTO, heat cured concrete with 0.46 w/c ratio has less surface chloride concentration in comparison with 0.46 w/c ratio of moist cured concrete (P. C. I. P. S. Committee, 1989).

2.3 Exterior Protection Systems

2.3.1 Sealers

Sealers are protective coatings that are used to minimize moisture absorption rate and chloride penetration in concrete surfaces by making concrete less permeable in which boost concrete durability (VanderMeid et al., 1994). The service life of concrete surfaces can be extended by using sealers. However, bridging cracks can't be accomplished by using sealers (Chrest, 1996). In general, Sealers can be categorized into two groups :Penetrants and surface sealers (P. C. I. P. S. Committee, 1989). Concrete surfaces that sealers are applied to should be prepared and cleaned by sand blasting, shot blasting or high pressure water blasting so sealers can work properly (VanderMeid et al., 1994). The initial cost for sealers is relatively low and they can be reapplied every 3-5 years when it is necessary (Chrest, 1996).

2.3.2 Membranes

Membranes are used to prevent moisture and waterborne salts from invading the underlying concrete which will minimize corrosion and enhance the durability of the parking structure (Chrest, 1996). Membrane systems can be divided into two types: traffic bearing membranes and non-traffic bearing membranes. Unlike sealers, bridging narrow cracks is an important property for traffic bearing membranes (VanderMeid et al., 1994). Inspecting and repairing traffic bearing membranes is required periodically to ensure that the system is working properly (P. C. I. P. S. Committee, 1989). On the other hand, non-traffic bearing membranes are harder to inspect and repair due to their construction where removing the protection layer especially if it was cast-in-place concrete is very difficult (Chrest, 1996). The initial cost for membranes is relatively high and they can be reapplied every 10-15 years when it is necessary (Chrest, 1996).

2.4 Brief history of Life-365 software

There was some confusion among the engineering community in the 1990s when many models used to predict service life for concrete structures exposed to chloride and calculate Life Cycle Cost (LCC) for various protection strategies had significant differences in their results (Thomas & Bentz, 2013). Therefore, the need for developing a new standard model was raised and the American Concrete Institute (ACI) took that step by starting a workshop for this purpose. In addition to ACI sponsorship, the National Institute of Standards and Technology (NIST) and the American Society for Testing and Materials (ASTM) sponsored the workshop. This workshop lead to constructing a consortium that was funded by some industry figures such as Silica Fume Association and Master Builders Incorporated (Ehlen, Thomas, & Bentz, 2009). The product of this consortium was the software Life-365 version 1.0 in 2000 that was updated with additional versions in subsequent years. Life-365 version 2.2.2 is used in this study and it was released in 2015. This software has the capabilities to predict the service life and LCC over the entire design life for different structures that are exposed to chloride from ambient environment especially decks in parking garages and bridges (Ehlen et al., 2009). In Life-365 software, the estimated service life period has two components: the initiation period and the propagation period. In addition, LCC is calculated as the sum of approximate cost for construction at the beginning of the project, external protection strategies (Barriers) and future repair costs.

3 METHODS

Parking structures' durability design, as well as structural design, should be evaluated. There are many factors that contribute to the durability of reinforced or prestressed concrete elements and structures including the concrete mix, the reinforcement, and external treatments. The focus of this study will be about investigating the effects of different design variables on Life Cycle Cost (LCC) of a slab element through different alternatives in multiple cases. In addition, the contribution of each design variable for durability of the slab is examined. The design variables include using various water/cementitious materials ratios in the concrete mixtures. Using different cementitious materials that include Supplementary Cementitious Materials (SCMs) such as fly ash "Class F", slag cement and silica fume in addition to Portland cement from a recommended dosage range. Also, examining the effects of using different concrete covers and different types of barriers and reinforcement on the estimated service life and life cycle cost of a slab in a parking structure will be conducted. This focus will help owners and designers of these structures to look at different life cycle costs scenarios that would be spent during the design life of a slab at a parking structure and will help the owners to allocate their resources.

Service life is the period of time between construction and first repair while life cycle cost is the sum of construction cost, barrier cost and repair cost (Thomas & Bentz, 2013). More details about service life estimation and life cycle cost will be discussed later in section 3.1 and section 3.2. Life-365 software was used as an analysis tool to conduct this study on a reinforced concrete slab element in a parking structure to predict the service life and life cycle cost when it is exposed to chlorides. Life-365 software emerged as the need for a model that is used to evaluate service life and life cycle cost in concrete structures ,specifically parking structures and bridges elements, had been raised (Violetta, 2002). A concrete service life workshop that had been sponsored by the American Concrete Institute (ACI), the National Institute of Standards and Technology (NIST) and the American Society for Testing and Materials (ASTM) started the work of finding and developing this software (Ehlen & Kojundic, 2014).

The slab section that is used in this study is shown in Figure 3.1 where the chloride ingress is 1D (one dimensional) through the slab thickness as it was assumed in the software manual (Thomas & Bentz, 2013). The rebar size is not defined in the slab sections in Life-365 software. All sizes will corrode after the chloride threshold concentration is reached on the rebar surface and chloride will disrupt the protective passive layer to initiate corrosion.

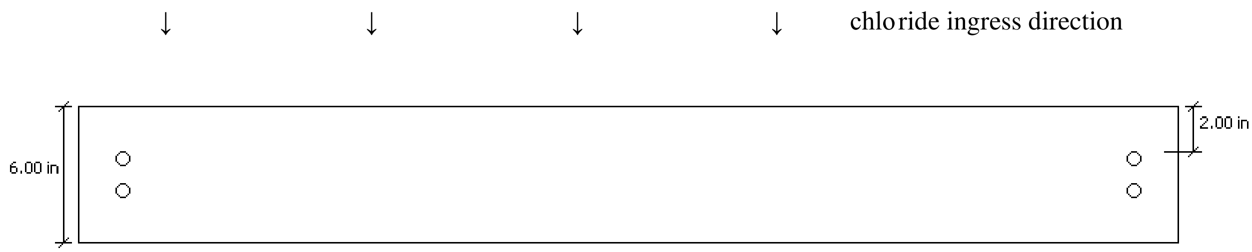

Figure 3.1: Life-365 model for a reinforced concrete slab in a parking structure

Parking structure's slabs are horizontal elements that can potentially be penetrated by seawater and deicing salts, which have chloride ions, through the concrete surface that can result in corrosion of embedded steel. Therefore, evaluating the durability and cost associated for different alternatives that can be used in slabs are important for the integrity of the whole parking structure.

3.1 Service life estimation

The service life for concrete structures is a measure of their durability. Deterioration in reinforced concrete parking structures exposed to chloride from deicing salts, groundwater and seawater is the main reason for reducing their service life due to embedded reinforcement corrosion (Thomas & Bentz, 2013). The period of time between construction and first repair or any unacceptable damage is called service life (Thomas & Bentz, 2013). This period consists of the following two phases: initiation period and propagation period as shown in Figure 3.2.

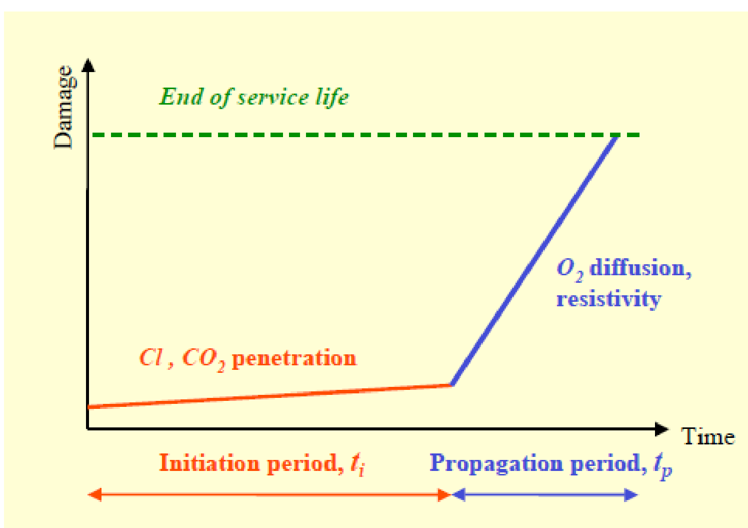

Figure 3.2: Concrete service life periods (Thomas & Bentz, 2013)

3.1.1 Initiation period

It is the period of time that an adequate chloride quantity needs to penetrate the concrete cover and reach to the embedded steel level and start to accumulate in an adequate quantity until it reaches the limit or the concentration that would initiate corrosion in steel (Thomas & Bentz, 2013). Equation 3.1, which represents Fick's second law and the governing differential equation, can be solved using the Crank Nicolson finite difference approach to find the initiation period of service life (Thomas & Bentz, 2013).

$$\frac{dC}{dt} = D.\frac{d^2 C}{dx^2} \qquad \text{Equation 3.1}$$

Where "C" is the chloride content, "D" is the apparent diffusion coefficient, "x" is the depth of from the exposed surface and "t" is time. There are many factors that would affect the length of this period such as the ambient environment, type of the structure, quality and cover of concrete, type of barriers and the chloride threshold concentration which would be affected by the steel type and the use of corrosion inhibitor or not (Violetta, 2002). These factors are required as an input to the software so the model can choose the necessary modeling coefficients to use in solving Equation 3.1 such as the diffusion coefficient "D" which is a function of both temperature and time. More details about the input factors and the modeling parameters (modeling coefficients) are shown in section 3.3.

3.1.2 Propagation period

The period of time that corrosion needs to progress to cause unacceptable damage that needs to be repaired is called the propagation period (Thomas & Bentz, 2013). This period is assumed to be fixed, 6 years, by the software when black steel or stainless steel is used while epoxy-coated steel is the only factor that would extend this period to 20 years. Temperature, moisture content and the quality of concrete are some factors that affect the propagation period but the current version of Life-365 assumes it as a fixed value and depending on reinforcement type.

3.2 Life Cycle Cost Analysis (LCCA)

Billions of dollars are spent to rehabilitate and replace deteriorated concrete infrastructures due to corrosion damage in the United States every year (Violetta, 2002). Many strategies that have different costs have been implemented during the construction phase in parking structures to increase their service life and reduce costs associated with the repair phase. Life cycle cost in Life-365 software is the sum of the estimated initial construction costs such as concrete mixtures and reinforcement, protection costs such as barriers and future repair costs during the service life of the concrete structure (Thomas & Bentz, 2013). The process of estimating life cycle costs in Life-365 requires the following inputs from the user:

- The costs for concrete mixtures that are used in the analysis, cost of reinforcement, cost of barriers and corrosion inhibitors, cost for repair and the fixed time period to conduct repair after carrying out the first repair which helps in calculating repair's schedule and future repair costs (Thomas & Bentz, 2013).
- For the year of the analysis, real discount rate that represents the time value for money and inflation rate that represents the annual increase rate for goods and services costs in the future.
- A base year and a study period for the analysis.

Life-365 calculates the costs in a discounted present value. First, all costs should be inflated to the future by using the annual inflation rate. Second, each future inflated cost would be discounted to the present value or the analysis year using the nominal discount rate that represents the combined effects of inflation and real discount rates. Concrete mixtures costs should be calculated as ($/cubic yard) of concrete including all SCM's prices and will be inputted to the software as a one unit. Reinforcement costs are calculated in ($/lb.), barriers and repair costs are calculated in ($/sq.ft) and corrosion inhibitors costs are calculated in ($/gallon) and all these prices are inputted individually. Life-365 graphs show the costs by phases like construction costs, barrier costs if it was applied and repair costs which would give a life cycle cost comparison between different alternatives for each phase. Finally, costs that are calculated in LCCA can be obtained as a total amount of dollars for the concrete volume analyzed or costs can be obtained as dollars per unit of surface area or dollars per unit of concrete volume.

3.3 Project data

3.3.1 Analysis parameters and modeling parameters

Life-365 software requires the following analysis parameters for this study that include the parking structure's slab dimensions, concrete cover distance to the embedded steel and the economic parameters.

- The structure element type that was investigated is a 1D slab with a total thickness of 0.5 ft., total surface area of 10000 ft^2 and a concrete volume of 185.2 yd^3.
- Two different clear concrete covers of 2 in. and 2.5 in. will be used in this study (Committee). More details about design variables to be examined beside the concrete cover in the parking structure's slabs are discussed in section 3.3.3.

The economic parameters are:

- The base year for the analysis was chosen as 2015.
- The analysis period was taken as 100 years (Ehlen, Thomas, & Bentz, 2009).
- The inflation rate was taken as 2 % and the real discount rate was taken as 1.4% for the year of 2015. These values were chosen based on suggested rates from Office of Management and Budget (OMB) for long term analysis (Lavappa & Kneifel, 2015) which was recommended in the software manual (Thomas & Bentz, 2013).

The modeling parameters that were used in the analysis are as follows:

- Diffusion coefficient (D_t): It is a material property that is either a default value determined by Life-365 depending on the concrete mixture proportions provided by the user or can be inputted directly by the user after conducting ASTM C1556 test and collecting the data (Thomas & Bentz, 2013). The diffusion coefficient at any time is a function of both time dependent and temperature dependent changes in diffusion (Thomas & Bentz, 2013). The coefficient is affected by the change in w/cm ratio and silica fume percentage at 28 days. The diffusion coefficient in 28 days can be calculated using Equation 3.2 below if only w/cm ratio change and both Equation 3.2 and Equation 3.3 if both w/cm ratio and silica fume percentage change (Thomas & Bentz, 2013).

$$D_{28} = 1*10^{(-12.06+2.40*w/cm)} \qquad \text{Equation 3.2}$$

$$D_{SF} = D_{PC}*e^{-0.165*SF} \qquad \text{Equation 3.3}$$

Where D_{SF} is the diffusion coefficient at 28 days when silica fume is present in the concrete mix, D_{PC} is the diffusion coefficient at 28 days for Portland cement as calculated from Equation 3.2 and SF is the percentage of silica fume in the concrete mixture. For example, the diffusion coefficient value for the base mix, which has no SCM's, when w/cm=0.3 and silica fume percentage is zero can be calculated using Equation 3.2 as follows:

$D_{28} = 1 \text{ x } 10^{(-12.06 + 2.40*0.3)} = 4.57*10^{-12}\ m^2/sec = 7.08*10^{-9}\ in^2/sec$

Equation 3.4 is used to account for time dependent changes:

$$D(t) = D_{ref}.\left(\frac{t_{ref}}{t}\right)^m \qquad \text{Equation 3.4}$$

Where D (t) is the diffusion coefficient at a specific time (t), "D_{ref}" is the diffusion coefficient at a reference time (t_{ref}= 28 days in Life-365.) and "m" comes from Equation 3.6.

While Equation 3.5 is used to account for temperature dependent changes:

$$\mathrm{D(T)} = \mathrm{D_{ref}}.\exp[\frac{\mathrm{U}}{\mathrm{R}}.(\frac{1}{\mathrm{T_{ref}}} - \frac{1}{\mathrm{T}})] \qquad \text{Equation 3.5}$$

Where D(t) is the diffusion coefficient at time "t" and temperature "T", "D_{ref}" is the diffusion coefficient at time "t_{ref}" and temperature "T_{ref}", U is the activation energy of the diffusion process (35000 J/mol), R is the gas constant and "T" is the absolute temperature. t_{ref} is 28 days and T_{ref} is 20^{o} C in the model. The value of "D" in Equation 3.1 is modified at every time step using Equation 3.4 and Equation 3.5.

- <u>Diffusion decay index (m):</u> it is a material property that describes the time dependent changes in the diffusion coefficient because of the continued hydration of the concrete (Thomas & Bentz, 2013). This value can be set as a default value calculated by Equation 3.6 in Life-365 depending on concrete mix proportions that are provided by the user or can be input directly by the user. In addition, Life-365 assumes that hydration of all cementitious materials will occur over 25 years and after that, the time dependent effects of "m" will not influence the diffusion coefficient and the coefficient will stay constant. This diffusion decay index is affected by the presence of fly ash "Class F" and slag cement in the concrete mixture. This index is dimensionless and can be calculated by using Equation 3.6 below.

$$\mathrm{m} = 0.2 + 0.4\,(\frac{\%\ \mathrm{FA}}{50} + \frac{\%\ \mathrm{SG}}{70}) \qquad \text{Equation 3.6}$$

For example, for the base mix when fly ash "Class F" and slag cement percentages are zero:

m = 0.2 + 0.4*(0/50 + 0/70) = 0.2

- <u>Chloride threshold (C_t)</u>: This input represents the chloride concentration required to initiate corrosion in the steel reinforcement that is embedded in concrete (Thomas & Bentz, 2013). This value can also be set as a default value by Life-365 or can be input directly by the user. The chloride threshold concentration is affected by the use of different quantities for corrosion inhibitors as shown in Table 3.1 below or using stainless steel as reinforcement. The chloride threshold value is fixed in this study and equal to 0.05 % wt. concrete.

Table 3.1 : Effects of Calcium Nitrite Inhibitor on C_t (Thomas & Bentz, 2013)

Calcium Nitrite Inhibitor		Chloride threshold concentration Ct
liters/m^3	gal/yd^3	(% wt. concrete)
0	0	0.05
10	2	0.15
15	3	0.24
20	4	0.32
25	5	0.37
30	6	0.40

The values for diffusion coefficient and diffusion decay index as modeling parameters would vary for different alternatives that will be investigated depending on proportions for SCMs in a concrete mixture and w/cm ratio. For example, Figure 3.3 below shows the relationship between the diffusion coefficient and w/cm ratio at 20°C which was determined by conducting many diffusion tests to establish the software database (Thomas & Bentz, 2013).

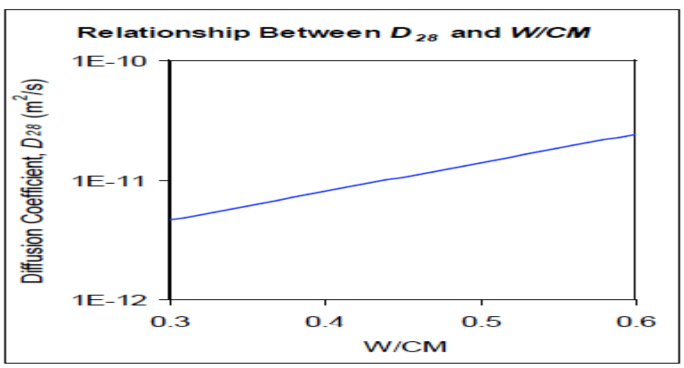

Figure 3.3: Relationship between D_{28} and w/cm (Thomas & Bentz, 2013)

3.3.2 Location, Temperature and Chloride surface concentration Data

Concrete structures' geographic location is a major factor for their durability performance. The importance of geographic location is that it plays a main role in defining the temperature changes that would occur during the year which would affect the estimated service life through determining the diffusivity coefficient and the rate of corrosion (Thomas & Bentz, 2013). Besides that, the surface chloride concentration (C_s) , which represents the chloride concentration at the surface of concrete, that would penetrate the concrete cover and cause corrosion for the embedded reinforcement steel is affected by the concrete structure's geographic location (Violetta, 2002). In Life-

365 software, the user can define the monthly temperature profile and the chloride surface concentration profile for their region in any part of the world if it was not available in the software database (Thomas & Bentz, 2013).

The location for this parking structure was chosen as Denver, Colorado. The severe weather in this city during winter seasons would expose the parking structure to a lot of snow that is falling directly into it or carried in on the underside of the vehicles that park there (VanderMeid et al., 1994). In addition, using deicing salts to prevent snow from accumulating and helping melt could have detrimental effects on the parking structure where these salts can penetrate the slab surface and may cause corrosion to the embedded reinforcement (Portland Cement, 2002). In the exposure zones shown in Figure 3.4, Denver can be seen within zone III where deicing salts are commonly used and corrosion is likely to occur (VanderMeid et al., 1994). Depending on this location and the software database where the temperature history was collected, the monthly temperature profile for Denver, Colorado is shown in Figure 3.5. In addition, the surface chloride concentration (C_s) was calculated based on a build up rate of (0.06 % / year) and a maximum concentration of (0.8 % wt.concrete.) as shown in Figure 3.6. These values for calculating C_s represent the default values in Life-365 for this specific geographic location and type of structure (Thomas & Bentz, 2013).

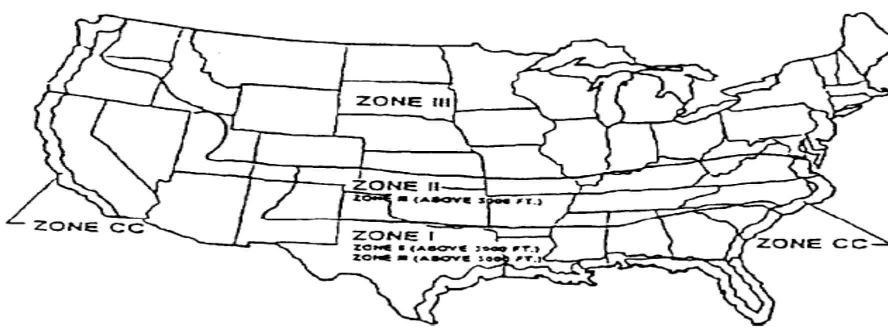

Figure 3.4: Exposure zone map (VanderMeid et al., 1994)

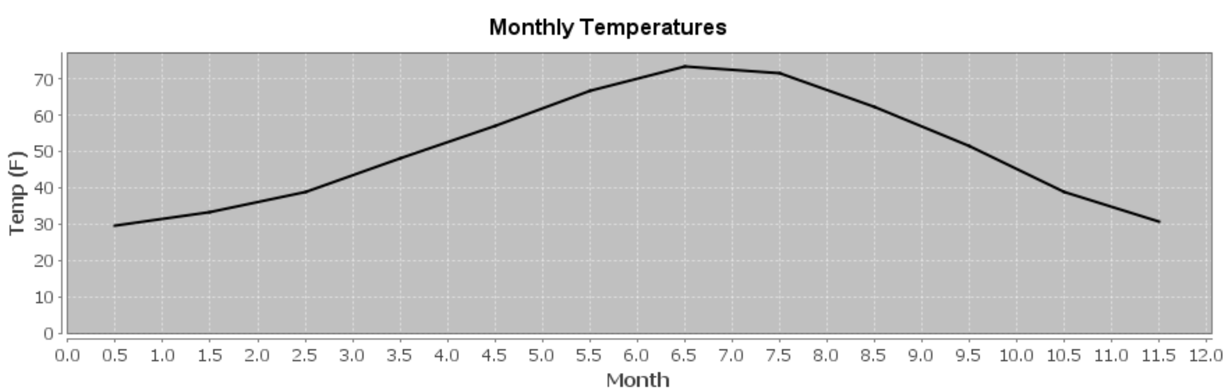

Figure 3.5: Monthly temperature profile for Denver, Colorado (Life-365 software database)

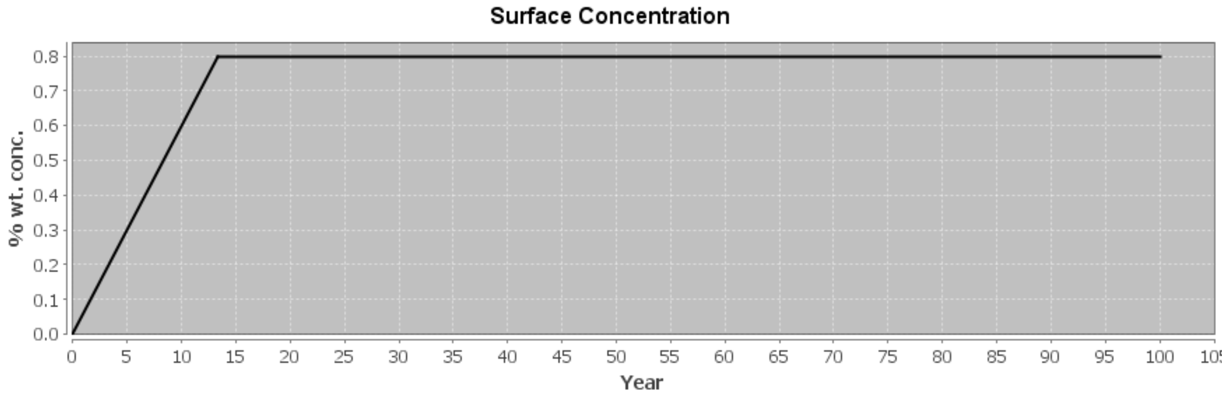

Figure 3.6: Chloride surface concentration profile along the study period (Life-365 software database)

3.3.3 Concrete slab materials, repair and cost

The effects of barrier type, reinforcement type and supplementary cementitious materials which include fly ash" class F", slag cement and silica fume on the estimated service lives and life cycle cost for a parking structure's slab will be investigated in this study. Besides that, changing the concrete cover distance and changing the w/cm ratio will be investigated. In general, seven cases will be addressed in this study. Cases 1, 2, 3 and 4 possess two concrete covers, each with two different w/cm ratios. Table 3.2 summarizes the design variables in each of the first four cases in this study. All design variables for case 1 are considered in Table 3.3 for each alternative with SCMs percentages, reinforcement type, barrier type, w/cm ratio and the concrete cover as an example for the first four cases. The exception with cases 2, 3 and 4 is varying the concrete cover distance and changing the w/cm ratio. An alternative represents a concrete mixture with reinforcement embedded in it and an applied barrier. A detailed design example for concrete mixtures' proportioning is shown in appendix A.

Table 3.2: Variables for analysis cases 1, 2, 3 and 4

Design variable	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Concrete cover	2 in.	2 in.	2.5 in.	2.5 in.
W/CM ratio	0.3	0.34	0.3	0.34
Silica fume	5% in mix# 2,5,6	5% in mix# 2,5,6	5% in mix# 2,5,6	5% in mix# 2,5,6
Slag cement	35% in mix# 3,6	35% in mix# 3,6	35% in mix# 3,6	35% in mix# 3,6
Fly ash "Class F"	20% in mix# 4,5	20% in mix# 4,5	20% in mix# 4,5	20% in mix# 4,5
Membrane	Used "all alternatives"	Used "all alternatives"	Used "all alternatives"	Used "all alternatives"
Sealer	Used "all alternatives"	Used "all alternatives"	Used "all alternatives"	Used "all alternatives"
Epoxy-coated steel	Not used	Not used	Not used	Not used

Table 3.3: SCMs, reinforcement and barriers for case 1

		Supplementary Cementitious Materials "SCM's"			Reinforcement	Barrier
	Alternative or Mix #	**Fly ash "Class F" %**	**Slag Cement %**	**Silica Fume %**	**Black Steel "B"**	**Membrane or Sealer "M or S"**
Case 1 *Concrete cover =2 in. *w/cm=0.3	1-Base mix	0	0	0	B	M or S
	2	0	0	5	B	M or S
	3	0	35	0	B	M or S
	4	20	0	0	B	M or S
	5	20	0	5	B	M or S
	6	0	35	5	B	M or S

Table 3.4 summarizes the design variables in cases 5, 6 and 7.

Table 3.4: Variables for analysis cases 5, 6 and 7

Design variable	**Case 5**	**Case 6**	**Case 7**
Concrete cover	2	2	2
W/CM ratio	0.3	0.3	0.3
Silica fume	Not used	5% in mix# 1, 2	5% in mix# 1, 2
Slag cement	Not used	35% in mix#3, 4	35% in mix#3, 4
Fly ash "Class F"	Not used	20% in mix#5, 6	20% in mix#5, 6
Membrane	Used "in alternatives 3,4"	Used "in alternatives 2,4,6"	Not used
Sealer	Used "in alternatives 5,6"	Used "in alternatives 2,4,6"	Not used
Epoxy-coated steel	Used " in alternative 2"	Not used	Used "in alternatives 2,4,6"

Each of these cases included six different alternatives. Using a High Range Water Reducer (HRWR) minimized the w/cm ratio for all mixtures, which is desirable to increase the concrete strength and reduce its permeability and the diffusion coefficient. Besides that, increasing the concrete cover would increase the time needed by chloride to reach the upper reinforcement which would delay the process of corrosion initiation.

3.3.3.1 Supplementary Cementitious Materials (SCMs)

SCMs ratios were chosen from a recommended dosage range that will improve the concrete mix permeability and strength without exceeding the maximum limit for SCMs content in a mix (Kosmatka, Kerkhoff, & Panarese, 2011). Concrete mixtures' durability can be improved by using SCMs. The use of fly ash "Class F" and slag cement in concrete mixtures increase the long-term mix strength (Oner & Akyuz, 2007). Besides that, reducing the mix permeability that will minimize the chloride percentage to penetrate the concrete cover and postpone corrosion initiation in the embedded reinforcement in slabs (Cheng, Huang, Wu, & Chen, 2005). In addition, silica fume concrete mixtures have a high density where silica fume fills the empty spaces between cement particles which helps in reducing the mixture permeability (Chrest, 1996). SCMs affect the diffusion coefficient and the diffusion decay index.

These concrete mixtures were not mixed neither tested their strength in a laboratory where they were designed using hand calculations only. It is intended to evaluate the effects for each of these SCMs individually and how they influence the service life and life cycle cost for the reinforced concrete slab in a parking structure using Life-365. After that, a combination of these SCMs effects would be checked to recognize how these SCMs work with each other and if they are compatible.

3.3.3.2 Reinforcement

In reinforced concrete parking structures, corrosion of steel reinforcement is the main problem that faces parking structures and negatively affects their durability (Portland Cement, 2002). Chloride can penetrate concrete cover and start to accumulate at the upper embedded reinforcement level in parking structures' slabs and initiate corrosion once the chloride threshold concentration has been achieved. In precast/prestressed concrete structures and elements, there are two types of reinforcement. First, an upper steel reinforcement that is used to resist shear and shrinkage forces and this reinforcement would be less influenced by corrosion where good quality concrete mixtures have more strength and lower permeability where they were cast in more controlled conditions (Smith & Virmani, 2000). Second, a prestressed strand reinforcement that has an adequate concrete cover above it where it is located more than one foot below the concrete surface (Chrest, 1996). Life-365 is used to analyze the reinforced concrete slab. The type of reinforcement affects the chloride threshold concentration, which is necessary to initiate corrosion, and the propagation period in service life.

In this study, the use of black steel and epoxy-coated steel in different alternatives are investigated. The use of black steel in Life-365 model assume a propagation period of 6 years (Weyers, 1998; Weyers et al., 1994). In contrast, the use of Epoxy-coated steel can lower the rate of damage build up and this can be seen in the corrosion propagation period that increased into 20 years (Thomas & Bentz, 2013). However, the damage of epoxy steel coating during fabrication or transportation may cause significant localized corrosion in it (Yeomans, 1994). Life-365 does not consider any changes for the value of propagation period due to the possibility of using a damaged epoxy-coated steel.

3.3.3.3 Barriers

Sealers and membranes are moisture barriers that are used to minimize the amount of chloride dissolved in water or melted snow from penetrating the concrete surface and causing corrosion to the embedded reinforcement (Litvan, 1996). Both sealers and membranes have the ability to extend the service life of concrete structures. However, membranes have the capability of bridging narrow cracks while sealers don't have this capability (VanderMeid et al., 1994). In Life-365 software, membranes and sealers are used in the model as two types of exterior protection systems and they affect the chloride build-up rate only at the concrete surface and can only reapplied up to the time of first repair (Thomas & Bentz, 2013). Figure 3.7 shows the effects of both membranes and sealers.

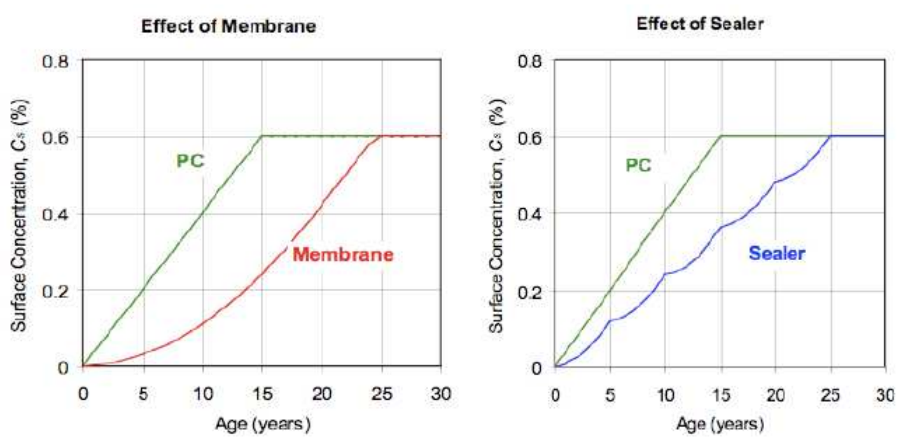

Figure 3.7: Effect of membranes and sealers on the chloride concentration at the concrete surface (Thomas & Bentz, 2013)

3.3.3.4 Repair

Embedded reinforcement corrosion is one of the biggest sources of parking structures' deterioration. Steel corrosion increases the original volume of steel embedded in concrete which applies tensile stresses on concrete that can't be resisted and this leads to scaling, delamination and cracking (Portland Cement, 2002). These defects in concrete need to be repaired periodically. In Life-365, the time for first repair is defined as the sum of the following two periods: initiation period and propagation period (Thomas & Bentz, 2013). Life-365 requires the user to estimate the cost of repair in $/ft^2, the percentage of the area to be repaired and a fixed interval between future repairs. It has been assumed that 10% of the area need to be repaired every 10 years (Ehlen et al., 2009).

3.3.3.5 Costs

The costs for concrete mixtures, reinforcement, barriers and repairs are presented below. Costs and quantities for concrete mixture #5 are summarized in Table 3.5 while a detailed example of determining the proportions of a concrete mixture is shown in appendix A. Costs for other concrete mixtures are summarized in Table 3.6. A feature of Life-365 software is that it gives the user the ability to switch between SI and US units. The concrete mix proportions and costs calculations were done using SI units then the last cost value had been changed into US units since the study is discussing a project in the US. Water and air-entraining agents costs were neglected due to the fact that the total volume for the concrete mix in this study is small.

Materials' costs for the concrete mixture were obtained from Mr.David Figurski from Brannan Sand and Gravel Companies at Denver, Colorado while Mr. Matthew McMeeking from Encon Corporation at Denver, Colorado provided other materials' cost such as reinforcement and barriers as shown in Table 3.7. All materials costs are approximate, and this study is intended to show the relative impact of different design decisions rather than provide exact costs.

Table 3.5: Concrete mix cost calculations (Case 1, w/cm=0.3, Mix #5)

Materials	**Percentage "%"**	**Quantity "Kg"**	**Specific Gravity**	**Volume "m^3"**	**Cost "$/metric ton"**	**Cost "$"**
Cement	75	360	3.14	0.114	143	51.48
Fly Ash class F	20	96	2.6	0.0369	66	6.336
Slag Cement	0	0	2.9	0	50	0
Silica Fume	5	24	2.3	0.0104	990	23.76
Coarse Aggregate		992	2.68	0.37	18	17.8
Fine Aggregate		691.28	2.64	0.2618	12	8.29
Water		144	1	0.144	Neglected	0
HRWR		1.992	1	0.001992	3170	6.31
Air Entraining		0.24	1	0.00024	Neglected	0
Air	6			0.05976	0	0
Sum				1		114 for 1 m^3 **Or** 87.2 for 1 yd^3

Table 3.6: Concrete mixtures costs for w/cm=0.3 and w/cm=0.34

Supplementary Cementitious Materials "SCMs"			**Cost ($/$yd^3$)**	
Fly ash "Class F" %	**Slag Cement %**	**Silica Fume %**	**w/cm=0.3**	**w/cm=0.34**
0	0	0	76.8	70.1
0	0	5	93.8	85.1
0	35	0	65.5	60.1
20	0	0	71.8	65.7
20	0	5	87.2	79.4
0	35	5	81	73.2

Table 3.7: Reinforcement, Barriers and Repair Costs

Material	cost	
	$/lb	$/Sq.ft
Black Steel	0.55	
Epoxy-coated steel	0.8	
Membrane		2.15
Sealer		0.58
Repair		27

3.4 Software capabilities

The software is capable of predicting service life and calculating Life Cycle Cost in a deterministic analysis as explained before at the beginning of chapter 3. In addition to deterministic analysis, uncertainty analysis can be conducted in Life-365. Uncertainty analysis estimates the probability density function of corrosion initiation period by varying these parameters: diffusion rate at 28 days, the diffusion decay index, the maximum surface chloride concentration, the chloride threshold concentration of steel and the clear concrete cover to the reinforcement (Thomas & Bentz, 2013). The diffusion rate and the diffusion decay index are related to concrete mix proportions and w/cm ratio while the maximum surface chloride concentration is related to the geographic location, type of structure and the nature of exposure. This uncertainty in initiation period can be used to calculate the effects on Life Cycle Cost “LCC”. In addition, uncertainty in economic parameters such as the inflation rate and the real discount rate over the study period can be accounted for in Life-365. The software assumes a log-normal distribution for time to corrosion initiation for uncertainty analysis. Besides that, the software is capable of generating an initiation variation graph for uncertainty where the graph shows the effects of each of the above parameters on uncertainty of the initiation period. Deterministic analysis is used in conducting this study to examine a large number of scenarios with various protection systems that can be implemented to enhance the service life and lower the life cycle cost. After that, uncertainty analysis can be used in future research to delve deeper about the best protection systems and scenarios that were obtained through deterministic analysis, which would allow decision-makers to optimize their choices.

3.5 Software limitations

Life-365 software has some limitations incorporated into its design and development. The software’s assumptions, which lead to the limitations, were made to simplify sophiticated phenomena that describe actions necessary in the process of corrosion for embedded steel that is exposed to chloride. For example, it is assumed that diffusion is the dominant mechanism for chloride ingress into concrete and that ionic diffusion is the only mechanism of chloride transport to predict corriosn initiation where ions move from higher to lower concentrations (Thomas & Bentz, 2013). In addition, the use of a single value for the chloride threshold concentration is a limitation. It is assumed that no corrsion occurs below the threshold and corrsion is initiated above it. The relationship between corrosion and chloride content is affected by many parameters such as the pore structure of the concrete and the moisture content and temperature inside the concrete, meaning a single threshold value is a major approximation. Also, it is assumed that barriers affect the chloride built-up rate only at the concrete surface and do not prevent or minimize water-soluable chlorides from penetrating the concrete. This assumption of barriers will not show the real effects of using or reapplying barriers on extending service life. Therefore, the cost of preventive maintenance as part of the life cycle cost will not be accurate because reapplying of barriers is not delaying repair times as they should. Besides that, it is assumed that the propagation period is a fixed length of time, depending on the reinforcement type, despite the fact that is depends on many parameters such as the concrete quality (Thomas & Bentz, 2013). The reason for these assumptions or limitaions is that these topics are not completely researched or understood, and there is a lack of knowledge and data/model validation (Thomas & Bentz, 2013). Limitations in the model mean that service life predictions and life cycle costs are approximate and not definitive values. The relative change in values can be investigated to develop a better understanding of how different Supplementary Cementitious Materials (SCMs) and protection strategies impact LCC and service life.

4 RESULTS AND DISCUSSION

This chapter presents and discusses the findings for service life estimation and life cycle cost of a slab element meant to represent the top of a parking garage t-beam. Various cases with different design variables are considered, including changes in concrete cover, w/cm ratio, SCMs percentages, barriers used and reinforcement type. Complete results for all analyses are presented in Appendix B.

4.1 Service life estimation

The estimated service life is the sum of the initiation period and the propagation period. These two periods are defined in section 3.1 in chapter 3. At the end of the estimated service life period, the repair phase begins and extends for the rest of the analysis period, 100 years for all cases. The service life of a reinforced or prestressed concrete slab is affected by the design variables identified in

Table 3.2 and Table 3.4. In the following sections, a selection of directly relevant results for estimated service life for each design variable are shown and discussed. Besides that, the effect of individual design variables on the estimated service lives is presented.

4.1.1 Concrete cover

The concrete cover distance was the first variable changed to investigate its effect on the estimated service life of the reinforced concrete slab. An increase in the lifetime of a slab with a concrete cover of 2.5 in. over a slab with a concrete cover of 2 in was observed for all of the analyses conducted. Figure 4.1 presents a sample that shows the effect of concrete cover on the estimated service lives where all variables are fixed except concrete cover distance. The comparison is between alternatives 2 and 4 in case 1 that has a concrete cover of 2in. and case 3 that has a concrete cover of 2.5in. The fixed variables are w/cm ratio of 0.3, concrete mixtures' proportions, the reinforcement type is black steel and the barrier type is membrane.

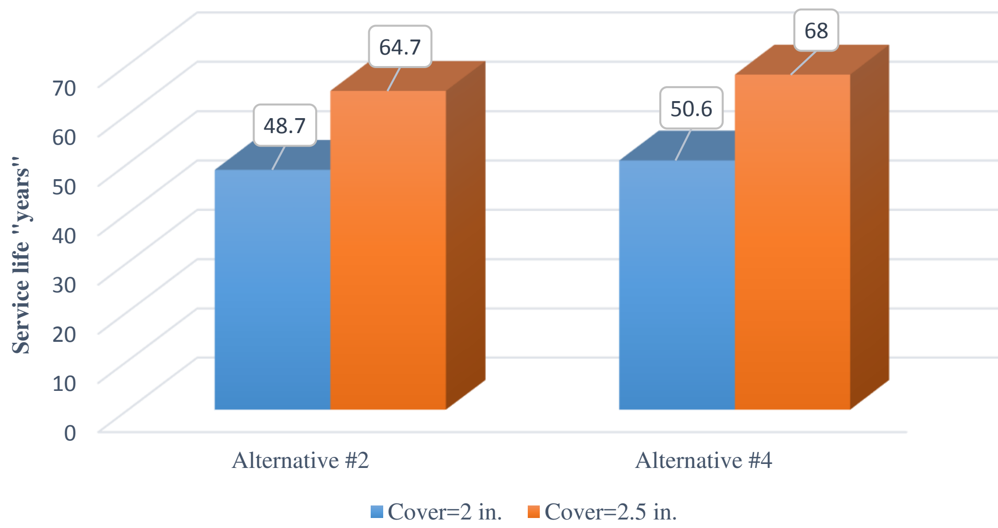

Figure 4.1 : Concrete cover effect on the estimated service life for alternatives 2 and 4 in cases 1 and 3

Increasing the concrete cover distance extends the time it takes for surface chlorides to reach the level of the upper embedded reinforcement. This delays the accumulation of chlorides on the reinforcement surface and extends the time until the threshold chloride concentration to initiate corrosion is reached. Therefore, there is a direct relationship between increased concrete cover distances and higher service life predictions.

Another example illustrating the importance of concrete cover in delaying corrosion initiation can be seen in Figure 4.2 and Figure 4.3. Alternative 1 (BS 1) in these two figures, case 1 (Figure 4.2) and case 3 (Figure 4.3), has the same w/cm ratio, SCM percentages, barrier type and reinforcement type and the only difference is in the concrete cover thickness. The time required for the chloride ions to achieve the chloride threshold necessary to initiate corrosion in the reinforcement (C_t=0.05 % wt. of concrete) was 19.2 years when the concrete cover distance for the slab was 2in. while it was 26.2 years when the concrete cover distance was 2.5in.

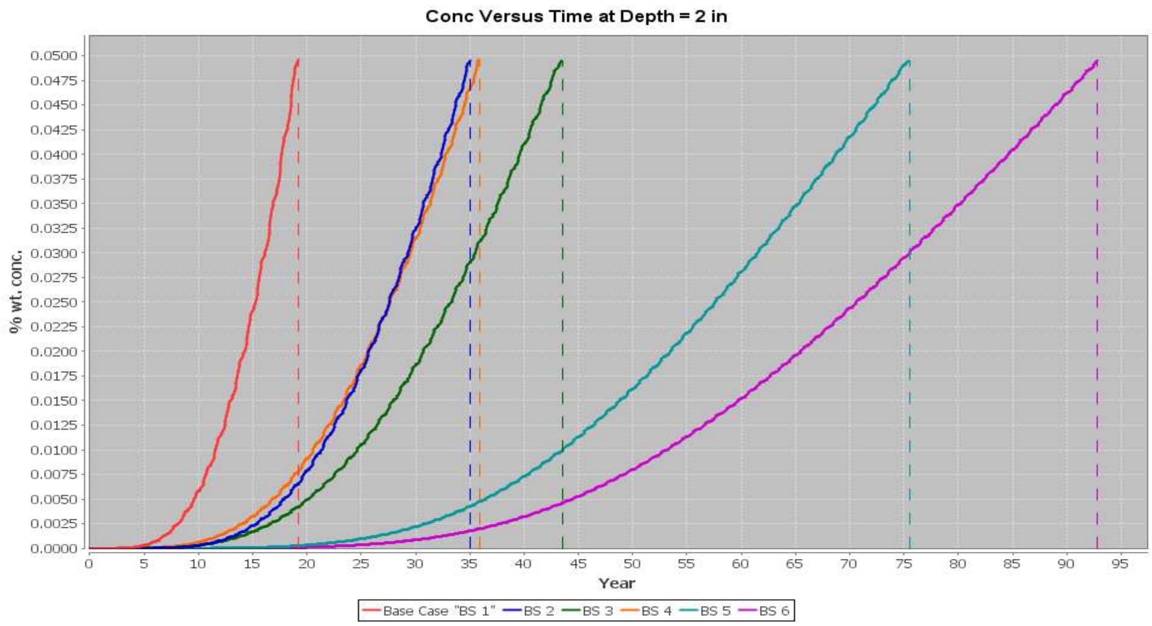

Figure 4.2: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case1 with sealer “cover of 2in. and w/cm of 0.3” (plotted by Life-365 software)

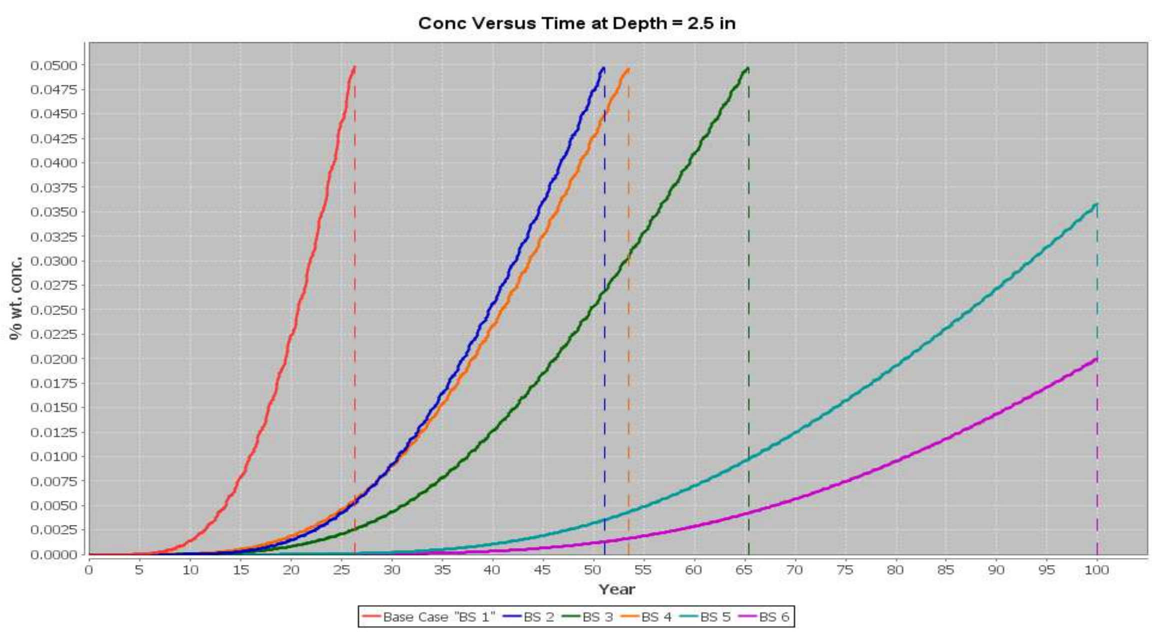

Figure 4.3: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case3 with sealer “cover of 2.5in.and w/cm of 0.3” (plotted by Life-365 software)

4.1.2 Water/cementitious materials ratio

Different ratios for w/cm were considered in various cases in this analysis. Decreasing the w/cm ratio from 0.34 to 0.3 resulted in an increase in the service life for all cases and alternatives investigated in this study. Figure 4.4 present a sample that show the effect of using different w/cm ratio on the estimated service lives where all variables are fixed except w/cm ratio. The comparison is between alternatives 4 and 5 in case 1 that has w/cm ratio of 0.3 and case 2 that has w/cm ratio of 0.34. The fixed variables are concrete cover of 2 in., concrete mixtures' proportions, the reinforcement type is black steel and the barrier type is sealer.

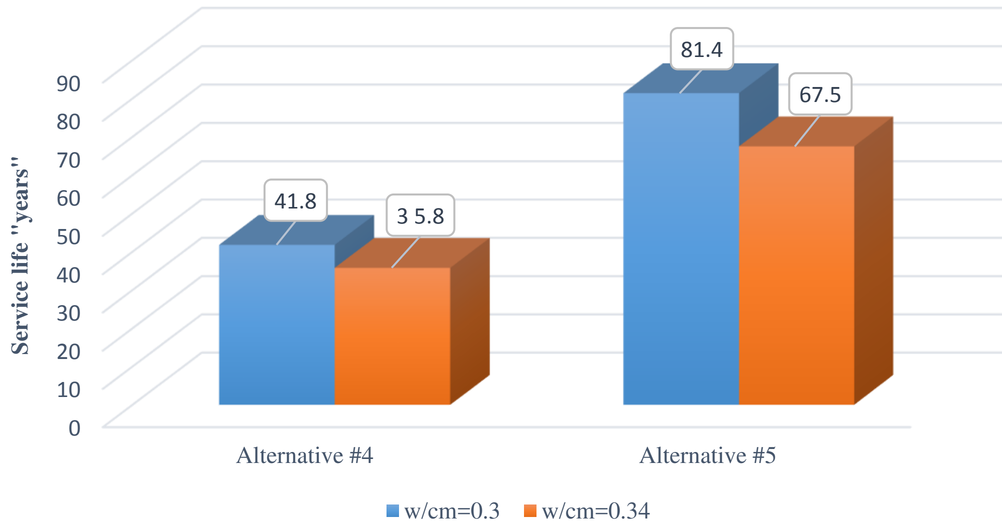

Figure 4.4: w/cm ratio effect on the estimated service life for alternatives 4 and 5 in cases 1 and 2

Low w/cm ratio decreases the permeability of the concrete mixtures which reduces the amount of chloride being absorbed through the concrete surface and reaching the embedded reinforcement steel. The reduced transport of chlorides results in a delay in corrosion onset and boosts the service life of the concrete slab. Therefore, there is a direct relationship between decreased w/cm ratio and higher service life predictions.

As an additional example, there is a clear delay in corrosion initiation and an enhancement in the estimated service life for alternatives that have the same concrete cover, same SCM percentages, same barrier type and reinforcement type and the only factor that is changing is w/cm ratio. Figure 4.5 shows concrete mixture 3 with membrane in case 3 (BM 3), which has a concrete cover=2.5 in. and w/cm ratio=0.3, has a corrosion initiation period equal to 74.2 years. On the other hand, Figure 4.6 shows concrete mixture 3 with membrane in case 4 (BM 3), which has a concrete cover=2.5 in. and w/cm ratio=0.34, has a corrosion initiation period equal to 62.2 years.

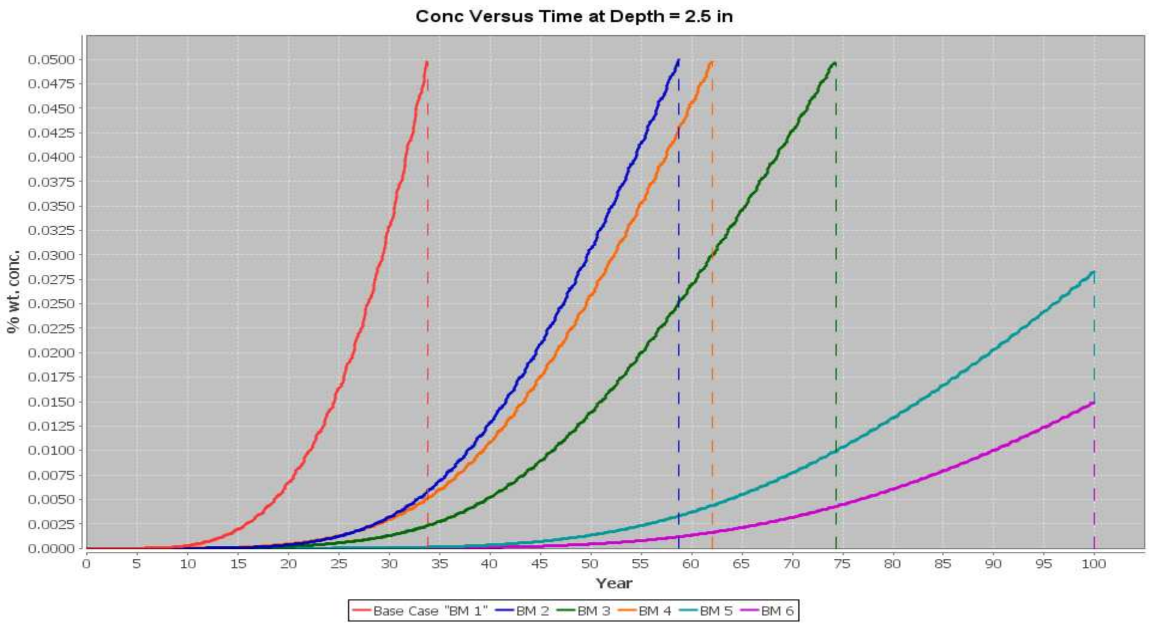

Figure 4.5: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case3 with membrane “cover of 2.5in.and w/cm of 0.3” (plotted by Life-365 software)

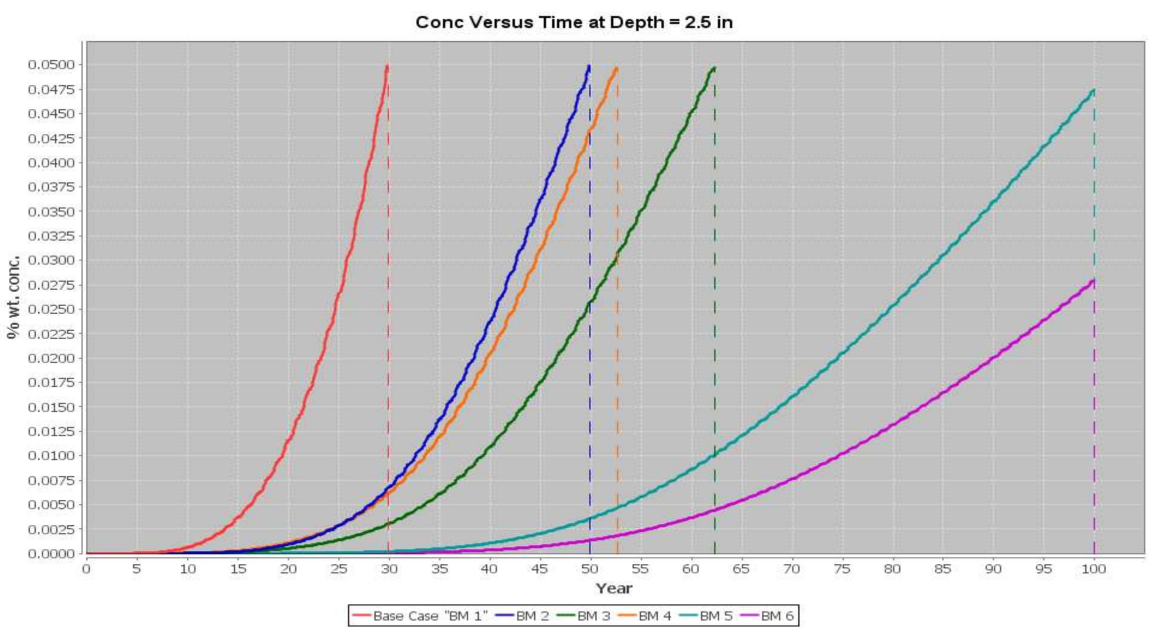

Figure 4.6: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 4 with membrane “cover of 2.5in.and w/cm of 0.34” (plotted by Life-365 software)

4.1.3 Supplementary Cementitious Materials “SCMs”

The analysis also considered the effect of different quantities of SCMs by considering the six different alternatives analyzed within each case. The mixture in alternative 1 is a base mix that has no SCMs. All other mixes in other alternatives, which include varying proportions of SCMs, have higher service lives than the base mix. This increase in service life varies for different concrete mixtures with different SCMs proportions, but in all cases, the increase can be attributed to the lower permeability of the reinforced concrete slab. Figure 4.7 presents a sample showing the effect of various SCM dosages on service life estimation where all variables are fixed except SCM percentages. The comparison is between alternatives within case 4: (1) has no SCMs, (2) has silica fume , (3) has slag cement and (4) has fly ash “Class F”. The fixed variables are concrete cover of 2.5 in., w/cm ratio of 0.34, the reinforcement type is black steel and the barrier type is membrane.

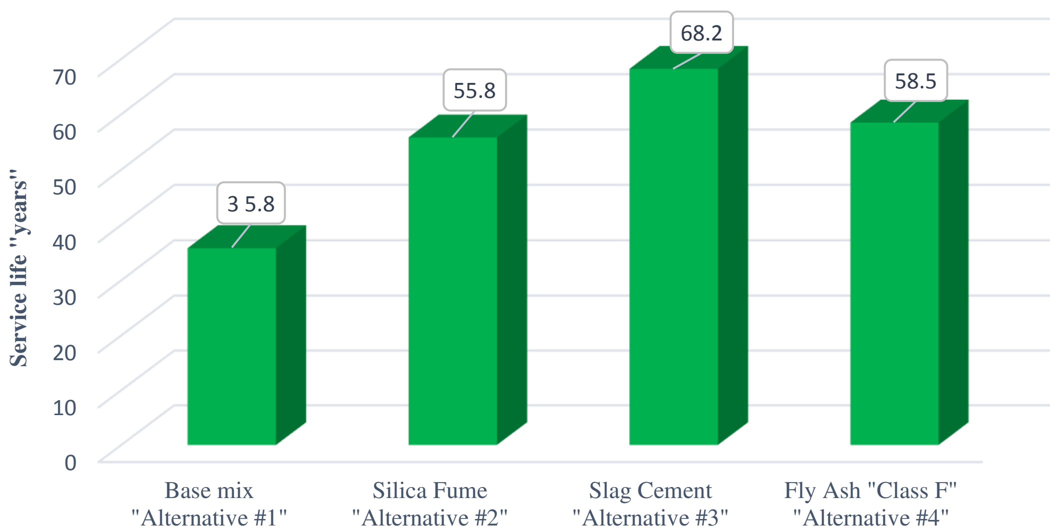

Figure 4.7: SCM effect on the estimated service life for alternatives 1, 2, 3 and 4 in case 4

The slag cement dosage used in alternative 3, 35 % of the total cementitious materials, was the best SCM option from those considered at increasing the service life. The concrete mixture in alternative 3 showed an increased value in the diffusion decay index which reduced permeability as early as possible by reducing the diffusion coefficient. The relationship between the diffusion coefficient at a specific time “t” and the diffusion decay index was presented Equation 3.6 in chapter 3. The fly ash dosage used in alternative 4, 20 % of the total cementitious materials, was the second in terms of increasing the service life. Fly ash has the same effect as adding slag cement. Finally, the silica fume dosage used in alternative 2, 5 % of the total cementitious materials, came after slag cement and fly ash in extending the service life. Although silica fume affects the diffusion coefficient directly, using the lowest possible value for the recommended silica fume dosage range has minimized the effect of this SCM on the estimated service lives.

The SCM percentages that are used in this study are chosen from a recommended dosage range that would reduce the concrete mix permeability without exceeding the maximum limit for SCMs content in a mix (Kosmatka, Kerkhoff, & Panarese, 2011). It has been observed that there is a direct relationship between using SCMs and higher service life predictions. Also for instance, Figure 4.8 for case 2 with sealer shows that the time needed for the chloride threshold concentration to be reached is 29.5 years for alternative 2 (BS 2) that has silica fume, 35.7 years for alternative 3(BS 3) that has slag cement and 29.8 years for alternative 4 (BS 4) that has fly ash.

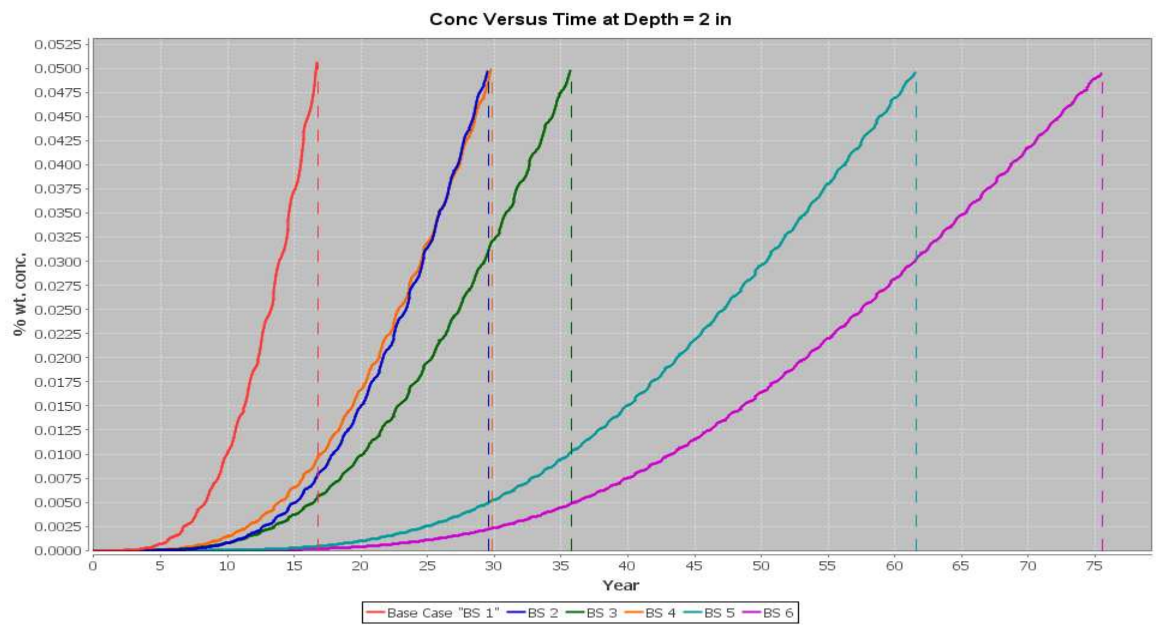

Figure 4.8: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case2 with sealer “cover of 2in.and w/cm of 0.34” (plotted by Life-365 software)

The delay in the initiation period is also true for different cases with different concrete covers and w/cm ratios when SCMs are used in the suggested percentages. In addition, the combined effects of SCMs have been investigated through alternatives 5 and 6 with various concrete covers, various w/cm ratios and different barriers. The combination of different SCMs has also shown to be very effective in increasing the service life for the reinforced concrete slab. For example, Figure 4.5 shows a good example of the high estimated service lives in alternatives 5 and 6 for case 3 where the chloride threshold concentration (C_t=0.05 % wt. of concrete) at the level of the upper embedded steel has not been reached to start the corrosion process within the analysis period, 100 years.

4.1.4 Barriers

Membranes and sealers are intended to reduce the chloride build-up rate at the concrete slab surface, and both type of barriers showed an improvement in estimated service life for all alternatives and cases investigated in this study. Applying barriers is carried out at the beginning of the project. Life-365 allows for the reapplication of barriers after the default age of failure of a barrier is reached- 20 years for membranes and 5 years for sealers- and up to the time of first repair where there are no reapplications after the first repair. Figure 4.9 presents an example that shows the effect of using barriers and reapplying them once on service life where all variables are fixed except the barrier type. The comparison is between alternatives 1, 3, 4, 5 and 6 in case 5. The fixed variables are concrete cover of 2 in., w/cm ratio of 0.3, concrete mixtures' proportions and the reinforcement type is black steel.

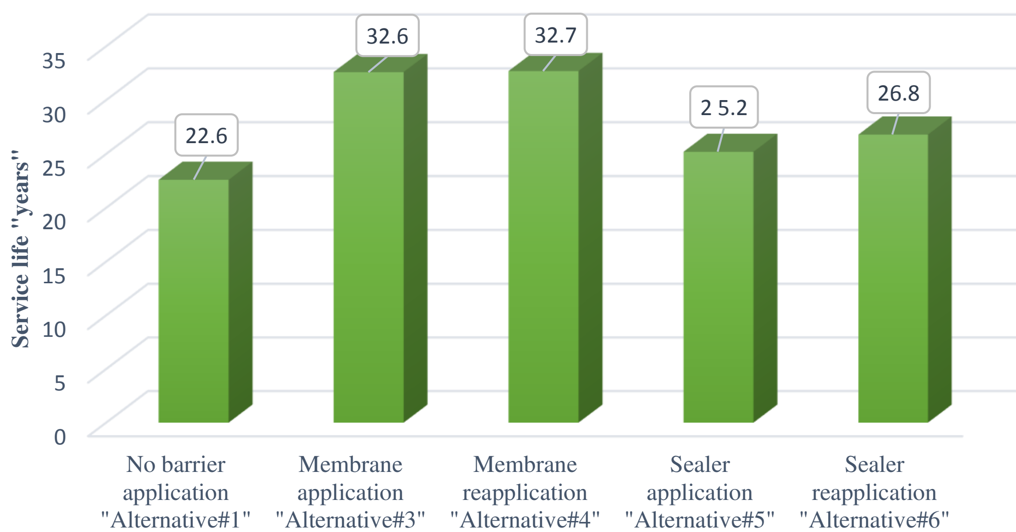

Figure 4.9: Barriers effect on the estimated service life for alternatives 1, 3, 4, 5 and 6 in case 5

This increase in estimated service life can be attributed to the ability of both types of barriers to minimize the chloride build-up rate at the concrete slab surface. This extends the length of time needed to reach the threshold chloride concentration at the reinforcement level. These results indicate that reapplying barriers does not improve the service life of the alternatives. The reason for that is barriers do not stop all chlorides from entering concrete where they only affect the chloride build-up rate at the concrete surface as it is assumed in Life-365 (Thomas & Bentz, 2013). Besides that, the chloride concentration at the level of the steel is already approaching the threshold concentration at the time of barrier reapplication. Membranes produce longer estimated service life in comparison with sealers because Life-365 assumes a longer time to failure and higher initial efficiency for membranes. It can be seen that there is a direct relationship between using barriers and longer predicted service lives.

In addition, Figure 4.10 shows the effect of using barriers and reapplying them once on corrosion initiation period. It is 16.6 years for alternative 1(B) that has no barrier, 26.6 years for alternative 3(BM) that has a membrane, 26.7 years for alternative 4 (BM (1)) that has reapplied membrane, 19.2 years for alternative 5(BS) that has applied sealer and 20.8 years for alternative 6 (BS (1)) that has reapplied sealer.

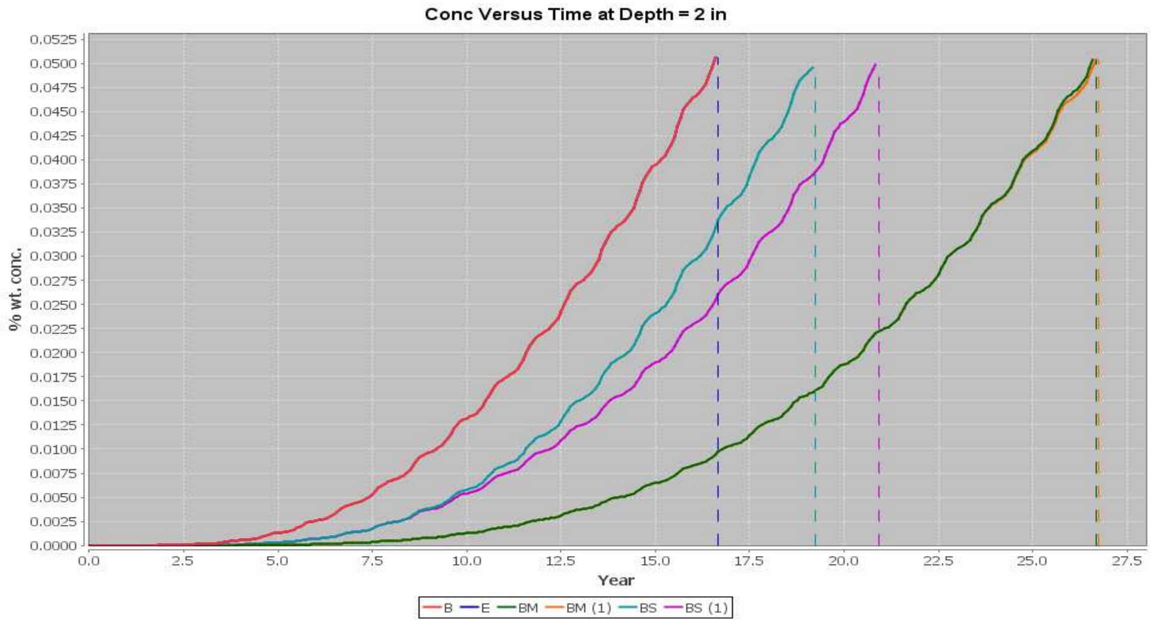

Figure 4.10: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 5 “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

4.1.5 Reinforcement

Whereas membranes and sealers serve as a barrier at the surface of the concrete, epoxy coating can serve as a barrier at the level of the steel reinforcement. An increase in the lifetime of a reinforced concrete slab with epoxy-coated steel embedded in it over a reinforced concrete slab with black steel embedded in it was observed in case 5. Using epoxy-coated steel in alternative 2 has extended the estimated service life to 36.6 years in comparison with 22.6 years when black steel is used in alternative 1. The increase in estimated service life when epoxy-coated steel is used can be attributed to the ability of the epoxy coating to increase the corrosion propagation period. Life-365 assumes that epoxy-coated bars have a propagation period of 20 years compared to 6 years when black steel is used (Thomas & Bentz, 2013).

4.1.6 Design variables effects on estimated service lives

The previous sections have demonstrated that the service life of reinforced concrete slabs can be affected by numerous variables. This section aims to begin to quantify the amount of service life gain that can be attributed to individual variables. This allows designers to consider the relative effectiveness of different design variables. The percentages of service life increment for each design variable for the parking structure slab are shown in this section.

Figure 4.11 has been obtained by comparing service lives for alternatives in cases 1 and 2 where the concrete cover distance is 2 inches to the same alternatives in cases 3 and 4 where the cover distance is 2.5 inches. For example, the value of service life increment percentage for alternative 1 has been obtained by calculating the percentage of difference between service life for alternative 1with membrane in case 1, which has a concrete cover of 2 inches, and service life for alternative 1 with membrane in case 3, which has a concrete cover of 2.5 inches. Then, the percentage of difference between service life for alternative 1with sealer in case 1, which has a concrete cover of 2 inches, and service life for alternative 1 with sealer in case 3, which has a concrete cover of 2.5 inches will be calculated. After that, the same will be done for alternative 1 in case 2, which has a concrete cover of 2 inches, and alternative 1 in case 4, which has a concrete cover of 2.5 inches. Finally, the average for these four values is calculated as the service life increment percentage for alternative 1 with changing the concrete cover distance (19.2 % as seen in Figure 4.11). The same calculations are used for other alternatives in Figure 4.11 to obtain a variation chart for service life increment percentage with concrete cover varying while fixing other design variables. Observations from Figure 4.11 indicate that increasing the concrete cover distance was mostly effective in alternatives 2, 3 and 4 where one SCM was used in each of these alternatives with a barrier. Concrete cover effect on service life increment percentage for alternative 6 was not high because the effect of SCMs working in combination was the most dominant.

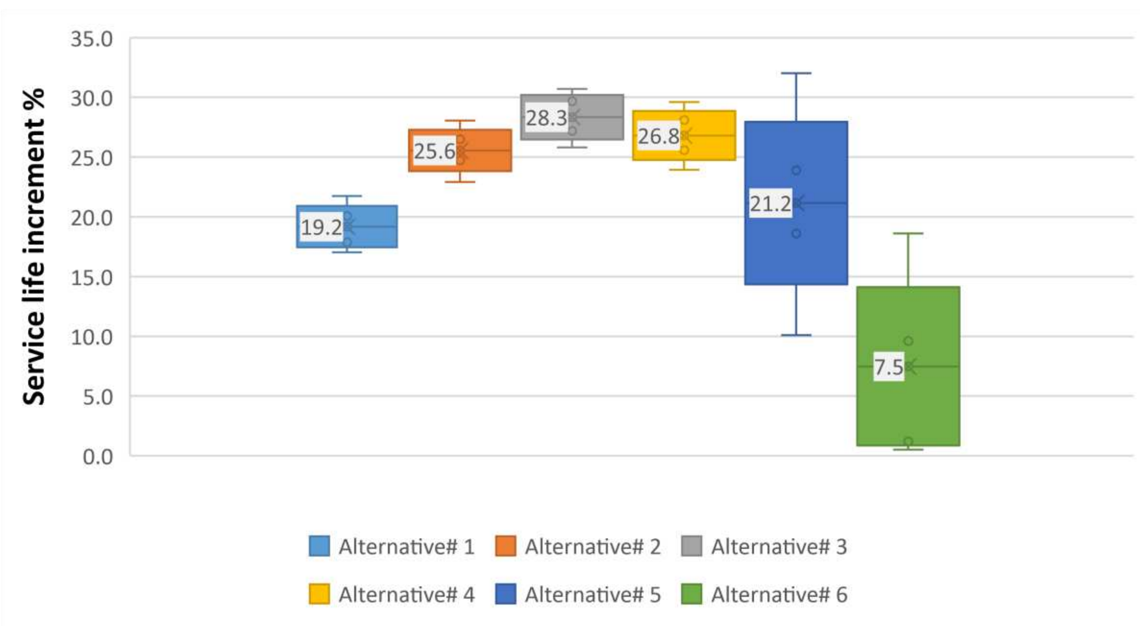

Figure 4.11: Average service life increment percentage due to increasing the concrete cover

The same calculations of varying the concrete cover distance to get a variation chart for service life were applied to Figure 4.12. The only difference is that Figure 4.12 has been obtained through changing the w/cm ratio from 0.34 in cases 2 and 4 to 0.3 in cases 1 and 3. It has been observed that decreasing the w/cm ratio was mostly effective in alternatives 2, 3 and 4 where one SCM was used in each of these alternatives with a barrier.

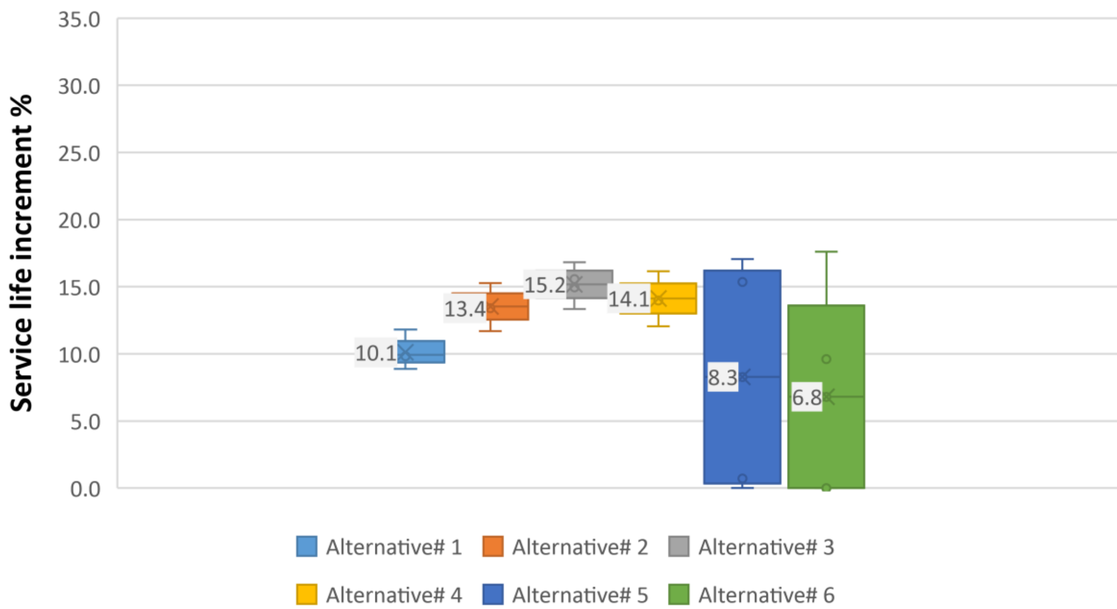

Figure 4.12: Average service life increment percentage due to decreasing the w/cm ratio

Figure 4.13 has been obtained using the 5% silica fume only mix in alternative 2 in cases 1, 2, 3 and 4. For example, the value of service life increment percentage for case 1 has been obtained by calculating the percentage of difference between service life for alternative 1with membrane, which has no SCMs in the concrete mixture, and service life for alternative 2 with membrane, which has 5% silica fume only in the concrete mixture. Then, the percentage of difference between service life for alternative 1with sealer, which has no SCMs in the concrete mixture, and service life for alternative 2 with sealer, which has 5% silica fume only in the concrete mixture, will be calculated. Finally, the average for these two values is calculated as the service life increment percentage for case 1 with changing silica fume percentage only (35.8% as seen in Figure 4.13). There are no whiskers in Figure 4.13 since the average in each case is obtained through two values instead of four values in each alternative as it was shown in Figure 4.11. The same calculations are used for other cases in Figure 4.13 that symbolize a variation chart for service life increment percentage with silica fume varying percentage while fixing other design variables. Using silica fume was most effective in cases 3 and 4 where the concrete cover distance was 2.5in.

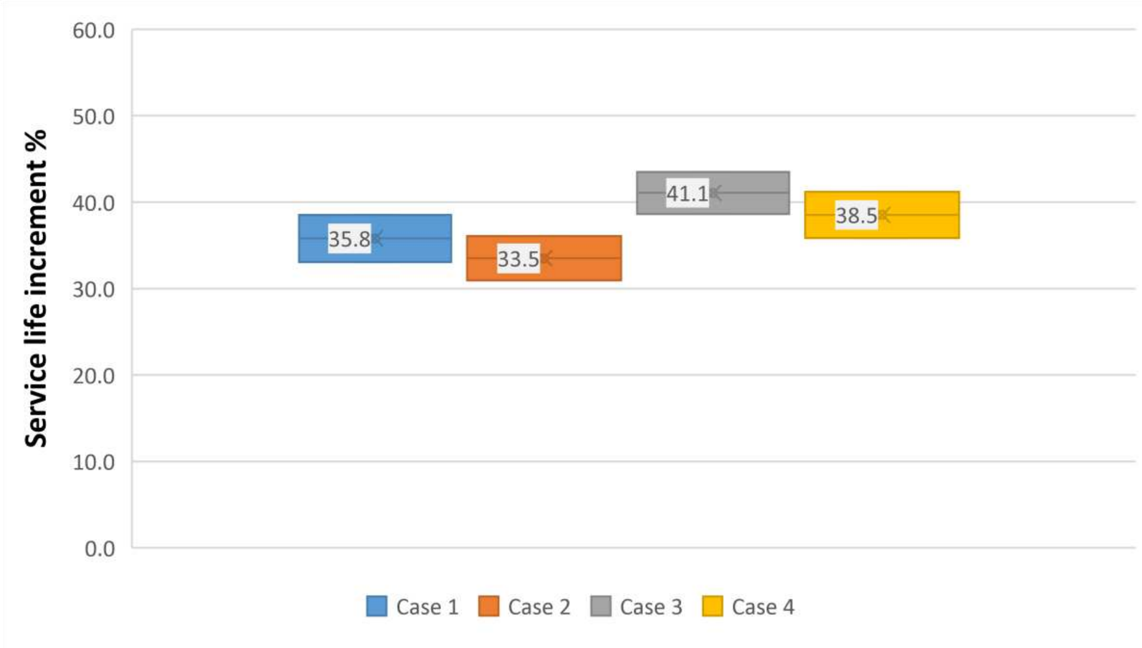

Figure 4.13: Average service life increment percentage due to silica fume usage

The same calculations of using silica fume to get a variation chart for service life were applied to Figure 4.14. The only difference is that Figure 4.14 has been obtained through using 35%slag cement only in alternative 3 in cases 1, 2, 3 and 4. It has been observed that the using slag cement was mostly effective in cases 3 and 4 where the concrete cover distance was 2.5in.

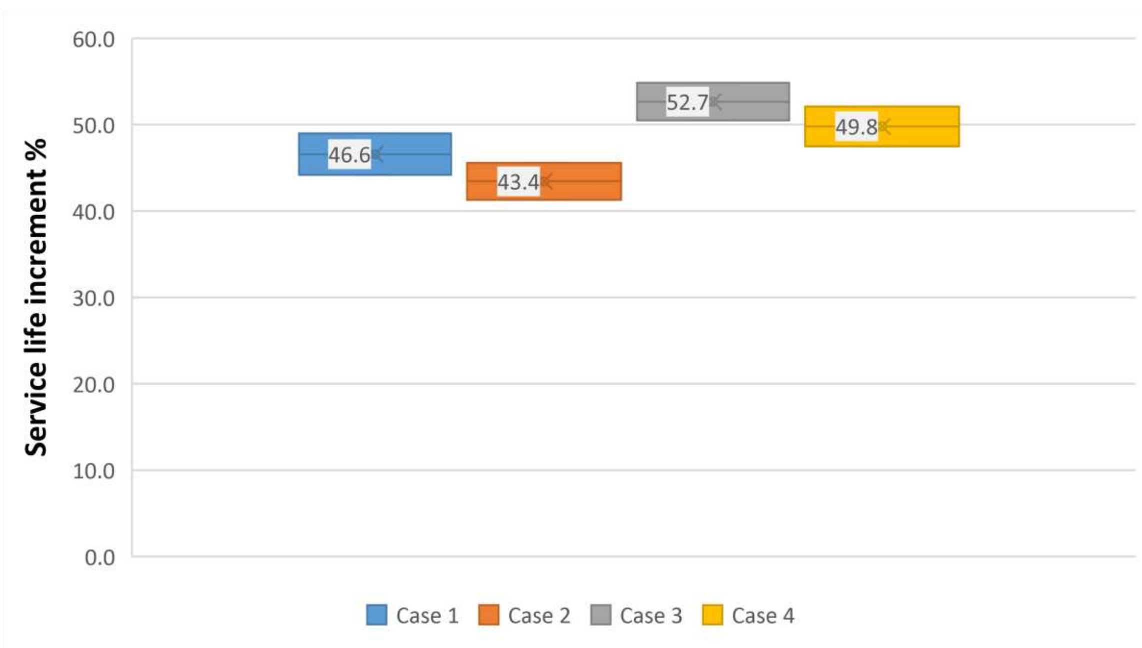

Figure 4.14: Average service life increment percentage due to slag cement usage

The same calculations of using silica fume to get a service life variation chart were applied to Figure 4.15. The only difference is that Figure 4.15 has been obtained through using 20% fly ash "Class F" only in alternative 4 in cases 1, 2, 3 and 4. Using fly ash was mostly effective in cases 3 and 4 where the concrete cover distance was 2.5in.

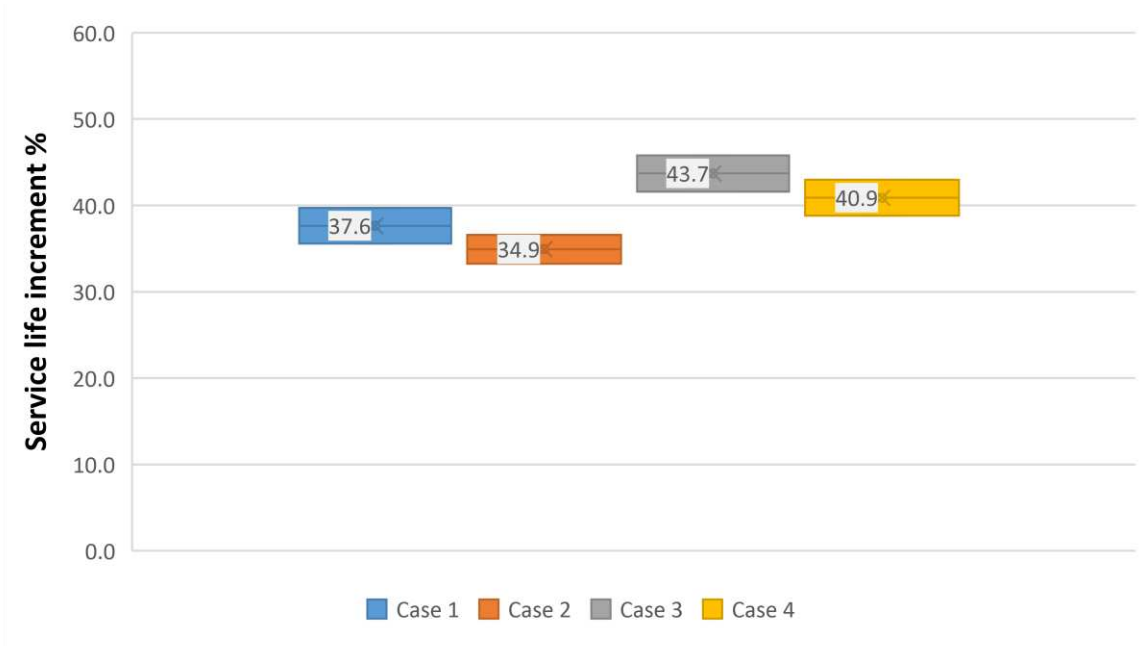

Figure 4.15: Average service life increment percentage due to fly ash usage

Figure 4.16 has been obtained through using membrane in cases 5 and 6. For example, the value of service life increment percentage for case 5 has been gained by calculating the percentage of difference between service life for alternative 1, which has no membrane, and service life for alternative 3, which has membrane (30.7% as seen in Figure 4.16). The same calculations are used within case 6 in Figure 4.16 , which symbolize a chart for service life increment percentage, with membrane used in an alternative and not used in another alternative while fixing other design variables. Using membrane was mostly effective when no SCMs where used in the mixtures because all the increment percentage is attributed to the use of membrane.

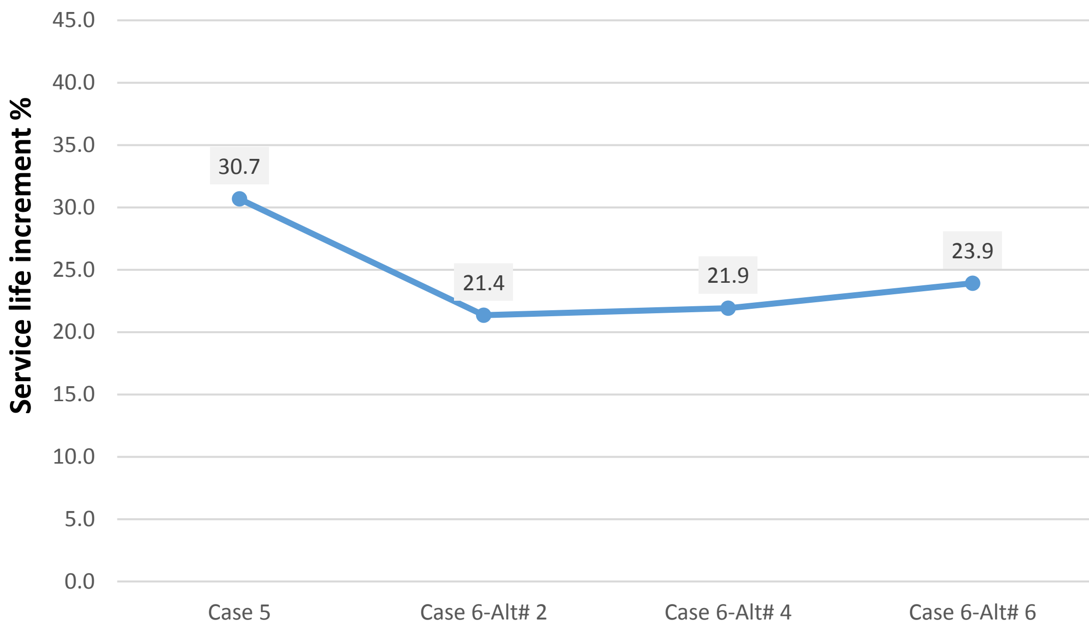

Figure 4.16: Average Service life increment percentage due to membrane usage

The same calculations of using membrane to get a chart for service life were applied to Figure 4.17. The only difference is that Figure 4.17 has been obtained through using sealer in cases 5 and 6 in different alternatives. Using sealer was mostly effective when no SCMs where used in the mixtures because all the increment percentage is attributed to the use of sealer.

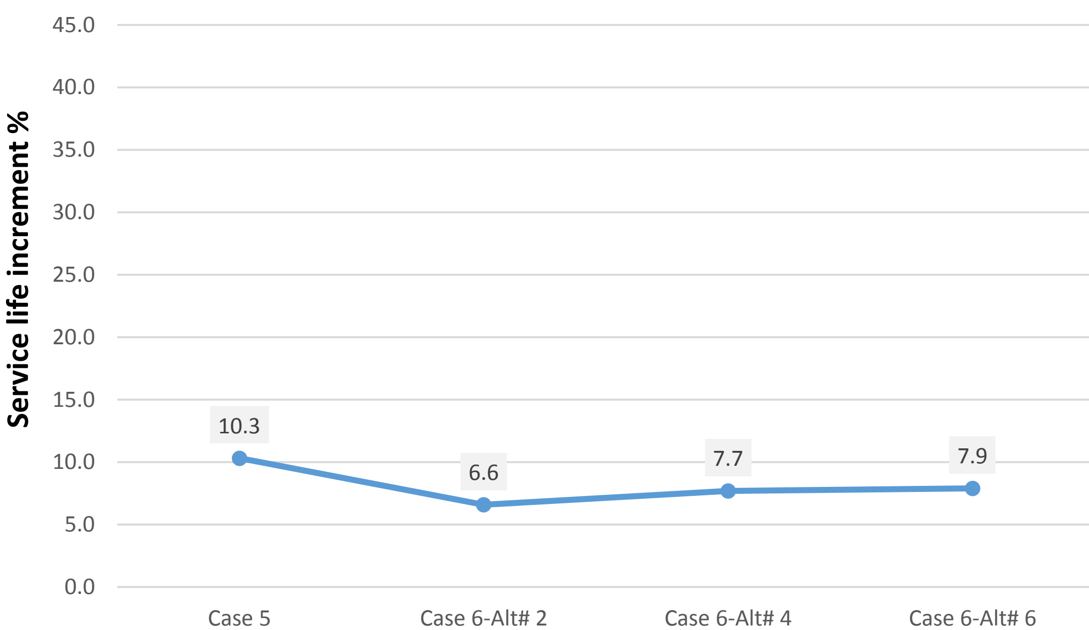

Figure 4.17: Average service life increment percentage due to sealer usage

The same calculations of using membrane to get a chart for service life were applied to Figure 4.18. The only difference is that Figure 4.18 has been obtained through using epoxy-coated steel in cases 5 and 7in different alternatives. Using epoxy-coated steel was mostly effective when no SCMs were used in the mixtures because all the increment percentage is attributed to the use of epoxy-coated steel.

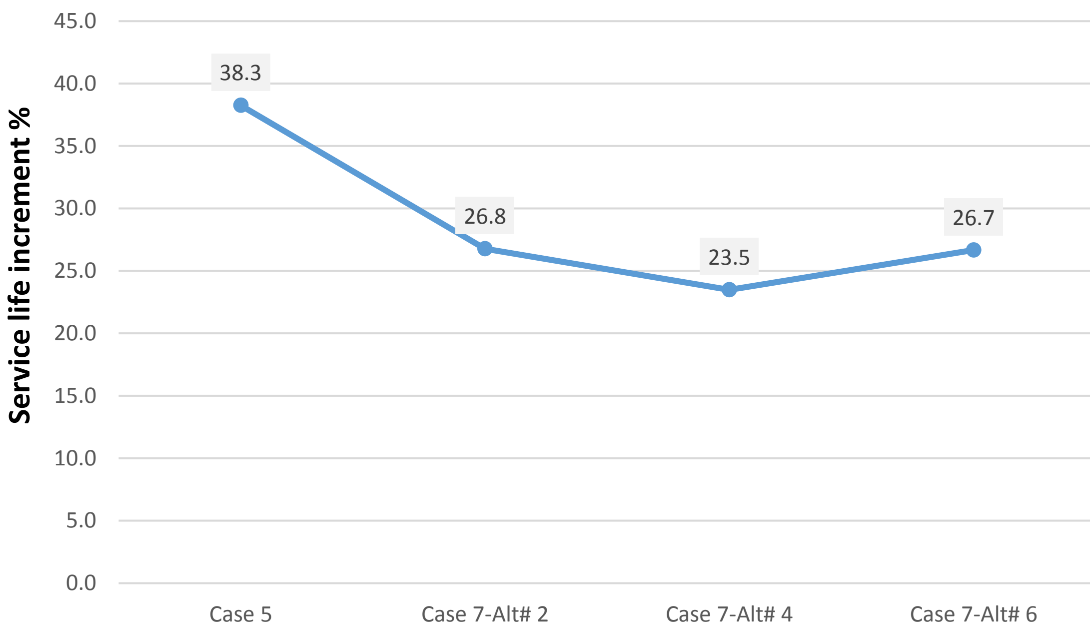

Figure 4.18: Average service life increment percentage due to epoxy-coated steel usage

Figure 4.19 summarizes the previous analyses by plotting the average increment percentage in the estimated service life for all design variables. The previous analysis has indicated that using SCMs in the recommended dosage range has the highest effect on enhancing the estimated service lives intervals among all other design variables that have been changed. Epoxy-coated steel as an embedded reinforcement in concrete, increasing the concrete cover, using barriers and reducing w/cm ratio comes after that with different increment percentages on the estimated service lives.

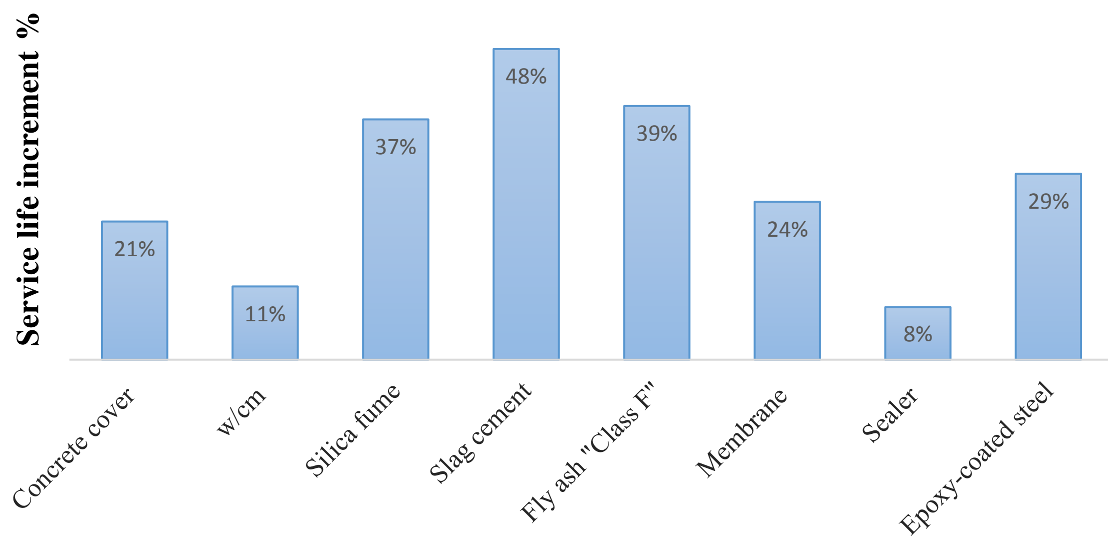

Figure 4.19: Average service life increment percentage for all design variables

4.2 Life Cycle Cost Analysis

Life Cycle Cost Analysis “LCCA” has been implemented throughout this study to evaluate the effects of changing design variables on the total costs incurred over the complete design life, which is 100 years, for a reinforced concrete slab in a parking structure. Design alternatives possess different properties such as concrete cover, w/cm ratio, various SCM percentages, and different reinforcement and barriers types. While the previous sections indicated which variables had the greatest impact on service life, this section incorporates the costs of different design choices to consider which choices are most cost effective. Besides that, results for life cycle cost from a relevant sample for each cost phase (construction, barrier application and repair) will be shown and discussed. All the costs are calculated in $/sq.ft for the concrete slab that has a thickness of 0.5 foot. Life cycle cost is the sum of construction phase cost, barrier phase cost and repair phase cost. More explanation for each of these phases is provided in sections 4.2.1 through 4.2.3. Complete results for life cycle cost for all alternatives in all cases are presented in appendix B.

4.2.1 Construction phase cost

The construction phase cost is an important part of the life cycle cost for a structure or an element in a structure to determine whether an alternative is cost effective or not. In this study, the construction cost is the sum of the concrete mixture cost and embedded reinforcement cost spent at the beginning of the project. The construction phase cost has varied for different alternatives where black steel reinforcement has been kept the same for all cases except that epoxy coated steel was embedded in alternative 2 in case 5 and in alternatives 2, 4 and 6 in case 7. The construction cost in all cases would be affected by changing the w/cm ratio, using different SCMs and using different reinforcement types.

4.2.1.1 W/cm ratio

Figure 4.20 presents a sample that show the effect of using different w/cm ratios on construction cost where all design variables are fixed except w/cm ratio. The comparison is between all alternatives in case 1 that has w/cm ratio of 0.3 and case 2 that has w/cm of 0.34. The fixed variables are a concrete cover of 2 in., concrete mixtures' proportions, the reinforcement type is black steel and the barrier type is sealer. It can be seen that there is a direct relationship between decreasing the w/cm ratio and higher construction costs because higher cementitious materials quantities are needed in mixtures.

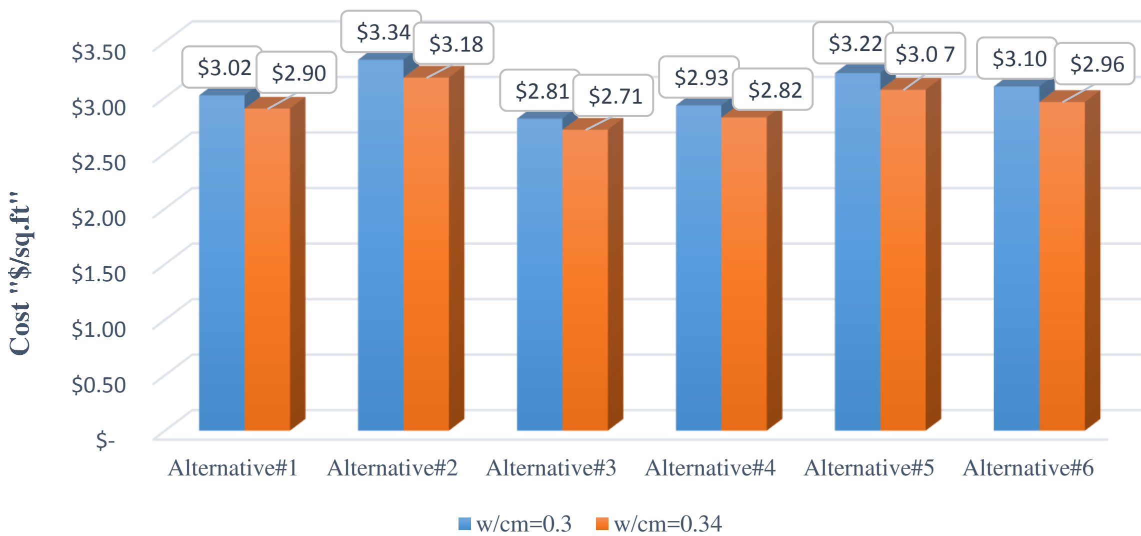

Figure 4.20: w/cm ratio effect on construction cost in case 1 and case 2 for all alternatives

4.2.1.2 Different SCM

The effect of using different SCMs on construction cost is explained through a sample in Figure 4.21 where all design variables are fixed except SCM. The comparison is between alternatives 1 that has no SCMs, 2 that has silica fume, 3 that has slag cement and 4 that has fly ash in case 3. The fixed variables are concrete cover of 2.5 in., w/cm ratio of 0.3, reinforcement type is black steel and barrier type is membrane. It can be seen that substituting 5% of the cementitious materials by silica fume increase the construction cost in comparison with the base mix because the price of silica fume is much higher than that of Portland cement. Also, it can be noticed that substituting 35 % of cementitious materials in mixture number 3 by slag cement and substituting 20 % of cementitious materials in mixture number 4 by fly ash “Class F” has decreased these mixtures construction cost in comparison with the base mix. The reason for this is that slag cement and fly ash are less expensive than Portland cement.

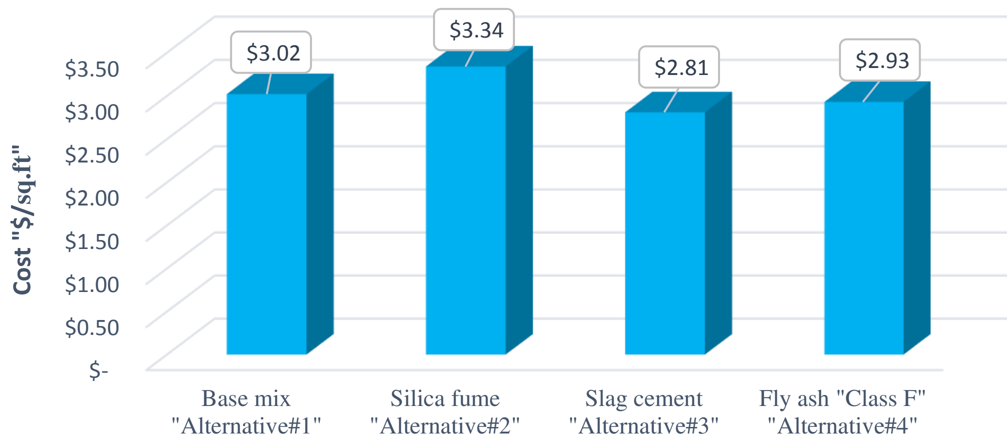

Figure 4.21: SCM effect on construction cost for alternatives 1, 2, 3 and 4 in case 3

4.2.1.3 Reinforcement type

Using different reinforcement types affect the construction phase cost. For example, this cost has varied in case 5 from $3.02 in alternative 1 where black steel is used while the cost was $3.75 in alternative 2 where epoxy-coated steel is used. The higher cost of epoxy-coated steel in comparison with black steel has a direct effect on the construction phase cost.

4.2.2 Barrier phase cost

The barrier cost includes the cost of membranes or sealers that are used in an alternative. Both membranes and sealers are applied to the reinforced concrete slab at the beginning of the project. After that, they were reapplied once after their default age of failure has been reached as assumed in Life-365 software, 20 years for membrane and 5 years for sealer, and up to the time of first repair. This means that barriers will not be reapplied if the concrete slab needed to be repaired before the default age of failure has been reached. The way Life-365 models applying and reapplying barriers is very simple where they affect the chloride build-up rate at the concrete surface only, which will not extend the estimated service life after reapplying a lot. Therefore, alternatives with reapplied barrier, without a significant extension in service life, will need repair after a short period of reapplying time. This can be considered as a limitation because it is not allowing the user to investigate the cost of preventive maintenance strategies properly. Figure 4.22 present a sample that show the effect of using different barrier type and reapplication times on barrier cost where all design variables are fixed except barrier type. The comparison is between alternatives 1, 3, 4, 5 and 6 in case 5. The fixed variables are concrete cover of 2 in., w/cm ratio of 0.3, concrete mixtures' proportions and reinforcement type is black steel.

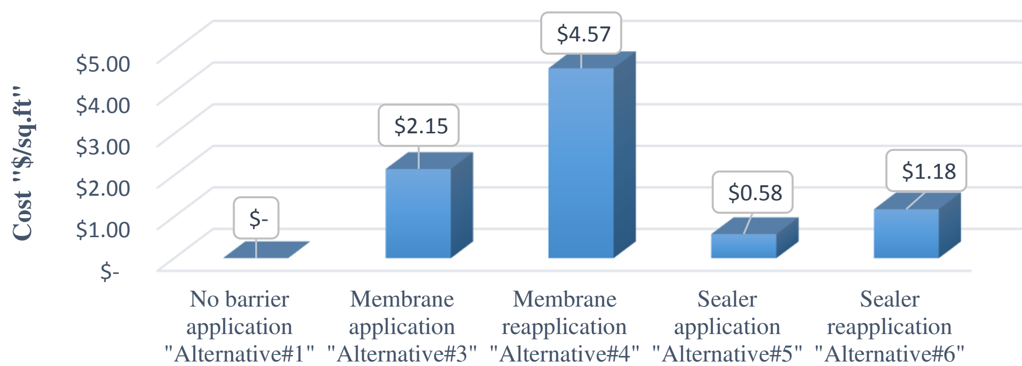

Figure 4.22: Barrier type effect on barrier cost for alternatives 1, 3, 4, 5 and 6 in case 5

Also, it can be noticed that membranes cost at first application and after reapplication is higher than sealers cost but the overall life cycle cost at the end of the estimated service life gives a clear explanation of cost effectiveness for these two barriers.

4.2.3 Repair phase cost

The repair costs include fixing and rehabilitation for the reinforced concrete slab. This phase starts after defects show on the slab mainly due to embedded reinforcement corrosion. Repair costs will be calculated every 10 years for the remainder of the design life, analysis period (100 years), after defects appear on the concrete slab surface at the end of the estimated service life. Results show that repair costs vary with different alternatives in different cases. This variation in repair costs can be attributed to multiple estimated service lives in different alternatives. Some alternatives that are used in the reinforced concrete slab start to deteriorate and show significant signs of damage such as cracking, spalling and delamination in concrete that requires repair before other alternatives. The repair cost in all cases are affected by changing the concrete cover distance, changing the w/cm ratio, using different SCMs, using different types of barriers and using different types of reinforcement.

4.2.3.1 Concrete cover

The repair phase cost has been affected by varying the concrete cover distance while fixing other design variables as shown in Figure 4.23. The comparison is between all alternatives in case 2 that has a concrete cover of 2in. and case 4 that has a concrete cover of 2.5 in. The fixed variables are w/cm ratio of 0.34, concrete mixtures' proportions, reinforcement type is black steel and barrier type is membrane. It can be seen that there is a direct relationship between increasing the concrete cover and lower repair costs. The reason for this is that the concrete slab deterioration is postponed because higher concrete cover distance leads to longer estimated service lives where the chloride threshold concentration that is necessary to initiate corrosion would be delayed. Therefore, the rest of the analysis period, which is 100 years, will require less repair. The repair cost for alternatives 5 and 6 with a concrete cover of 2.5 in. is equal to zero because the estimated service life for these two alternatives has exceeded the analysis period which means that they do not need repair.

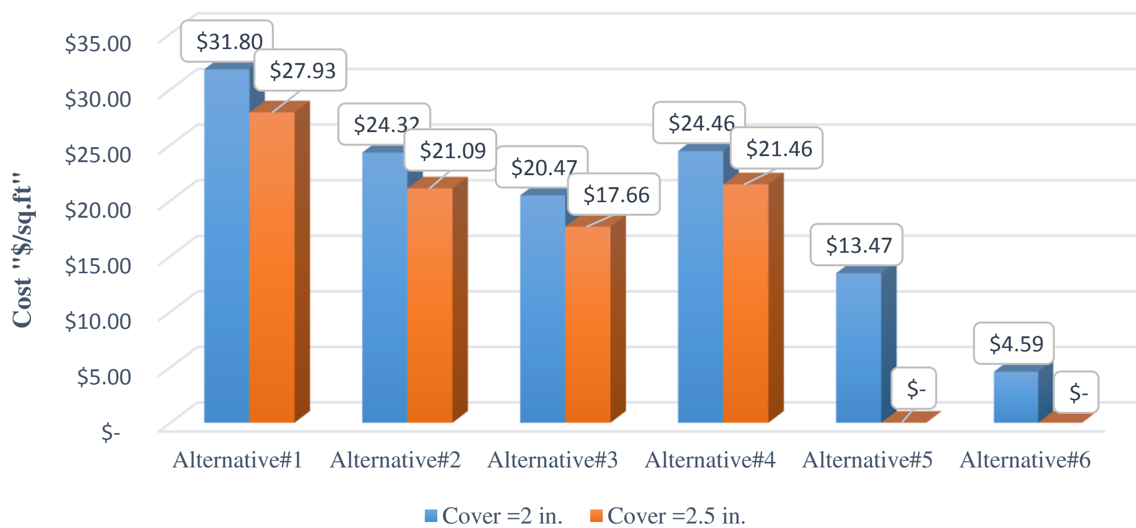

Figure 4.23: Concrete cover effect on repair cost in case 2 and case 4 for all alternatives

4.2.3.2 W/cm ratio

Using different w/cm ratio affects the repair phase cost as shown in Figure 4.24. The comparison is between all alternatives in case 1 which has a w/cm ratio of 0.3 and case 2 which has a w/cm ratio of 0.34. The fixed variables are concrete cover of 2in., concrete mixtures' proportions, reinforcement type is black steel and barrier type is sealer. It can be seen that there is a direct relationship between decreasing the w/cm ratio and lower repair costs. The reason for this is that the concrete slab deterioration would be postponed because lower w/cm ratio leads to longer estimated service lives for the concrete slab due to lower permeability of concrete.

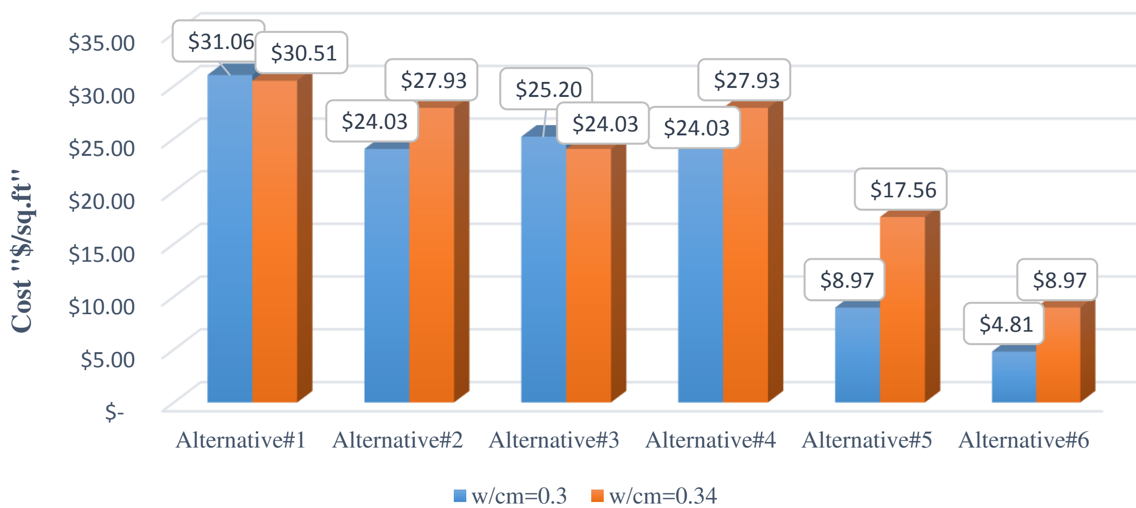

Figure 4.24: w/cm ratio effect on repair cost in case 1 and case 2 for all alternatives

4.2.3.3 Different SCM

Figure 4.25 present a sample that show the effect of using different SCM on repair cost where all design variables are fixed except SCM. The comparison is between alternatives 1 that has no SCMs, 2 that has silica fume, 3 that has slag cement and 4 that has fly ash in case 3. The fixed variables are concrete cover of 2.5 in., w/cm ratio of 0.3, reinforcement type is black steel and barrier type is membrane. It can be seen that substituting 5% of the cementitious materials by silica fume has decreased the repair cost in comparison with the base mix. Also, it can be noticed that substituting 35 % of cementitious materials in mixture 3 by slag cement and substituting 20 % of cementitious materials in mixture 4 by fly ash “Class F” has decreased these mixtures repair cost in comparison with the base mix. The outstanding ability of SCM to boost service life for the concrete slab is the major factor for low repair costs.

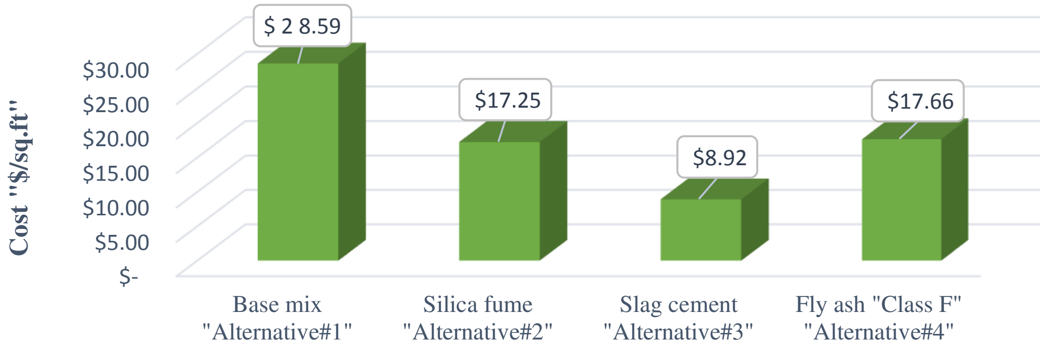

Figure 4.25: SCM effect on repair cost for alternatives 1, 2, 3 and 4 in case 3

4.2.3.4 Barrier type and reapplication

Applying barriers, membranes and sealers, and reapplying them once affects the repair phase cost as presented in Figure 4.26 where all design variables are fixed except barrier type. The comparison is between alternatives 1, 3, 4, 5 and 6 in case 5. The fixed variables are concrete cover of 2 in., w/cm ratio of 0.3, concrete mixtures' proportions and reinforcement type is black steel. It can be seen that there is a direct relationship between using barriers as an external protective material and lower repair costs when they are applied at the beginning of the project. However, it has been noticed that reapplying barriers in the way Life-365 assumes did not lower the repair cost because reapplying did not improve the estimated service life that is necessary to delay the repair phase. It can be concluded that membranes are better barriers in terms of saving money in future slab repairs such as spalling and delamination because membranes have higher age of failure and higher initial efficiency than sealers.

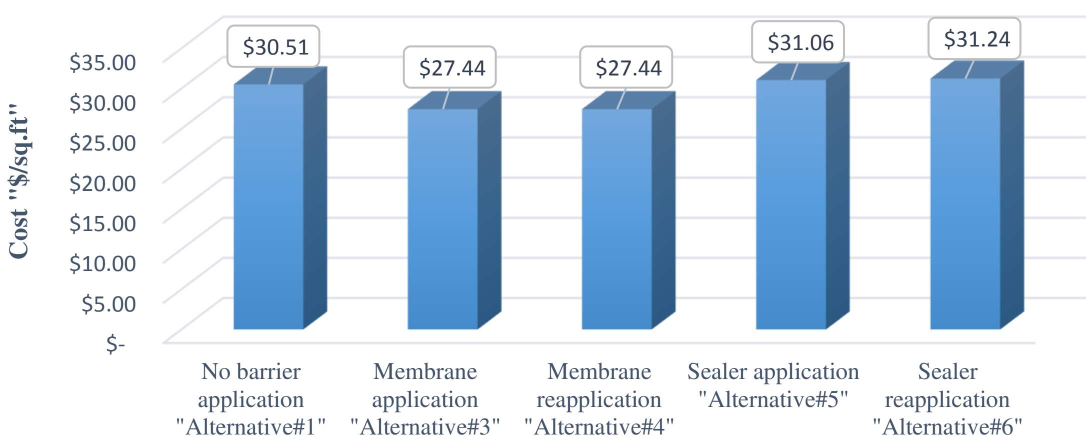

Figure 4.26: Barrier type effect on repair cost for alternatives 1, 3, 4, 5 and 6 in case 5

4.2.3.5 Reinforcement type

Using different reinforcement types affect the repair phase cost where this cost has varied in case 5 from \$30.51 in alternative 1 where black steel is used while the cost was \$28.09 in alternative 2 where epoxy-coated steel is used. The ability of epoxy-coated steel to extend the corrosion propagation period into 20 years in comparison with 6 years of black steel has lowered the repair cost where first repair time is delayed.

4.2.3.6 Repair cost observations

In general, the alternatives that have slag cement in their concrete mixtures have the lowest repair cost compared to other alternatives in the first four cases because they have higher estimated service life which reduces the future repair costs. In addition, alternatives with silica fume and fly ash in their concrete mixtures comes after slag cement alternatives in lowering the repair costs in all alternatives in the first four cases. However, the repair cost for alternative 3, which has 35% slag cement, is not the third lowest repair cost after alternatives 5, which has 20% fly ash and 5% silica fume, and 6, which has 35% slag cement and 5% silica fume, in all first four cases that are investigated in this study. Although alternative 3 has higher service life estimations in comparison with alternatives 2, which has 5% silica fume, and 4, which has 20% fly ash, in all first four cases. This observation can be attributed into two reasons.

First, the software requires the user to input a fixed repair interval after the first repair to calculate the repair cost for the rest of the analysis period, 100 years. This is not very accurate because the software calculates the repair cost even in the last year of the analysis period that raises the total number of repairs and equalize it with other alternatives that have lower estimated service lives. This will lead to higher repair cost for alternative 3 here. Second, alternative 3 could have the same number of repairs through its analysis period in comparison with alternatives 2 and 4 but in more distant years in the future which would affect the repair costs through the economic parameters, inflation rate and discount rate, where farther years would have higher repair costs than closer years. Besides that, it can be noticed that both alternatives 5 and 6 in case 3 have zero repair cost where their service life estimations exceeded the analysis period in this study.

4.2.4 Total cost "Life Cycle Cost"

The results of LCCA in this study have shown consistent outcome in almost all the cases that have been investigated. The design variables that affect the construction phase cost, the barrier phase cost and the repair phase cost are summarized in Table 4.1. To better understand the impact of individual variables on life cycle cost, the analysis described in section 4.1.6 for service life is repeated here for life cycle cost with different examples. The life cycle cost data for each design variable will be plotted within a variation chart.

Table 4.1: Design variables effects on LCC phases

Design variable	**Construction phase cost**	**Barrier phase cost**	**Repair phase cost**
Concrete cover			X
w/cm ratio	X		X
Silica fume	X		X
Slag cement	X		X
Fly ash "Class F"	X		X
Membrane		X	X
Sealer		X	X
Epoxy-coated steel	X		X

Figure 4.27 has been obtained by comparing Life Cycle Cost "LCC" for alternatives in cases 1 and 2 where the concrete cover distance is 2 inches to the same alternatives in cases 3 and 4 where the cover distance is 2.5 inches. For example, the value of LCC decrease percentage for alternative 2 has been obtained by calculating the percentage of difference between LCC for alternative 2 with membrane in case 1, which has a concrete cover of 2 inches, and LCC for alternative 2 with membrane in case 3, which has a concrete cover of 2.5 inches. Then, the percentage of difference between LCC for alternative 2 with sealer in case 1, which has a concrete cover of 2 inches, and LCC for alternative 2 with sealer in case 3, which has a concrete cover of 2.5 inches will be calculated. After that, the same will be done for alternative 2 in case 2, which has a concrete cover of 2 inches, and alternative 2 in case 4, which has a concrete cover of 2.5 inches. Finally, the average for these four values is calculated as the LCC decrease percentage for alternative 2 with changing the concrete cover distance (-13.8% as shown in Figure 4.27).

The same calculations are used for other alternatives in Figure 4.27 to obtain a variation chart for LCC decrease percentage with concrete cover varying while fixing other design variables. Observations from Figure 4.27 indicate that increasing the concrete cover distance was mostly effective in alternatives 5 and 6 where a combination of SCMs was used in each of these alternatives with a barrier. This high reduction in LCC in alternatives 5 and 6 with increasing the concrete cover distance can be attributed to very low repair costs for this combination of higher concrete cover and SCMs that are used in these alternatives.

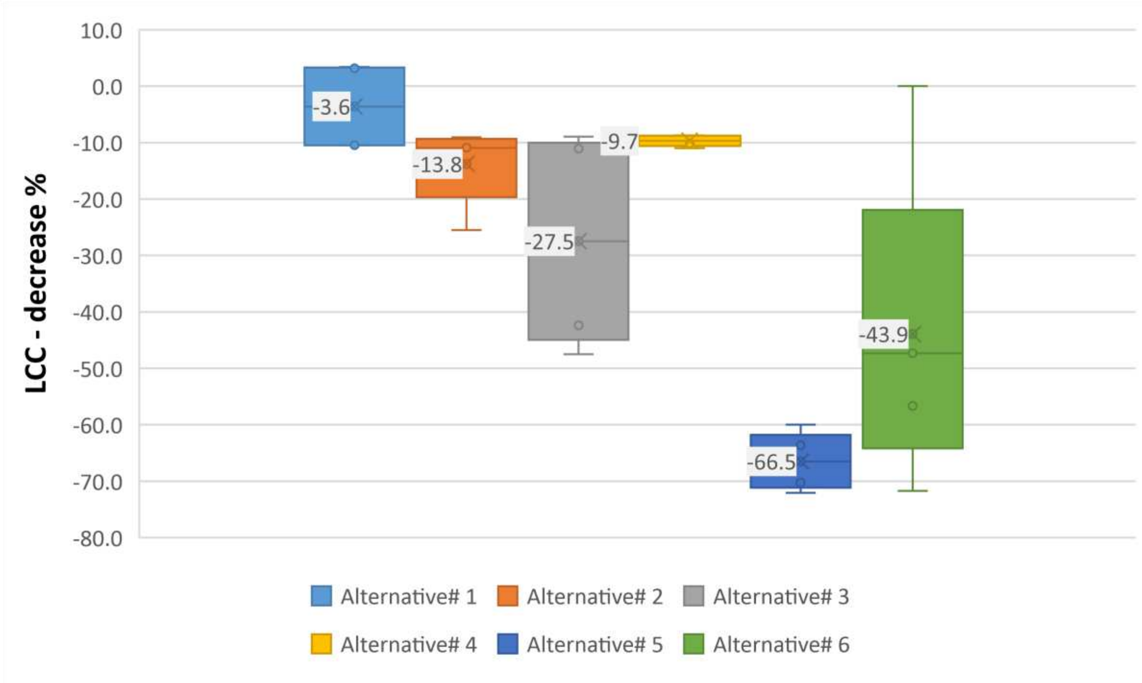

Figure 4.27: Average LCC decrease percentage due to increasing the concrete cover distance

The same calculations of varying the concrete cover distance to get a LCC variation chart were applied to Figure 4.28. The only difference is that Figure 4.28 has been obtained through changing the w/cm ratio from 0.34 in cases 2 and 4 to 0.3 in cases 1 and 3. It has been observed that decreasing the w/cm ratio was mostly effective in alternative 5 where a combination of SCMs was used in this alternative with a barrier. This high reduction in LCC in alternative 5 with decreasing the w/cm ratio can be attributed to very low repair costs.

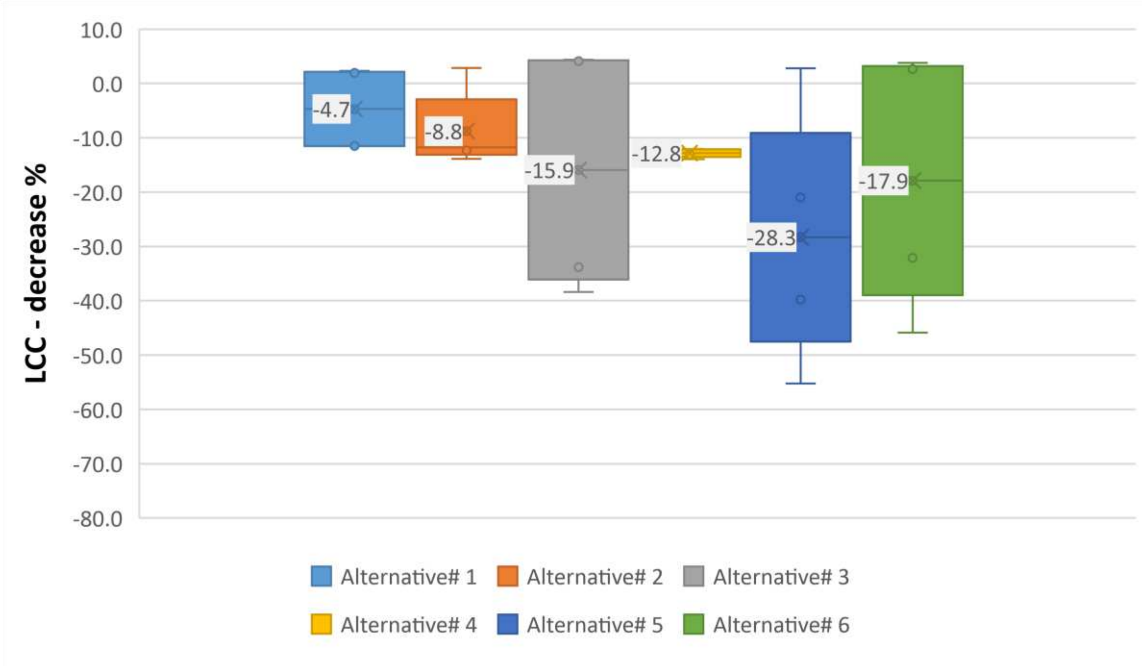

Figure 4.28: Average LCC decrease percentage due to decreasing w/cm ratio

Figure 4.29 has been obtained through using 5%silica fume only in alternative 2 in cases 1, 2, 3 and 4. For example, the value of LCC decrease percentage for case 2 has been obtained by calculating the percentage of difference between LCC for alternative 1with membrane, which has no SCMs in the concrete mixture, and LCC for alternative 2 with membrane, which has 5% silica fume only in the concrete mixture. Then in case 2 as well, the percentage of difference between LCC for alternative 1 with sealer, which has no SCMs in the concrete mixture, and LCC for alternative 2 with sealer, which has 5% silica fume only in the concrete mixture, will be calculated. Finally, the average for these two values is calculated as the LCC decrease percentage for case 2 with changing silica fume percentage only (-13.2% as seen in Figure 4.29). There are no whiskers in Figure 4.29 since the average in each case is obtained through two values instead of four values in each alternative as it was shown in Figure 4.27. The same calculations are used for other cases in Figure 4.29 that symbolize a variation chart for LCC decrease percentage with silica fume varying percentage while fixing other design variables. Using silica fume was mostly effective in case 3 where the concrete cover distance was 2.5in.and w/cm ratio was 0.3. This high reduction in LCC in case 3 with using silica fume can be attributed to very low repair costs.

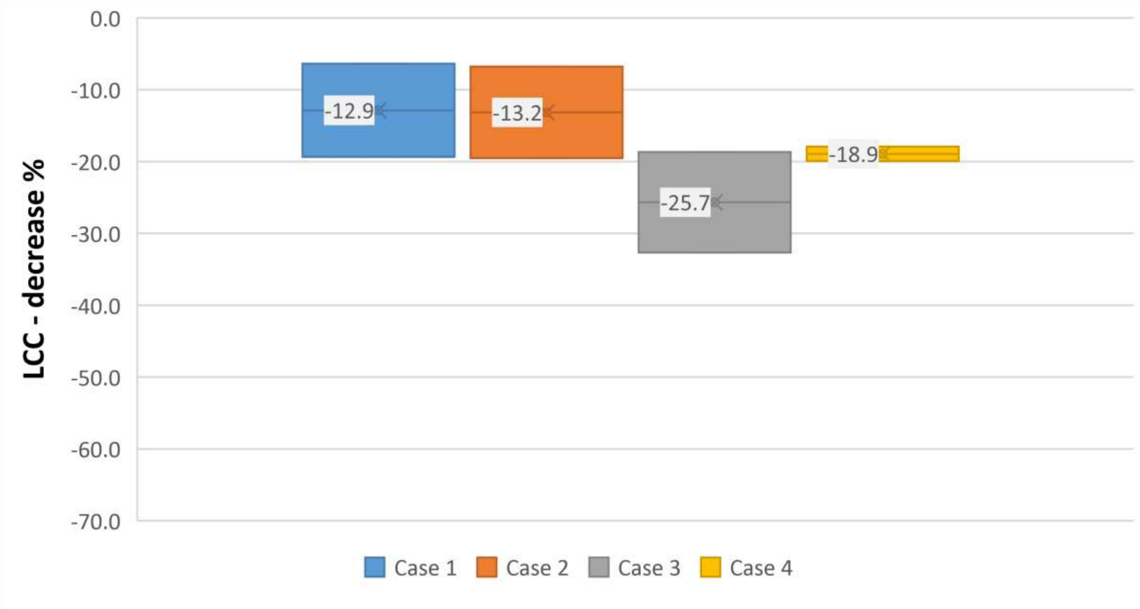

Figure 4.29: Average LCC decrease percentage due to silica fume usage

The same calculations of using silica fume to get a LCC variation chart were applied to Figure 4.30. The only difference is that Figure 4.30 has been obtained through using 35% slag cement in alternative 3 in cases 1, 2, 3 and 4. It has been observed that using slag cement was mostly effective in case 3 where the concrete cover distance was 2.5in.and w/cm ratio was 0.3. This high reduction in LCC in case 3 with using slag cement can be attributed to very low repair costs and low construction cost for slag cement mixtures.

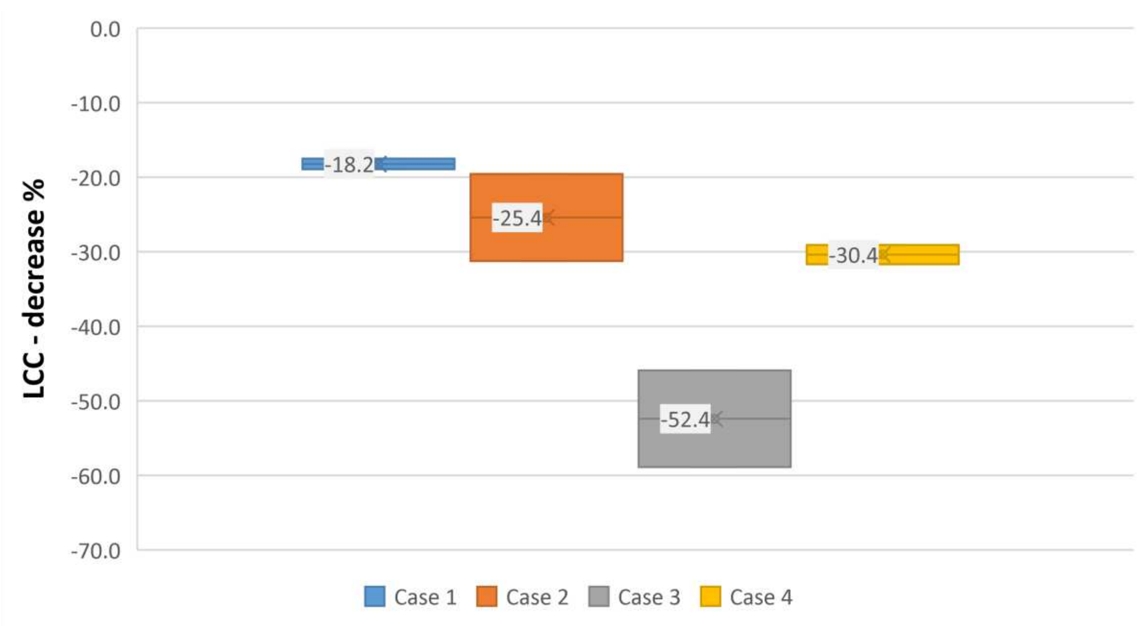

Figure 4.30: Average LCC decrease percentage due to slag cement usage

The same calculations of using silica fume to get a LCC variation chart were applied to Figure 4.31. The only difference is that Figure 4.31 has been obtained through using 20% fly ash “Class F” in alternative 4 in cases 1, 2, 3 and 4. Using fly ash was mostly effective in case 3 where the concrete cover distance was 2.5in.and w/cm ratio was 0.3. This high reduction in LCC in case 3 with using fly ash can be attributed to very low repair costs and low construction cost for fly ash mixtures.

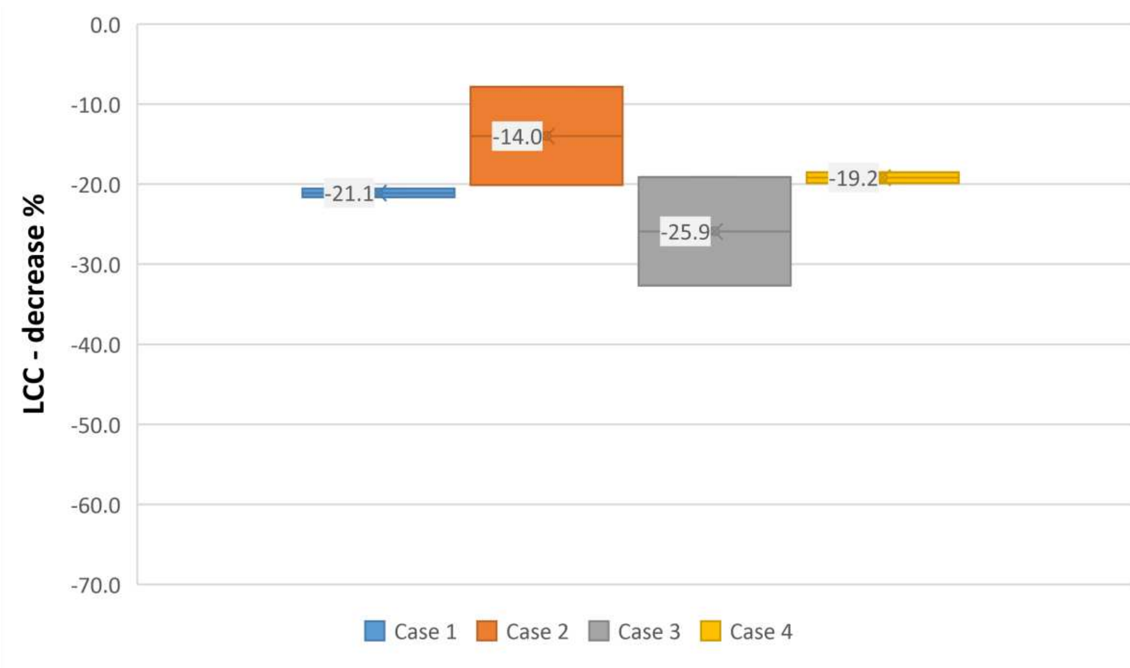

Figure 4.31: Average LCC decrease percentage due to fly ash usage

Figure 4.32 has been obtained through using membrane in cases 5 and 6. For example, the value of LCC decrease percentage for case 5 has been obtained by calculating the percentage of difference between LCC for alternative 1, which has no membrane, and LCC for alternative 3, which has membrane (-2.7% as seen in Figure 4.32). The same calculations are used within case 6 in Figure 4.32, which symbolize a variation chart for LCC decrease percentage, with membrane used in an alternative and not used in another alternative while fixing other design variables. Using membrane was mostly effective when fly ash was used in the concrete mixture. For slag cement mixture, the LCC was already low without using membrane therefore the reduction percentage was not high.

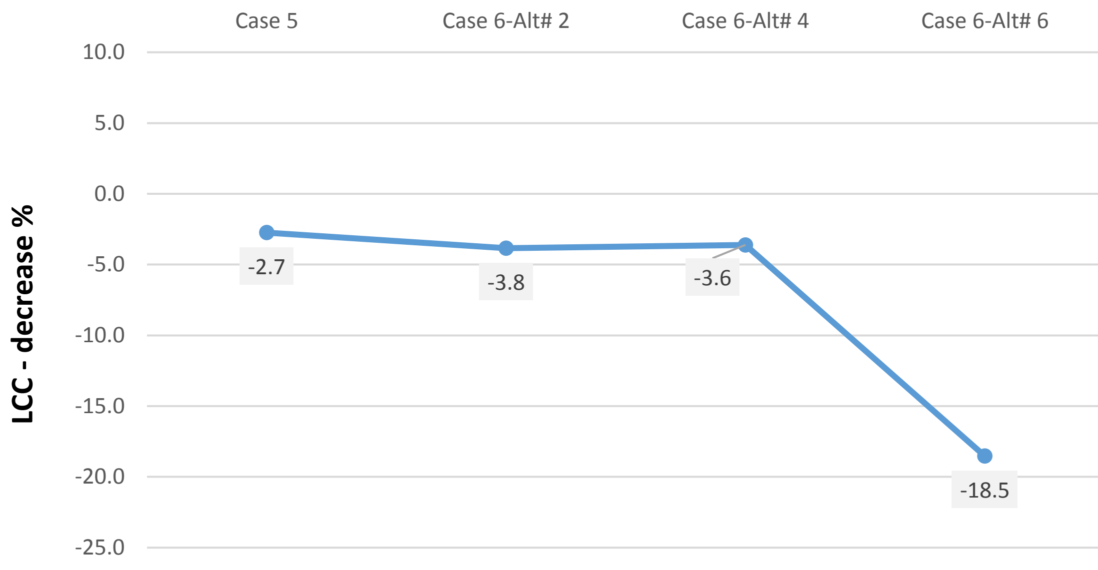

Figure 4.32: Average LCC decrease percentage due to using membrane

The same calculations of using membrane to get a LCC variation chart were applied to Figure 4.33. The only difference is that Figure 4.33 has been obtained through using sealer in cases 5 and 6 in different alternatives. It can be seen that using sealer was mostly effective in silica fume and fly ash mixtures. For Portland cement and slag cement mixtures with sealer, the results for an increment in the cost are not accurate because repair costs were calculated in the last year of the analysis period, where there is a fixed repair interval, 10 years, that Life-365 use for conducting repairs, which affected LCC results.

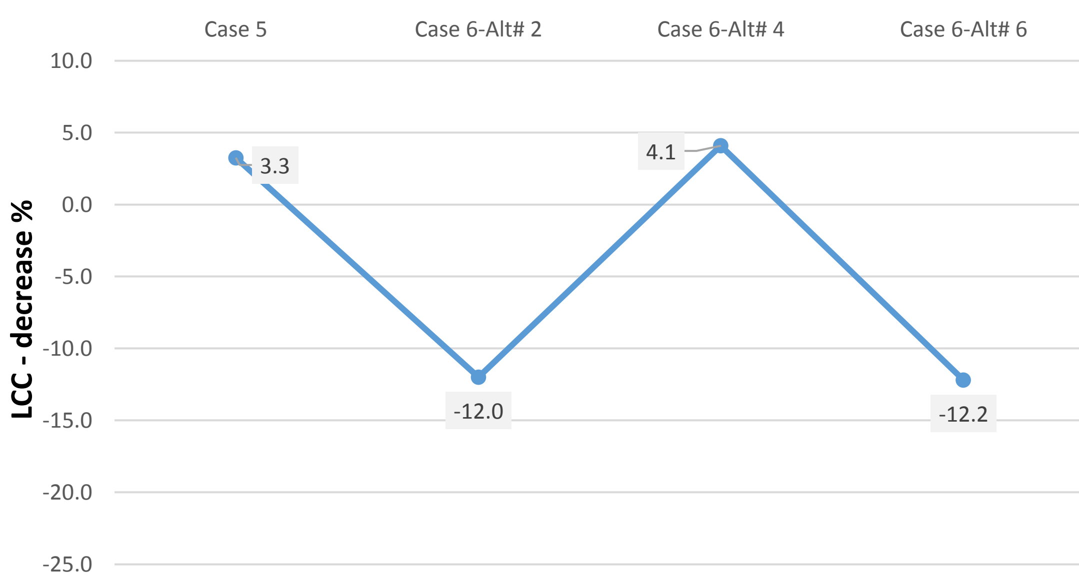

Figure 4.33: Average LCC decrease percentage due to using sealer

The same calculations of using membrane to get a LCC variation chart were applied to Figure 4.34. The only difference is that Figure 4.34 has been obtained through using epoxy-coated steel in cases 5 and 7 in different alternatives. Using epoxy-coated steel was mostly effective when silica fume and fly ash were used in the concrete mixtures. For slag cement mixture, the LCC was already low without using epoxy-coated steel therefore the reduction percentage was not high.

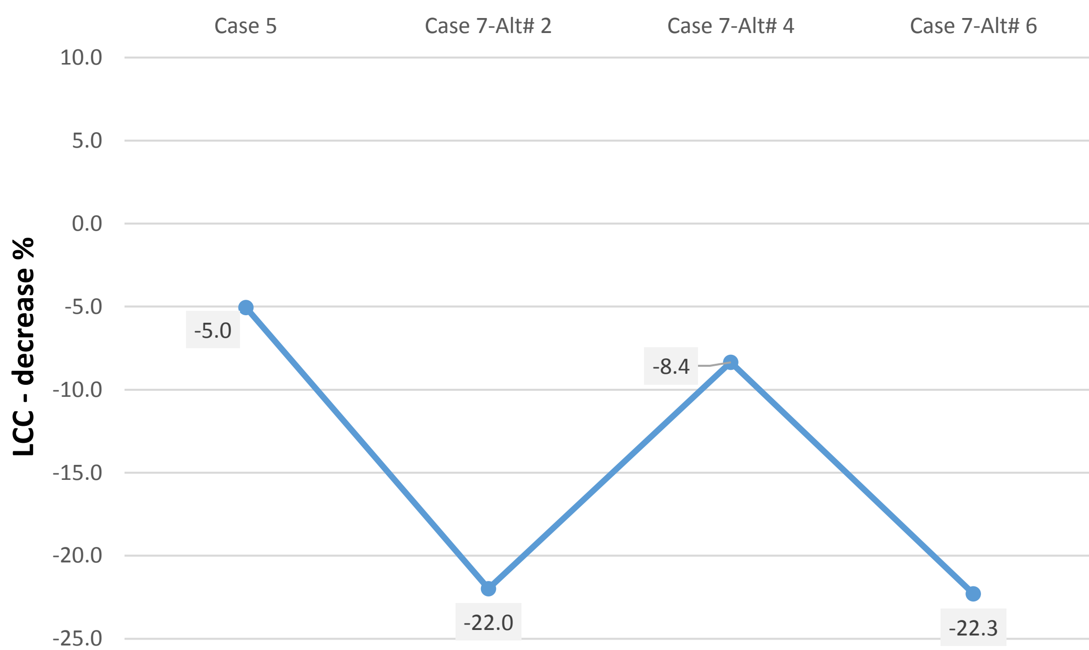

Figure 4.34: Average LCC decrease percentage due to using epoxy-coated steel

Finally and in general, it has been observed that the construction cost for some alternatives in some cases is higher than that for other alternatives in the same case. In addition, the barrier cost for some alternatives can vary in the same case depending on the type of barrier that is used and the number of reapplication times. However, the repair cost for the alternatives that have high construction and barrier cost is lower than that for the alternatives that have low construction and barrier cost. Therefore, the LCC for an alternative should be reviewed as a whole which means that alternatives can't be judged over their initial cost only. This is necessary to evaluate the cost effectiveness for an alternative when it is compared with other alternatives. The owners' desire to spend less money at the beginning of the project can cost them higher long-term costs through repairing the deteriorated elements of the structure. This conclusion shows the importance of investing money effectively at the beginning of the project that is necessary to extend the service life for parking structures and therefore spend less money on maintaining and repairing them. Figure 4.35 shows the average values for most effective design variables in terms of saving money and reducing LCC for a concrete slab in a parking structure.

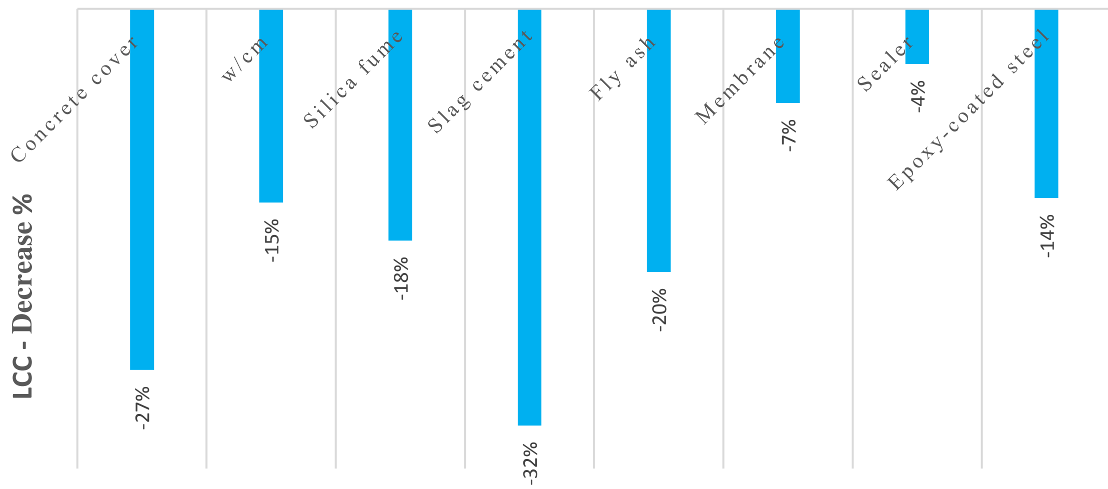

Figure 4.35: Variables change effects as an average percentage in decreasing LCC

Figure 4.36 shows the relationship between improving the service life and the reduction in LCC for each design decision,design variable. It is important to select the appropriate materials that are effective in increasing service life and saving money in different cost phases . For example, adding some extra cost at the beginning of the project has showed to enhance the durability of the concrete slab and to lower the total cost at the end of the design life.

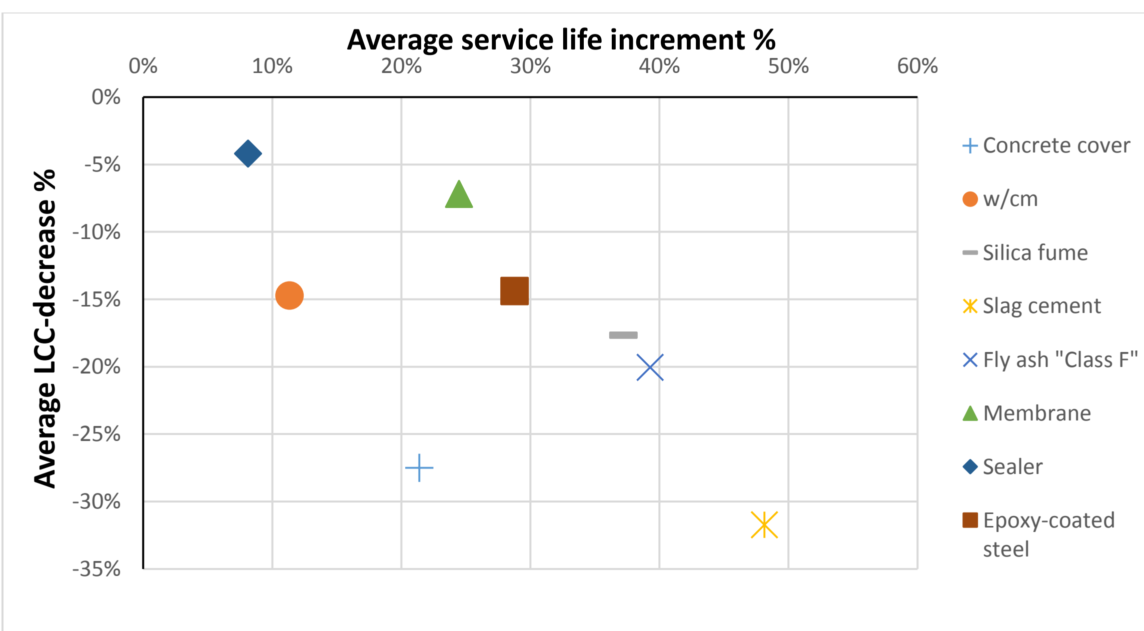

Figure 4.36: Average service life increment % vs Average LCC decrease %

5 CONCLUSIONS

The durability of parking garages is a significant characteristic that enhances their serviceability and helps determine costs associated with maintaining and repairing them. Chloride induced corrosion is one of the major problems that faces reinforced and prestressed concrete elements in parking structures. In this study, many design variables have been investigated to understand their individual effects on service lives and life cycle costs. The design decisions or design variables include changing the concrete cover distance to the embedded steel, using different w/cm ratios in concrete mixtures, using supplementary cementitious materials as a partial replacement for Portland cement in concrete mixtures, using different reinforcement and barriers types for the slab. All variables were considered through many simulations in Life-365 software using a 100-year analysis period.

5.1 Conclusions

The following conclusions were reached after conducting this study:

1- Slag cement was the best supplementary cementitious material and design variable for decreasing the life cycle cost of the concrete slab especially with a high concrete cover and low w/cm ratio. The percentage of slag cement in this study was 35% replacement of Portland cement as recommended by (Kosmatka, Kerkhoff, & Panarese, 2011). The reduction in LCC can be attributed to the low price of slag cement as a SCM in comparison with Portland cement, which means lower construction cost. In addition, the ability of slag cement to reduce permeability of the concrete, by increasing the diffusion decay index, enhanced the service life and minimized the repair cost required for the remainder of the design life. The average increase percentage in service life due to slag cement usage was 48% while the average percentage of decrease in LCC was 32%.

2- Increasing the concrete cover distance from 2in. to 2.5in.was of the second most effective techniques for decreasing the life cycle cost for the concrete slab especially when a combination of SCMs was used in the concrete mixture. The reduction in LCC can be attributed to zero change in construction cost (by assuming an increase in cover without an increase in the amount of cement). Furthermore, a longer distance to the embedded steel means longer times for corrosion to start and propagate, extending the service life and minimizing the repair. The average percentage for service life increase due to increasing the concrete cover distance was 21% while the average percentage for reduction in LCC was 27%.

3- Fly ash “Class F” was third in terms of decreasing the life cycle cost for the concrete slab especially with a high concrete cover and low w/cm ratio. The replacement percentage considered in this study was 20%. Fly ash affects LCC the same way as slag cement through lower construction costs and lower repair costs. The average percentage for service life increase due to fly ash usage was 39% while the average percentage of decrease in LCC was 20%.

4- Silica fume was fourth in terms of decreasing the life cycle cost for the concrete slab especially with a high concrete cover and low w/cm ratio. This study considered the replacement of 5 % of the Portland cement with silica fume. Using silica fume increases the construction cost for the concrete mixtures because of the high price of silica fume in comparison with Portland cement. However, the reduction in LCC can be attributed to the ability of silica fume to enhance the service life. Silica fume was particularly successful at extending the service life through reduction in concrete permeability by lowering the diffusion coefficient. The average increase percentage for service life due to silica fume usage was 37% while the average percentage of decrease in LCC was 18%.

5- Decreasing the w/cm ratio from 0.34 to 0.3 was fifth in terms of decreasing the life cycle cost for the concrete slab especially when a combination of SCMs was used in the concrete mixture. Reducing the w/cm ratio increases the construction cost for concrete mixtures because higher cementitious materials are required. However, the reduction in LCC can be attributed to the ability of low w/cm ratio to enhance the service life and minimize the repair cost required for the remainder of the design life. The average percentage for service life increase due to lower w/cm ratio was 11% while the average percentage of decrease in LCC was 15%.

6- Epoxy-coated steel comes after in its ability to decrease life cycle cost for the concrete slab. Using epoxy-coated steel increases the construction cost because of the high price of this steel in comparison with black steel. However, the reduction in LCC can be attributed to the ability of epoxy-coated steel to enhance the service life, where epoxy-coated steel has a corrosion propagation period that is higher than that of black steel, which minimizes the repair cost for the rest of the design life. The average increase percentage for service life due to using epoxy-coated steel was 29% while the average percentage of decrease in LCC was 14%.

7- Membrane was seventh in terms of decreasing the life cycle cost for the concrete slab. Using membrane at the beginning of the project and reapplying it once initiates a new cost phase that is the barrier cost. This cost will be added to the construction phase cost when membrane is used in an alternative. However, the reduction in LCC can be attributed to the ability of a membrane to enhance the service life. The membrane reduces the chloride built-up rate at the concrete surface and its age of failure is 20 years as assumed in Life-365, which minimizes the repair cost for the rest of the design life. Finally, sealer was the last effective design variable to minimize the life cycle cost for the concrete slab. Sealer has the same capabilities as a membrane with an age of failure of 5 years as assumed in Life-365. Membrane was more cost effective in reducing life cycle cost than sealer throughout the design life. The average percentage for service life increase due to using membrane and sealer was 24% and 8% respectively while the average percentage of decrease in LCC was 7% and 4% respectively.

8- The use of a combination of SCMs in a concrete mixture has proved to be very effective in decreasing the life cycle cost because low permeability mixtures are produced which means longer time to start first repair.

9- It has been noticed that investing money effectively at the beginning of the project by choosing the suitable design variables is important in reducing the life cycle cost for the concrete slab because lower repair cost would be required in the future due to high service lives.

5.2 Future work

1- The effects of severe weather conditions on service life and LCC in other cities around the US can be examined using Life-365.

2- Uncertainty analysis can also be investigated in Life-365.

3- Joints as another element in a parking garage with different types of fill-out concrete, which possess different characteristics, can be examined in terms of its effects on service life and LCC. Joints also represent an important element in parking structures where they can be penetrated by salty water and other deleterious materials that can cause corrosion and affect the serviceability of the structure.

4- The ability of joints to withstand volume change stresses due to temperature fluctuations during the year can also be investigated with different fill-out concretes. Then, the cost effectiveness can be evaluated using LCCA.

5- SCMs like fly ash and slag cement are environmental friendly materials. Therefore, Life Cycle Assessment “LCA” can be used to evaluate their impact on the environment.

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APPENDIX A
CONCRETE MIX PROPORTIONS DESIGN EXAMPLE

Note: The design and proportioning of concrete mixtures is an empirical process and these hand calculations were designed for the purpose of this study only. The quantities and costs provided may differ with different assumptions and they are intended to develop a better understanding on how different design variables, which include concrete mixtures, affect life cycle cost.

Concrete mixtures were designed using the absolute volume method (Kosmatka et al., 2011). Case 1 which has a concrete cover =2 in., w/cm ratio =0.3 and Mix #5 which has the following percentages for SCMs (Fly ash "class F"=20%, Slag cement=0%, Silica fume=5%) is chosen for this design example. Assume the following:

- The mix yields 1 m^3
- The concrete will be exposed to severe exposure classification"F3".
- Compressive strength required = 45 Mpa → w/cm= 0.3
- Slump required 75-100 mm , 19 mm size coarse aggregate , Air-entrained concrete

So, Water content= 184 Kg/m^3 (Table 9-5 in (Kosmatka et al., 2011))

Note: Rounded gravel was used in the mix and it should reduce the water content of the table by about 24 Kg/m^3. In addition, high range water reducer (HRWR) will reduce water content by 10%.

New water content= (184-24)-0.1*(184-24) =144 Kg/m^3

So, cementitious materials content=144/0.3=480 Kg > 320 kg OKAY (Table 9-7 (Kosmatka et al., 2011))

- Cement content= 0.75*480= 360 Kg
- Fly ash "Class F" content= 0.2*480=96 Kg
- Silica Fume content= 0.05*480=24 Kg

- Coarse Aggregate (C.A)

Assume the following:

1- Bulk density of 1600 Kg/m^3.

2- Bulk volume for 2.8 fineness modulus of fine aggregate=0.62 m^3.

C.A content= 1600*0.62= 992 Kg

- <u>Total Air Content in an air-entrained concrete</u>

Assume the following:

1- 6% for 19 mm size coarse aggregate and severe exposure (F3). (Table 9-5 in (Kosmatka et al., 2011))

2- Air-entraining dosage =0.5 g/Kg.

So, Air-entraining content =0.5 *480= 0.24 Kg.

- <u>HRWR dosage</u>

Assume this dosage to equal 4.15 g/Kg for these cementitious materials.

HRWR content= 480*4.15= 1.992 Kg

- <u>Volumetric computations</u>

Material volume= Material mass/ (Material specific gravity*water bulk density)

- Cement volume= 360/ (3.14*1000)=0.114 m^3
- Water volume= 144/ (1*1000)=0.144 m^3
- Fly ash "Class F" volume= 96/ (2.6*1000)=0.0369 m^3
- Silica fume volume=24/ (2.3 *1000)=0.0104 m^3
- Coarse Aggregate volume= 992/ (2.68*1000)=0.37 m^3
- HRWR volume= 1.992/ (1 *1000)=0.001992 m^3
- Total Air volume= (6/100) *1 m^3 = 0.06 m^3
- Fine Aggregate volume= 1-Total volume= 1-0.7382=0.2618 m^3

So, Fine Aggregate (F.A) content= 0.2618*1000*2.64 = 691.28 Kg

A summarized table for the mix quantities and cost calculation is provided in Table A.1 the below which is the same Table 3.5 in chapter 3.

Table A.1: Concrete mix cost calculations (Case 1, w/cm=0.3, Mix #5)

Materials	**Percentage "%"**	**Quantity "Kg"**	**Specific Gravity**	**Volume "m^3"**	**Cost "$/metric ton"**	**Cost "$"**	
Cement	75	360	3.14	0.114	143	51.48	
Fly Ash class F	20	96	2.6	0.0369	66	6.336	
Slag Cement	0	0	2.9	0	50	0	
Silica Fume	5	24	2.3	0.0104	990	23.76	
Coarse Aggregate		992	2.68	0.37	18	17.8	
Fine Aggregate		691.28	2.64	0.2618	12	8.29	
Water		144	1	0.144	Neglected	0	
HRWR		1.992	1	0.001992	3170	6.31	
Air Entraining		0.24	1	0.00024	Neglected	0	
Air	6			0.05976	0	0	
Sum				1		114 for 1 m^3	87.2 for 1 yd^3

APPENDIX B

RESULTS OF THE ESTIMATED SERVICE LIFE AND LIFE CYCLE COST ANALYSIS

B.1 Service life estimations

B.1.1 Case 1, Concrete cover =2 in. & w/cm=0.3

The estimated service life, which is initiation period plus propagation period, in case 1 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.1.

Table B.1: Service life estimation for case 1

	Supplementary Cementitious Materials "SCMs"			**Service life "years"**	
Alternative or mix #	**Fly ash "Class F" %**	**Slag Cement %**	**Silica Fume %**	**Black steel & Membrane "BM"**	**Black steel & Sealer "BS"**
1 "Base mix"	0	0	0	32.6	25.2
2	0	0	5	48.7	41
3	0	35	0	58.4	49.4
4	20	0	0	50.6	41.8
5	20	0	5	89.9	81.4
6	0	35	5	>100	98.8

B.1.1.1 Concrete mixtures with black steel and membrane

Figure B.1shows the effect of using black steel and membrane on the estimated service life for different alternatives. In addition, Figure B.2 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.3 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

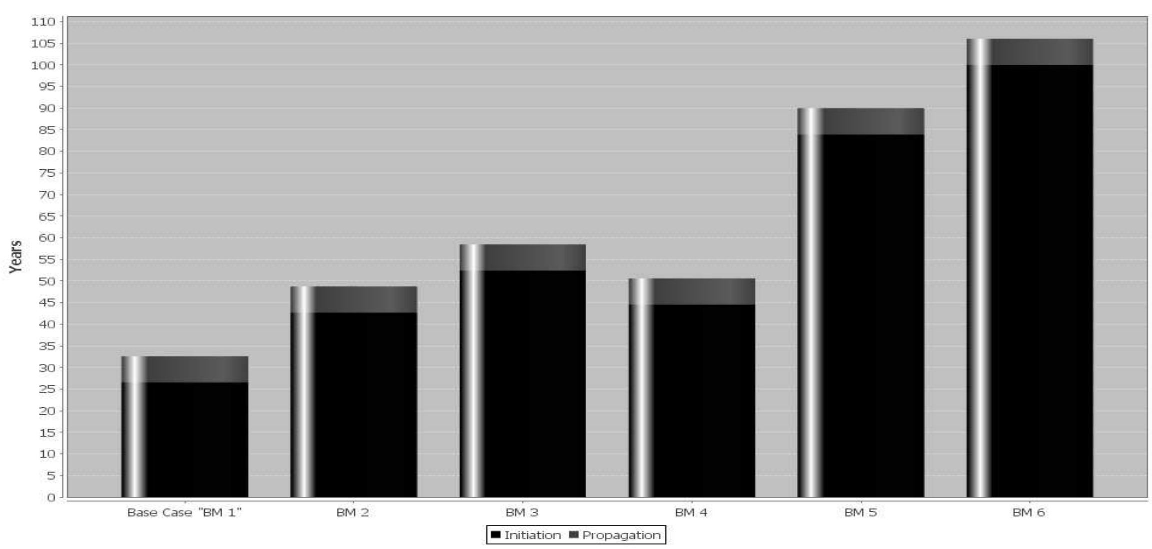

Figure B.1: Service life estimation for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

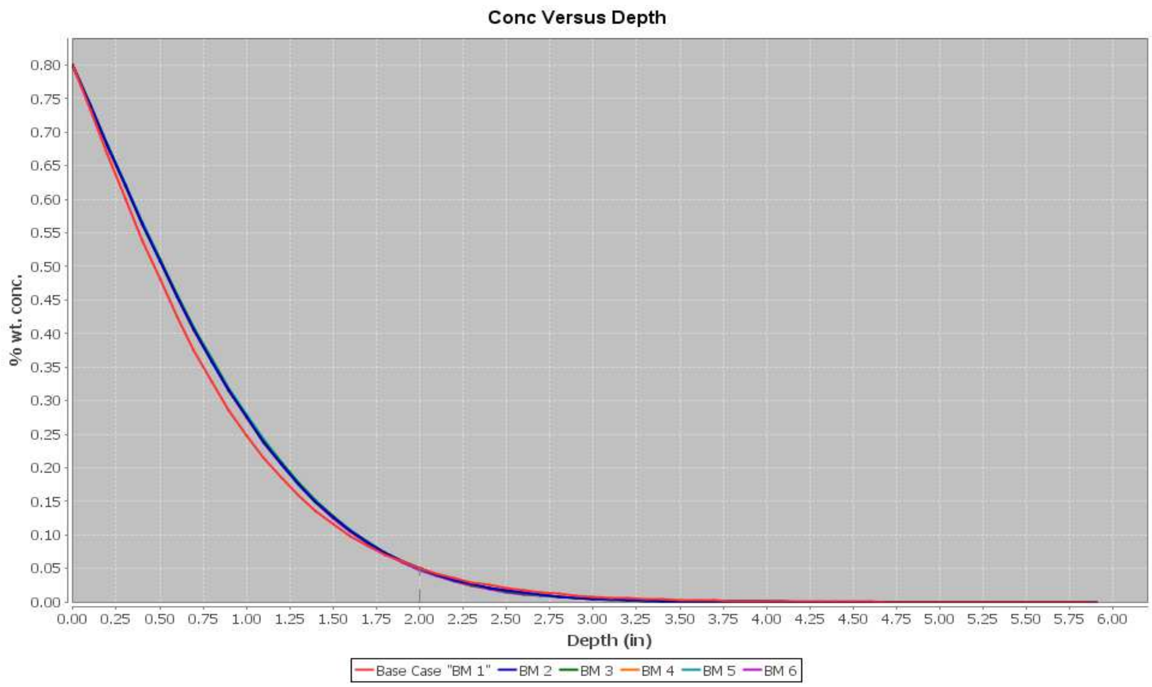

Figure B.2: Chloride concentration percentage as weight of concrete versus total slab depth for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

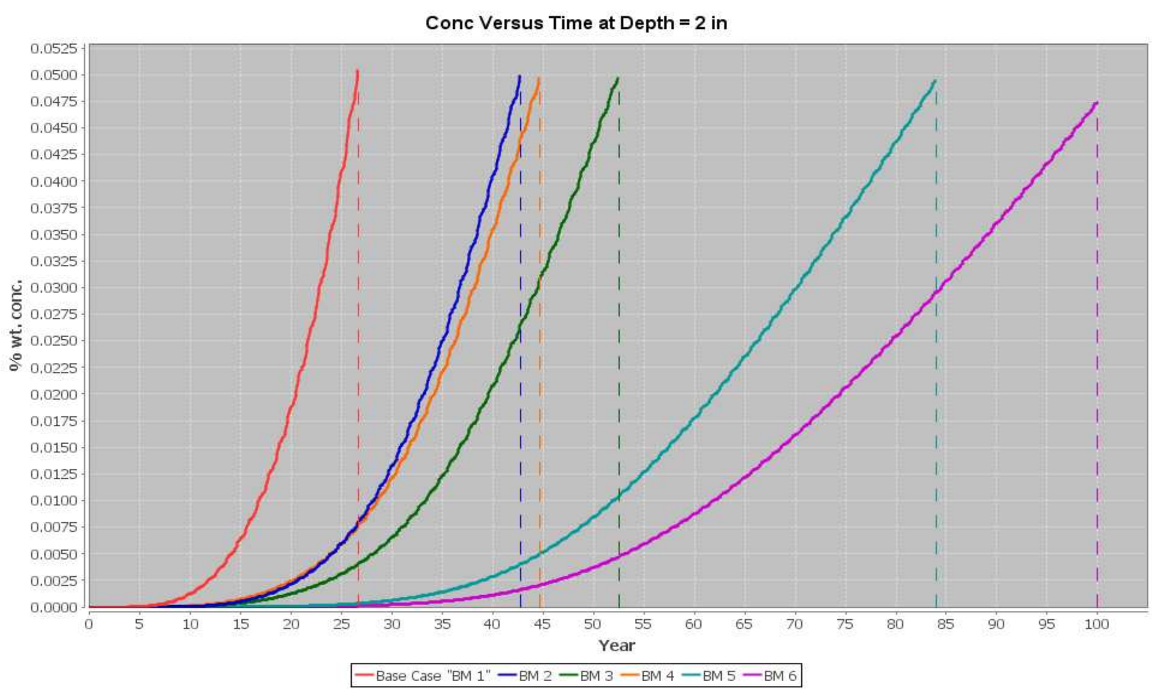

Figure B.3: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

B.1.1.2 Concrete mixtures with black steel and sealer

Figure B.4 shows the effect of using black steel and sealer on the estimated service life for different alternatives. In addition, Figure B.5 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.6 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

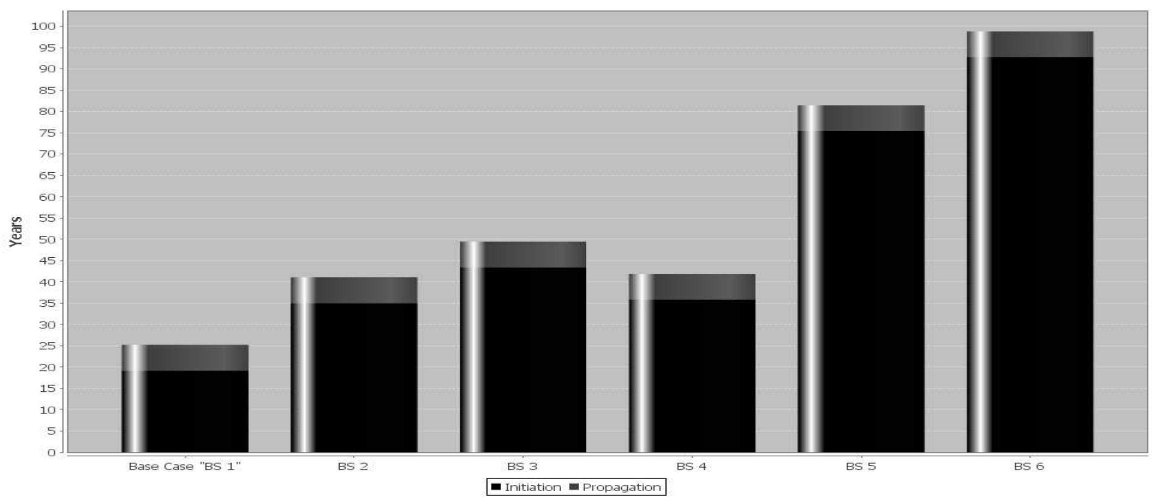

Figure B.4: Service life estimation for case1 with sealer “cover of 2in. and w/cm of 0.3” (plotted by Life-365 software)

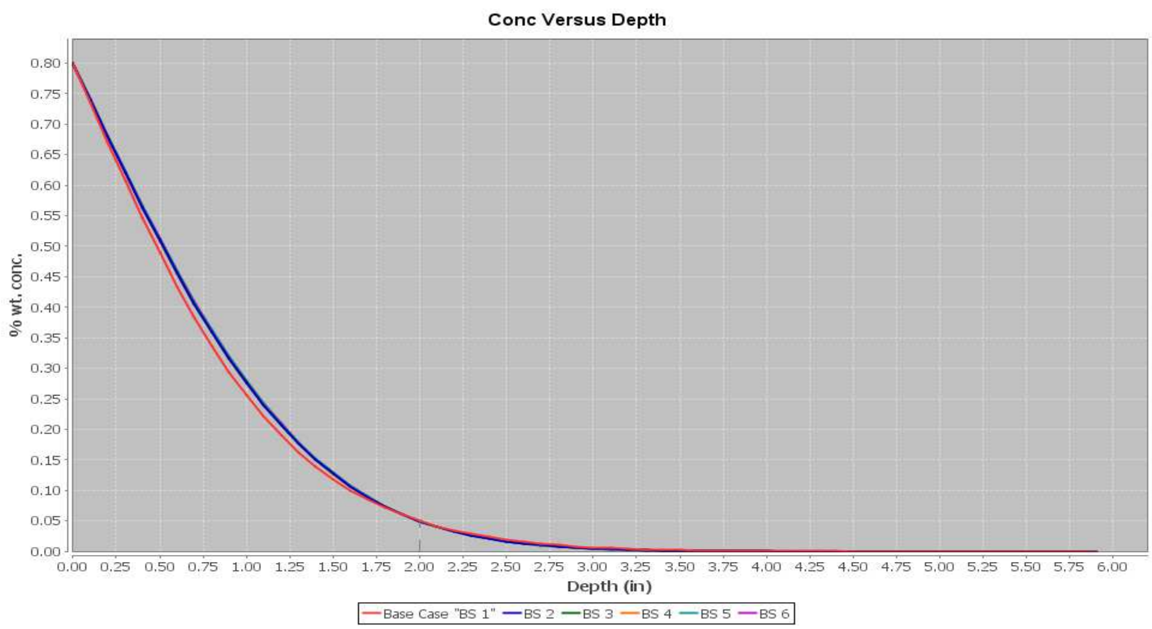

Figure B.5: Chloride concentration percentage as weight of concrete versus total slab depth for case1 with sealer “cover of 2in. and w/cm of 0.3” (plotted by Life-365 software)

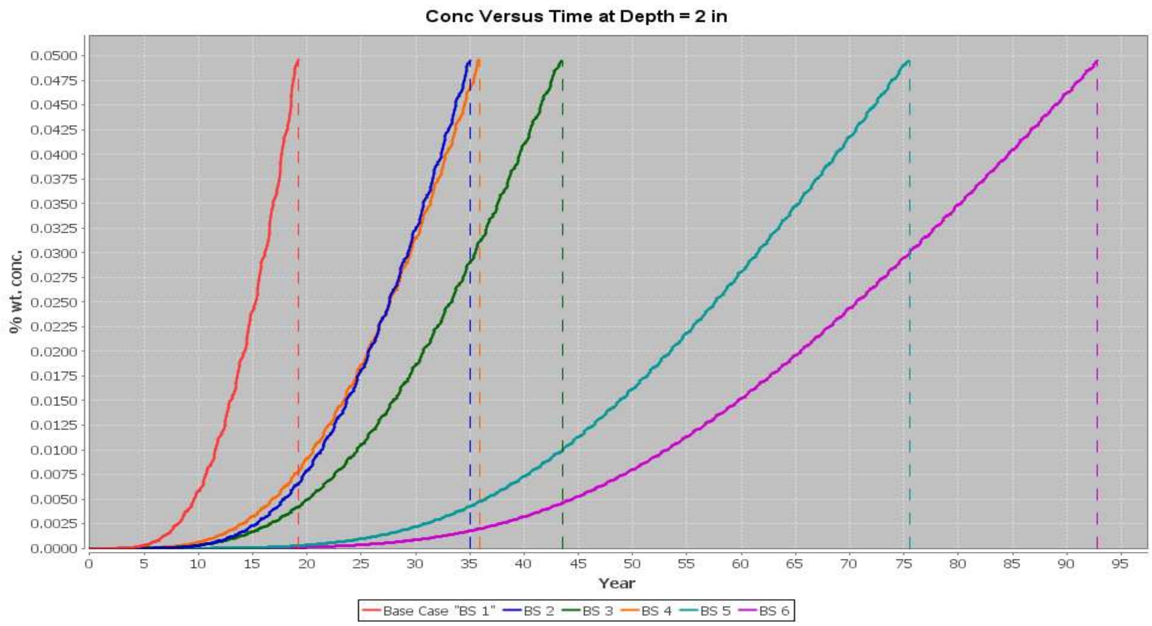

Figure B.6: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case1 with sealer "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

B.1.2 Case 2, Concrete cover =2 in. & w/cm=0.34

The estimated service life, which is initiation period plus propagation period, in case 2 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.2.

Table B.2: Service life estimation for case 2

	Supplementary Cementitious Materials "SCMs"			Service life "years"	
Alternative or mix #	Fly ash "Class F" %	Slag Cement %	Silica Fume %	Black steel & Membrane "BM"	Black steel & Sealer "BS"
1 "Base mix"	0	0	0	29.7	22.7
2	0	0	5	43	35.5
3	0	35	0	50.6	41.7
4	20	0	0	44.5	35.8
5	20	0	5	76.1	67.5
6	0	35	5	90.4	81.4

B.1.2.1 Concrete mixtures with black steel and membrane

Figure B.7 shows the effect of using black steel and membrane on the estimated service life for different alternatives. In addition, Figure B.8 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.9 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

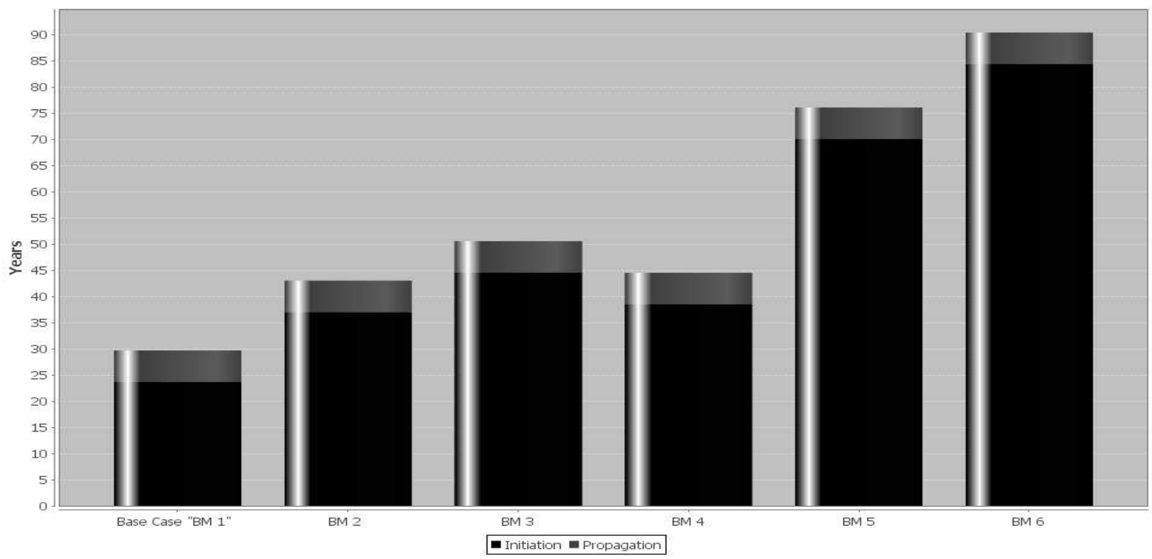

Figure B.7: Service life estimation for case2 with membrane “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

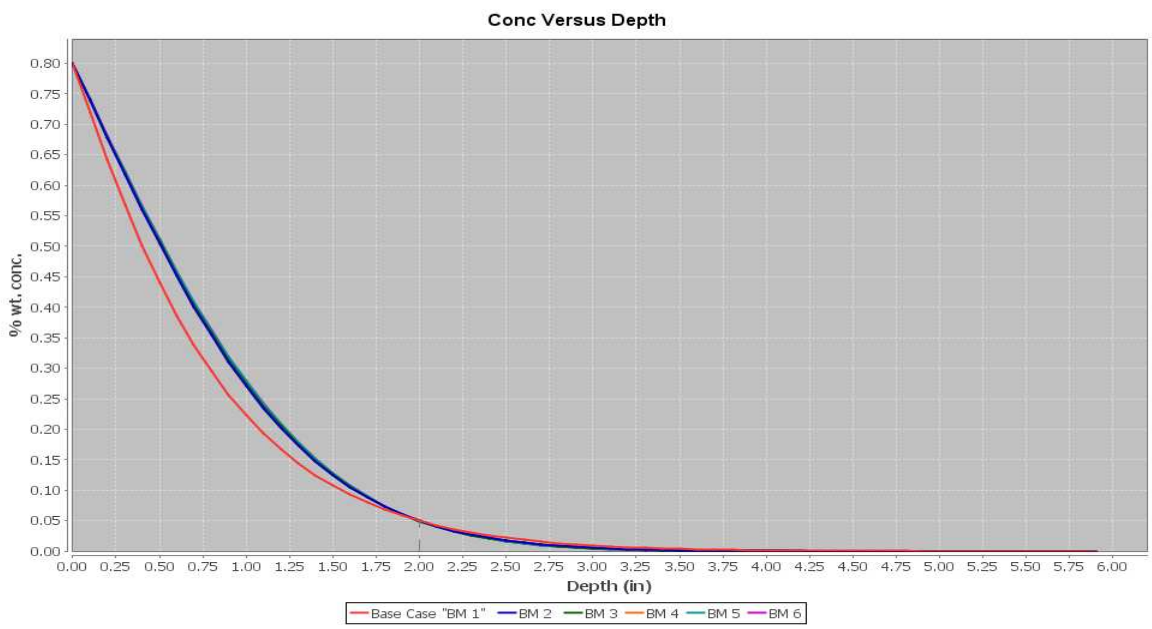

Figure B.8: Chloride concentration percentage as weight of concrete versus total slab depth for case2 with membrane “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

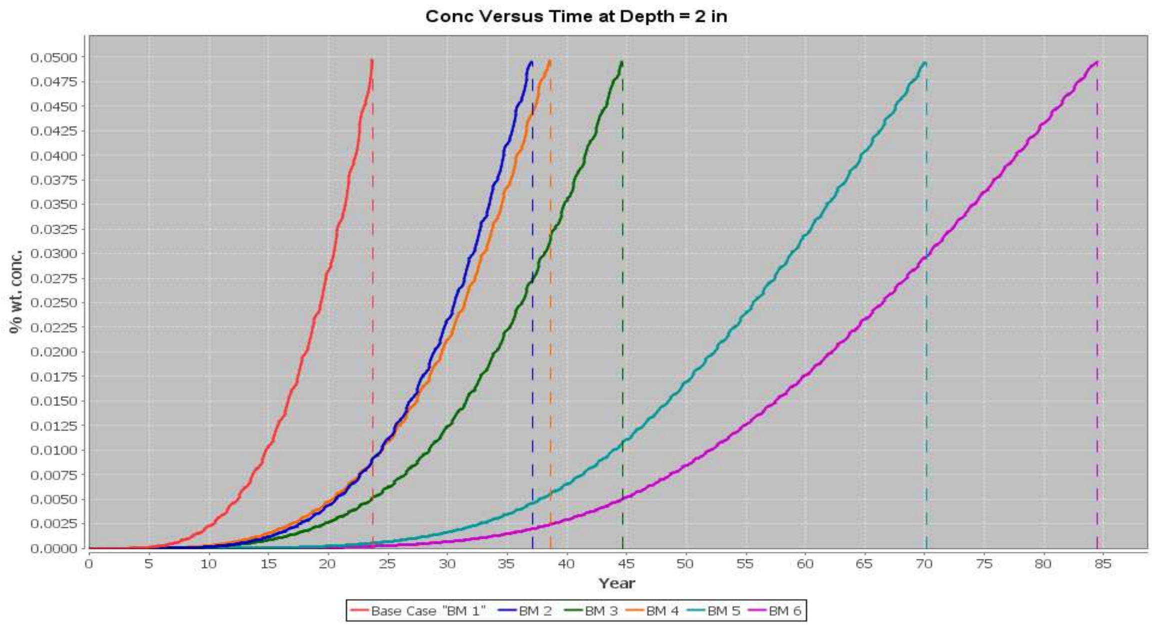

Figure B.9: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case2 with membrane “cover of 2in.and w/cm of 0.34” (plotted by Life-365 software)

B.1.2.2 Concrete mixtures with black steel and sealer

Figure B.10 shows the effect of using black steel and sealer on the estimated service life for different alternatives. In addition, Figure B.11 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.12 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

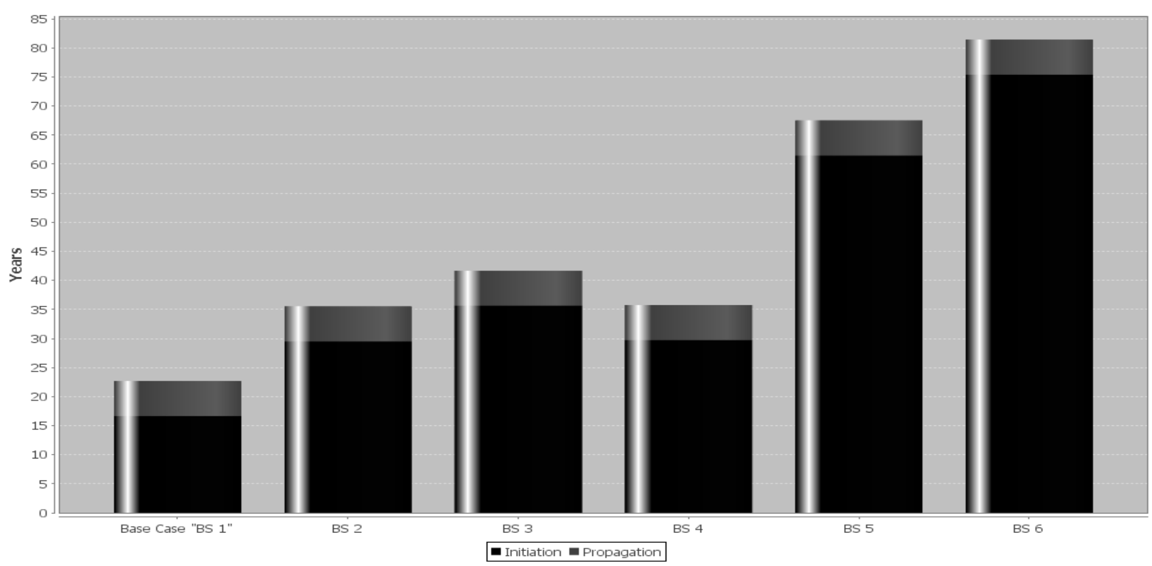

Figure B.10: Service life estimation for case2 with sealer “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

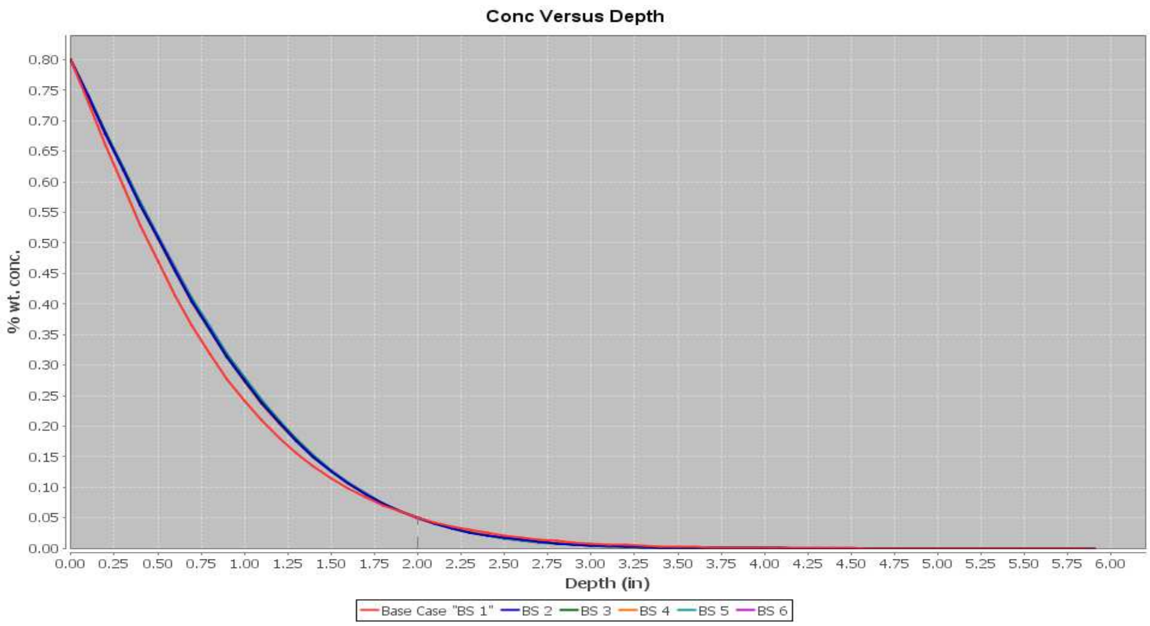

Figure B.11: Chloride concentration percentage as weight of concrete versus total slab depth for case2 with sealer "cover of 2in. and w/cm of 0.34" (plotted by Life-365 software)

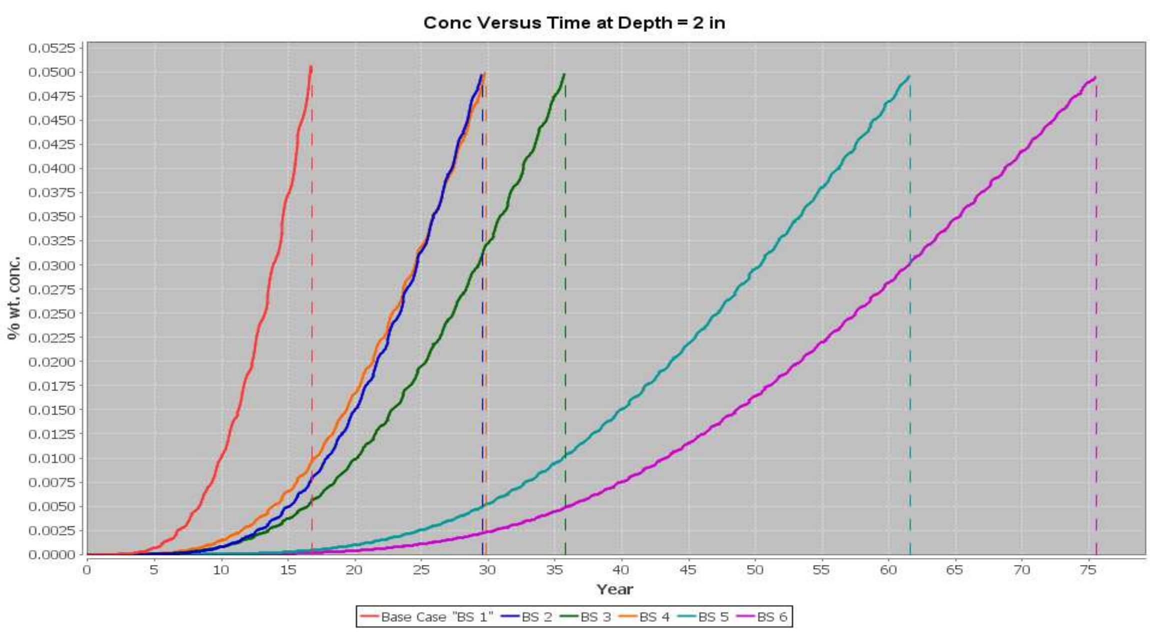

Figure B.12: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case2 with sealer "cover of 2in.and w/cm of 0.34" (plotted by Life-365 software)

B.1.3 Case 3, Concrete cover =2.5 in. & w/cm=0.3

The estimated service life, which is initiation period plus propagation period, in case 3 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.3.

Table B.3: Service life estimation for case 3

	Supplementary Cementitious Materials "SCMs"			Service life "years"	
Alternative or mix #	Fly ash "Class F" %	Slag Cement %	Silica Fume %	Black steel & Membrane "BM"	Black steel & Sealer "BS"
1 "Base mix"	0	0	0	39.7	32.2
2	0	0	5	64.7	57
3	0	35	0	80.2	71.3
4	20	0	0	68	59.4
5	20	0	5	>100	>100
6	0	35	5	>100	>100

B.1.3.1 Concrete mixtures with black steel and membrane

Figure B.13 shows the effect of using black steel and membrane on the estimated service life for different alternatives. In addition, Figure B.14 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.15 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

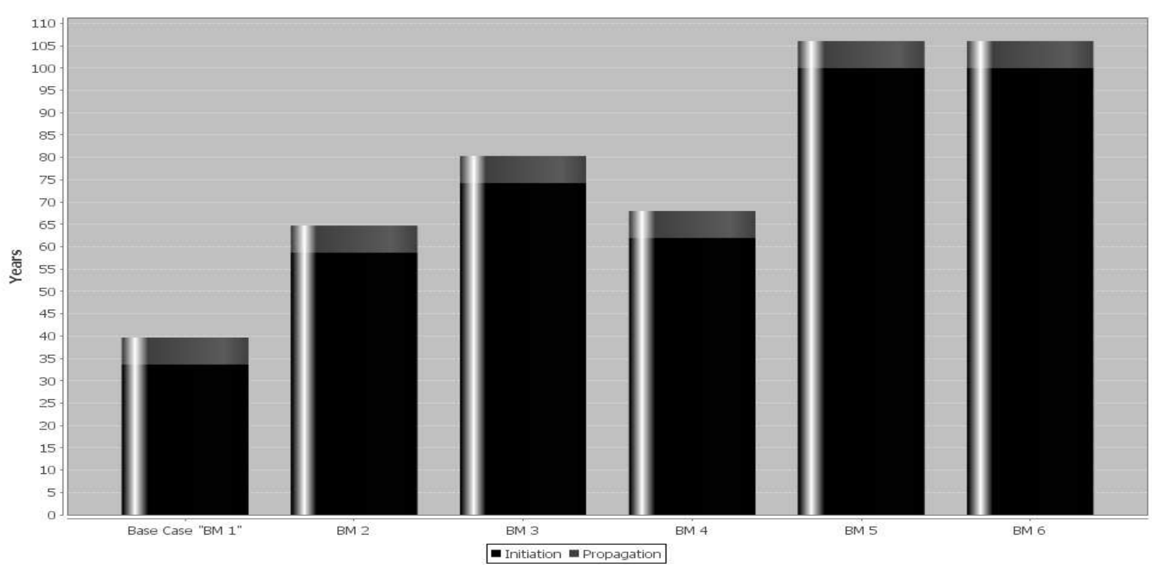

Figure B.13: Service life estimation for case3 with membrane "cover of 2.5in. and w/cm of 0.3" (plotted by Life-365 software)

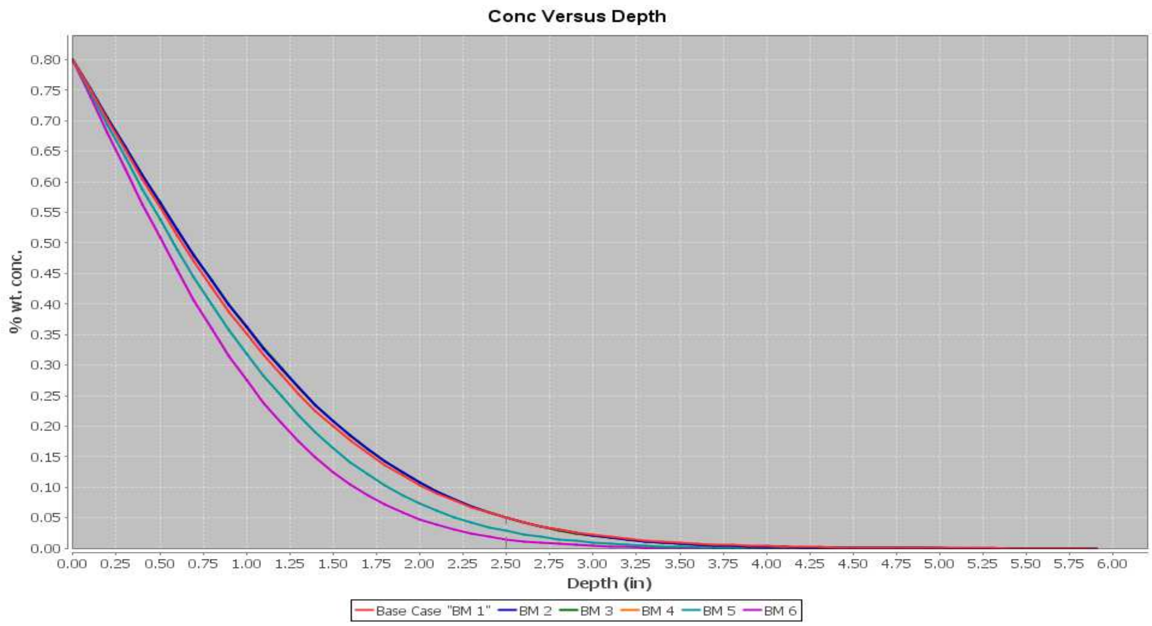

Figure B.14: Chloride concentration percentage as weight of concrete versus total slab depth for case3 with membrane “cover of 2.5in.and w/cm of 0.3” (plotted by Life-365 software)

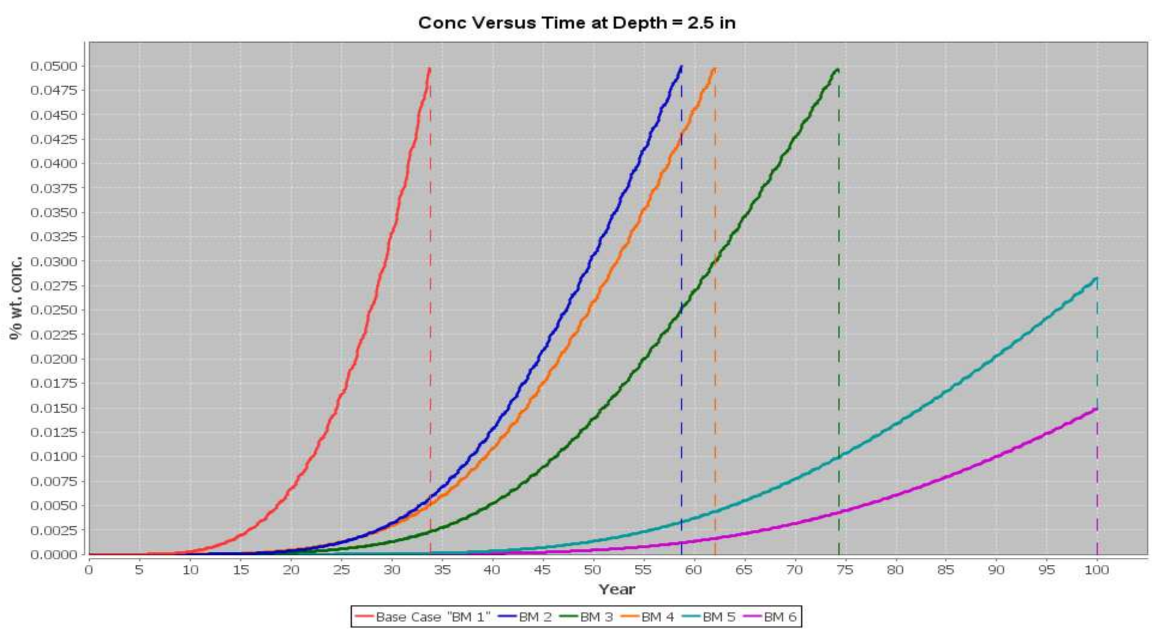

Figure B.15: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case3 with membrane “cover of 2.5in.and w/cm of 0.3” (plotted by Life-365 software)

B.1.3.2 Concrete mixtures with black steel and sealer

Figure B.16 shows the effect of using black steel and sealer on the estimated service life for different alternatives. In addition, Figure B.17 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.18 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

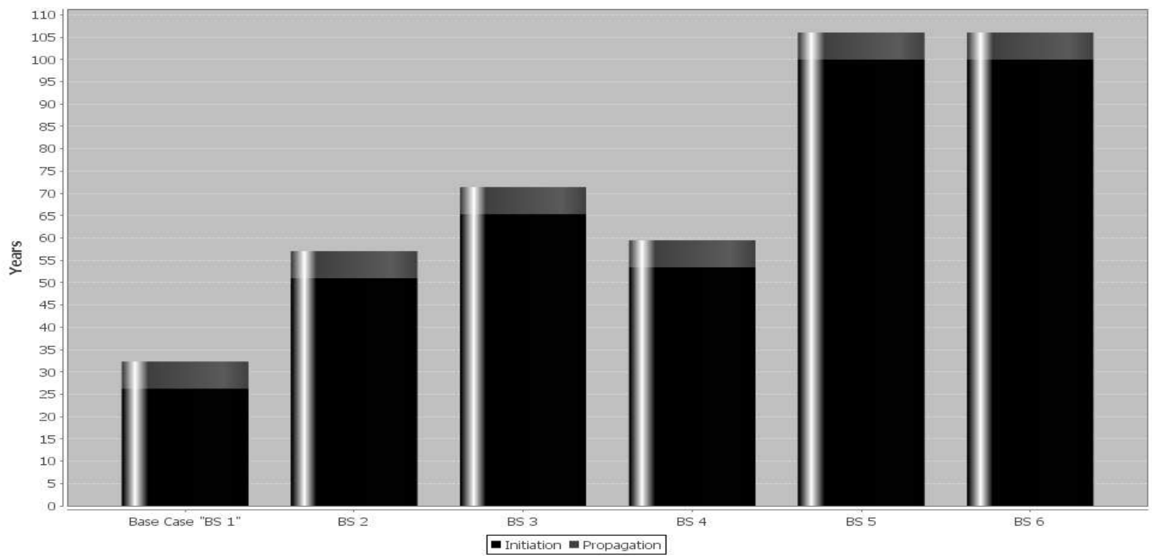

Figure B.16: Service life estimation for case3 with sealer “cover of 2.5in.and w/cm of 0.3” (plotted by Life-365 software)

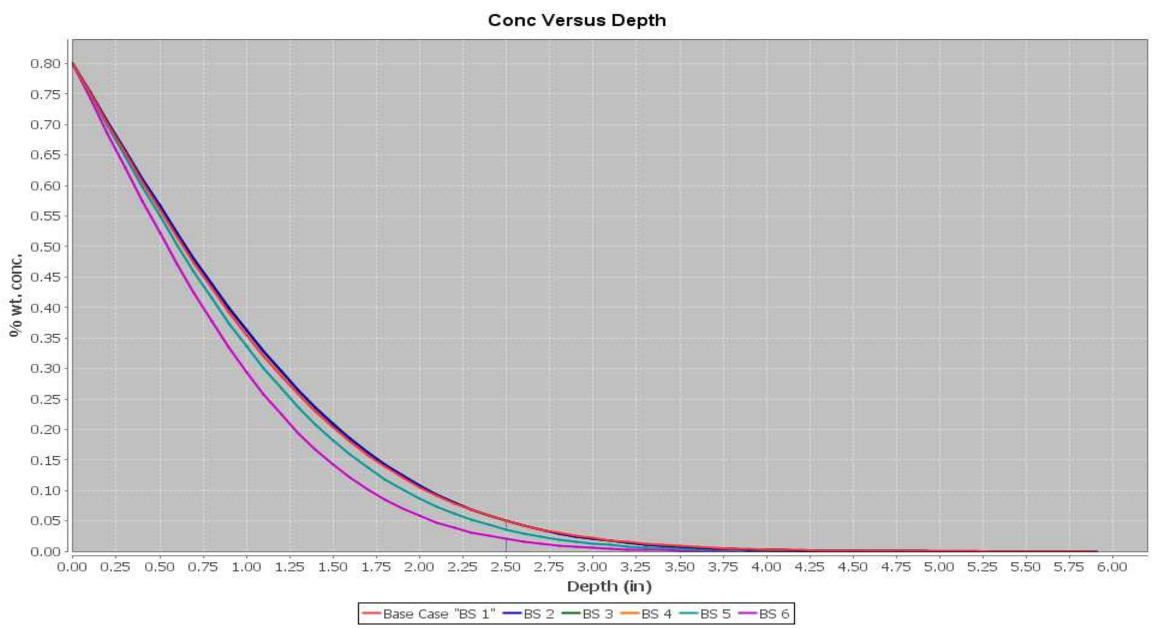

Figure B.17: Chloride concentration percentage as weight of concrete versus total slab depth for case3 with sealer “cover of 2.5in.and w/cm of 0.3” (plotted by Life-365 software)

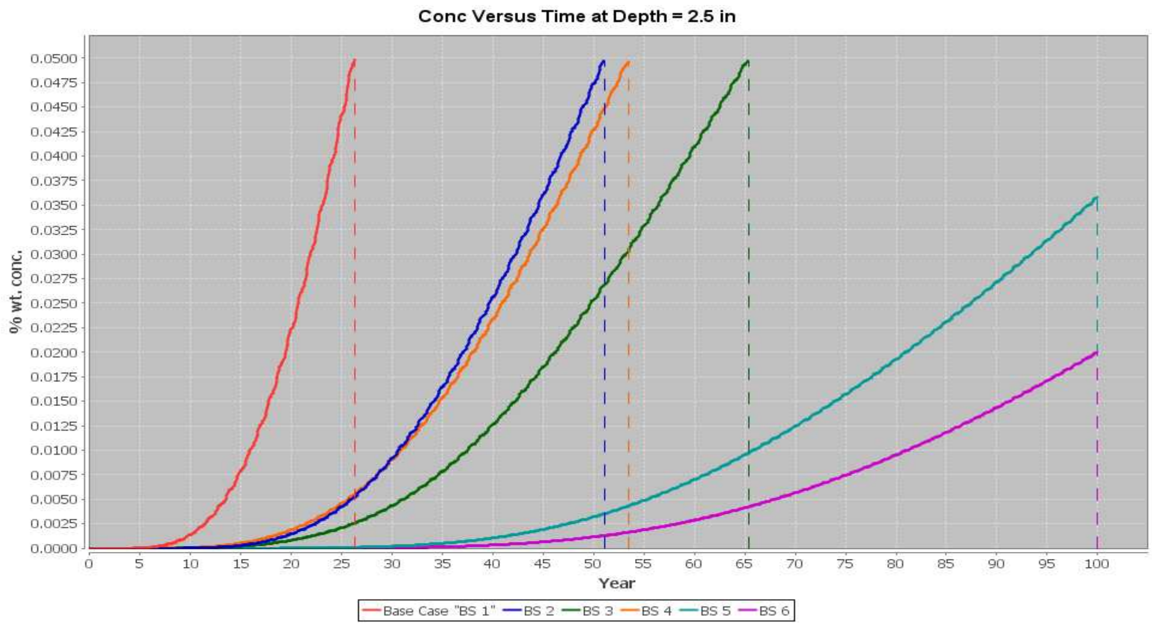

Figure B.18: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case3 with sealer "cover of 2.5in.and w/cm of 0.3" (plotted by Life-365 software)

B.1.4 Case 4, Concrete cover =2.5 in. & w/cm=0.34

The service life estimation, which is initiation period plus propagation period, in case 4 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.4.

Table B.4: Service life estimation for case 4

	Supplementary Cementitious Materials "SCMs"			**Service life "years"**	
Alternative or mix #	**Fly ash "Class F" %**	**Slag Cement %**	**Silica Fume %**	**Black steel & Membrane "BM"**	**Black steel & Sealer "BS"**
1 "Base mix"	0	0	0	35.8	28.4
2	0	0	5	55.8	48.3
3	0	35	0	68.2	59.3
4	20	0	0	58.5	49.8
5	20	0	5	>100	99.3
6	0	35	5	>100	>100

B.1.4.1 Concrete mixtures with black steel and membrane

Figure B.19 shows the effect of using black steel and membrane on the estimated service life for different alternatives. In addition, Figure B.20 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.21 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

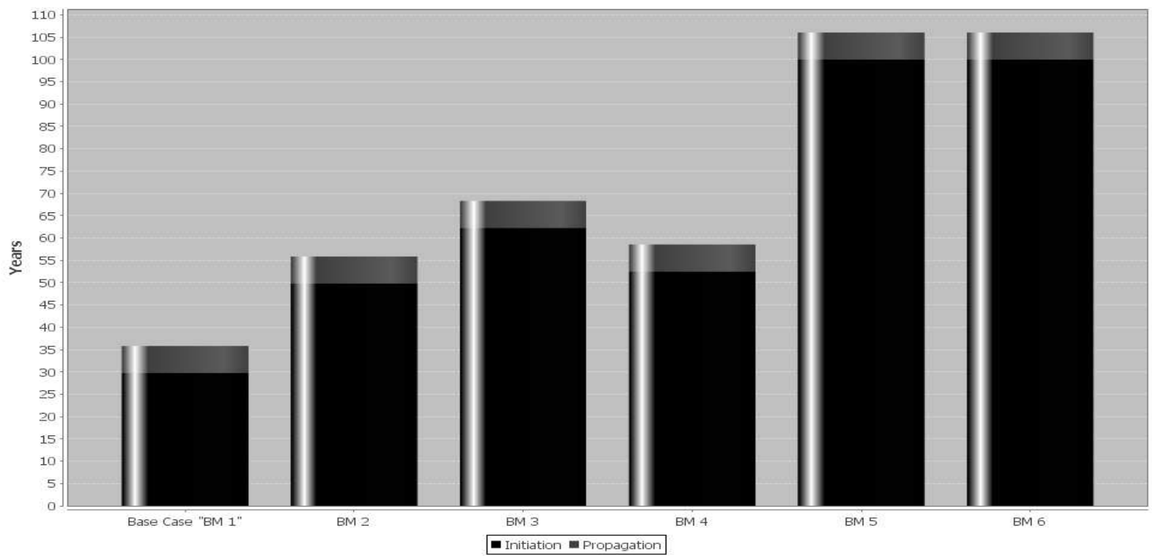

Figure B.19: Service life estimation for case 4 with membrane “cover of 2.5in.and w/cm of 0.34” (plotted by Life-365 software)

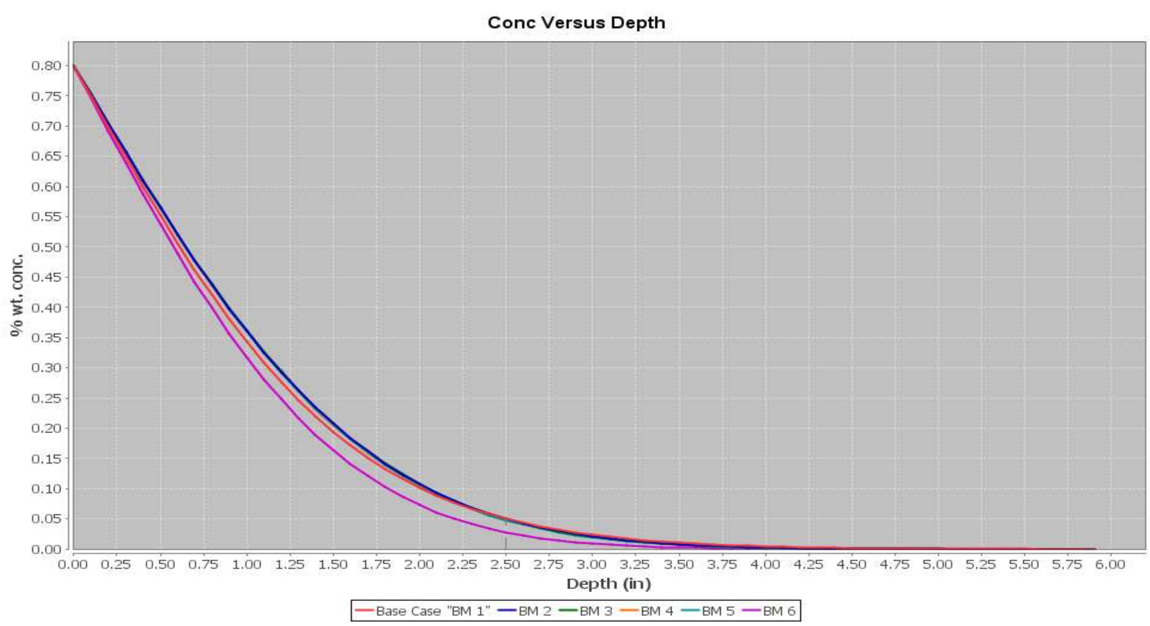

Figure B.20: Chloride concentration percentage as weight of concrete versus total slab depth for case 4 with membrane “cover of 2.5in.and w/cm of 0.34” (plotted by Life-365 software)

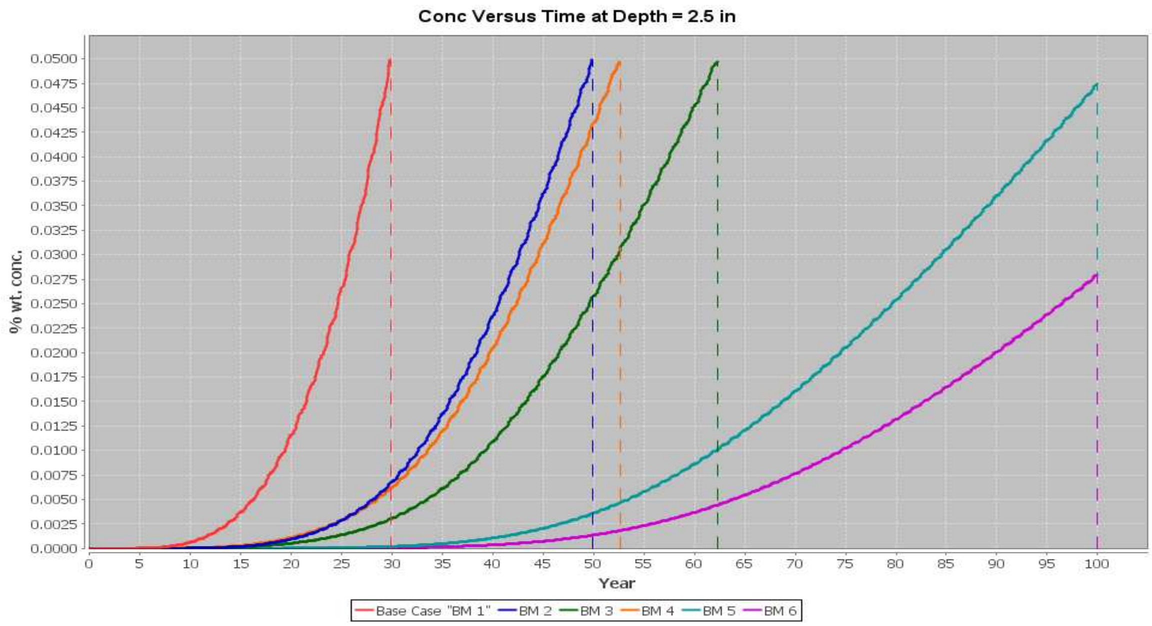

Figure B.21: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 4 with membrane “cover of 2.5in.and w/cm of 0.34” (plotted by Life-365 software)

B.1.4.2 Concrete mixtures with black steel and sealer

Figure B.22 shows the effect of using black steel and sealer on the estimated service life for different alternatives. In addition, Figure B.23 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.24 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

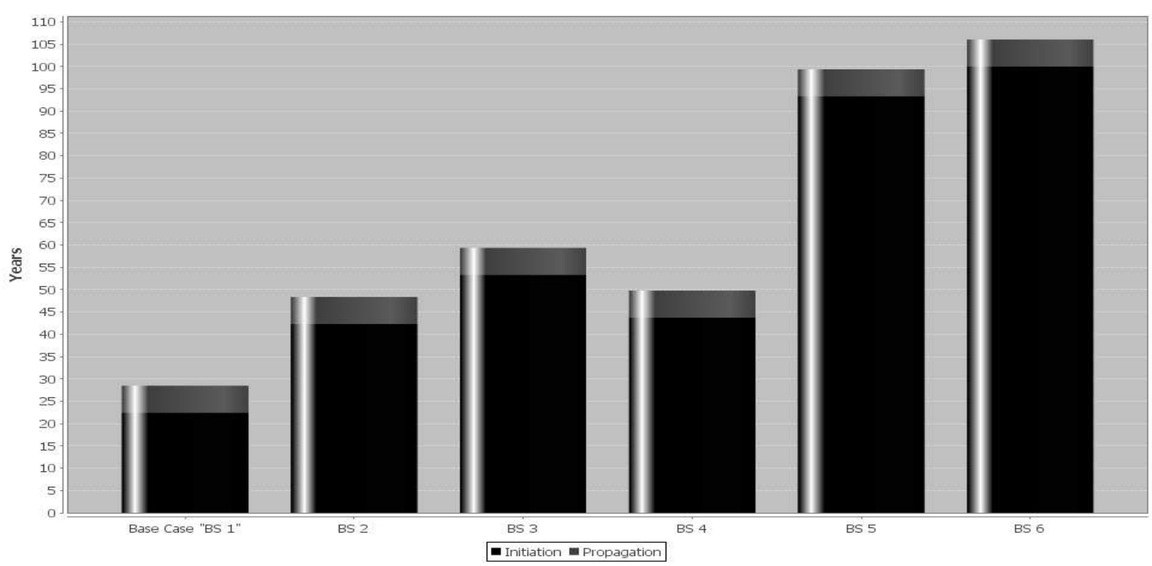

Figure B.22: Service life estimation for case 4 with sealer “cover of 2.5in.and w/cm of 0.34” (plotted by Life-365 software)

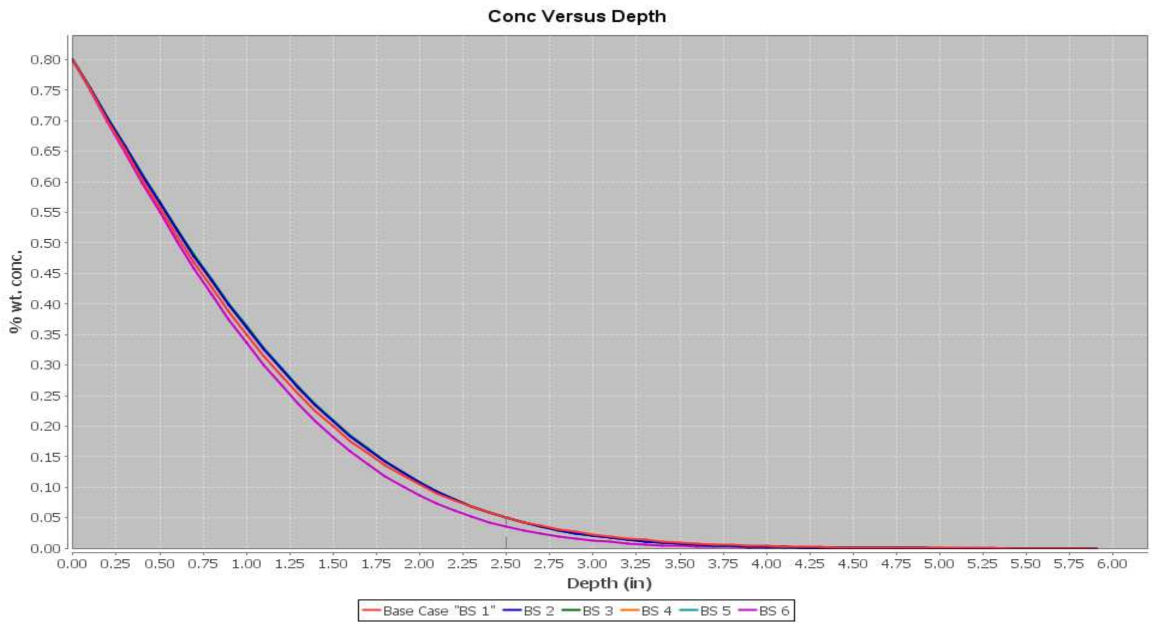

Figure B.23: Chloride concentration percentage as weight of concrete versus total slab depth for case 4 with sealer "cover of 2.5in.and w/cm of 0.34" (plotted by Life-365 software)

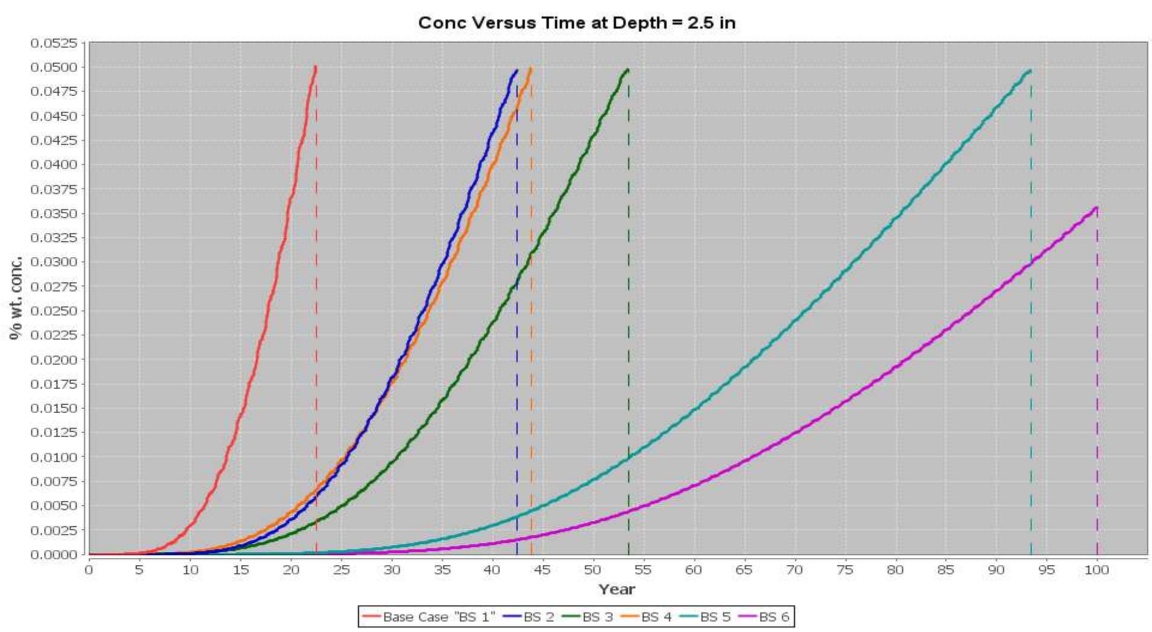

Figure B.24: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 4 with sealer "cover of 2.5in.and w/cm of 0.34" (plotted by Life-365 software)

B.1.5 Case 5, Concrete cover =2 in. & w/cm=0.3

The estimated service life, which is initiation period plus propagation period, in different alternatives for case 5 is shown in Table B.5.

Table B.5: Service life estimation for case 5

Alternative or mix #	Cementitious materials "Portland Cement %"	Reinforcement	Barrier	Service life "years"
1	100	Black steel	No application	22.6
2	100	Epoxy-coated steel	No application	36.6
3	100	Black steel	Membrane application	32.6
4	100	Black steel	Membrane reapplications	32.7
5	100	Black steel	Sealer application	25.2
6	100	Black steel	Sealer reapplications	26.8

Figure B.25 shows the estimated service life in case 5 for different alternatives. In addition, Figure B.26 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.27 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

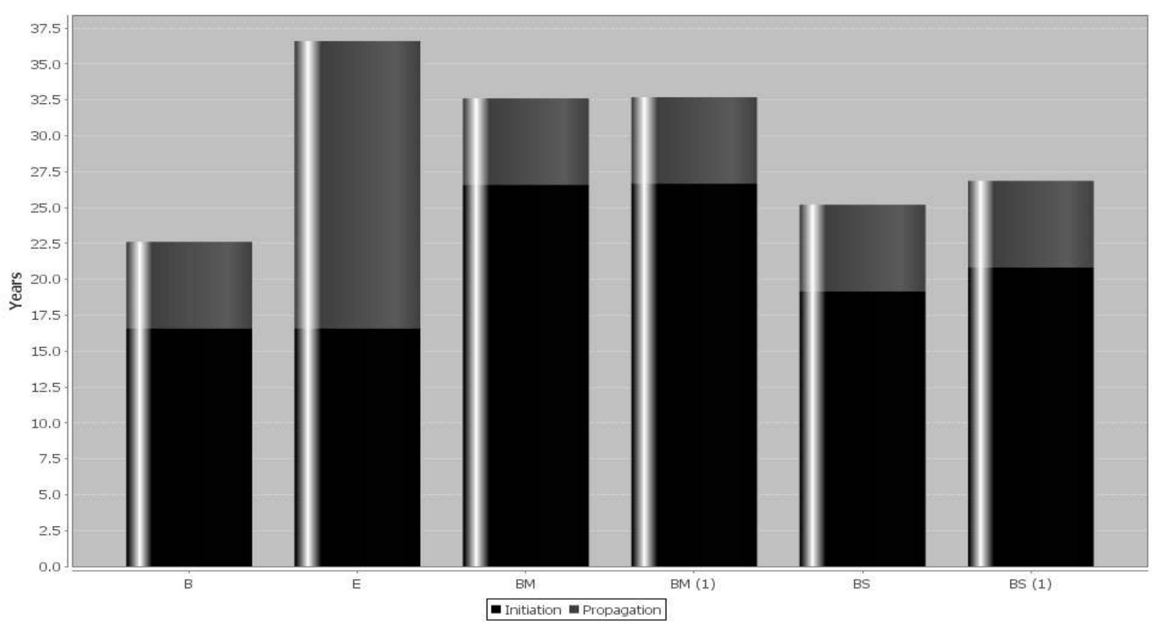

Figure B.25: Service life estimation for case 5 "cover of 2in.and w/cm of 0.3" (plotted by Life-365 software)

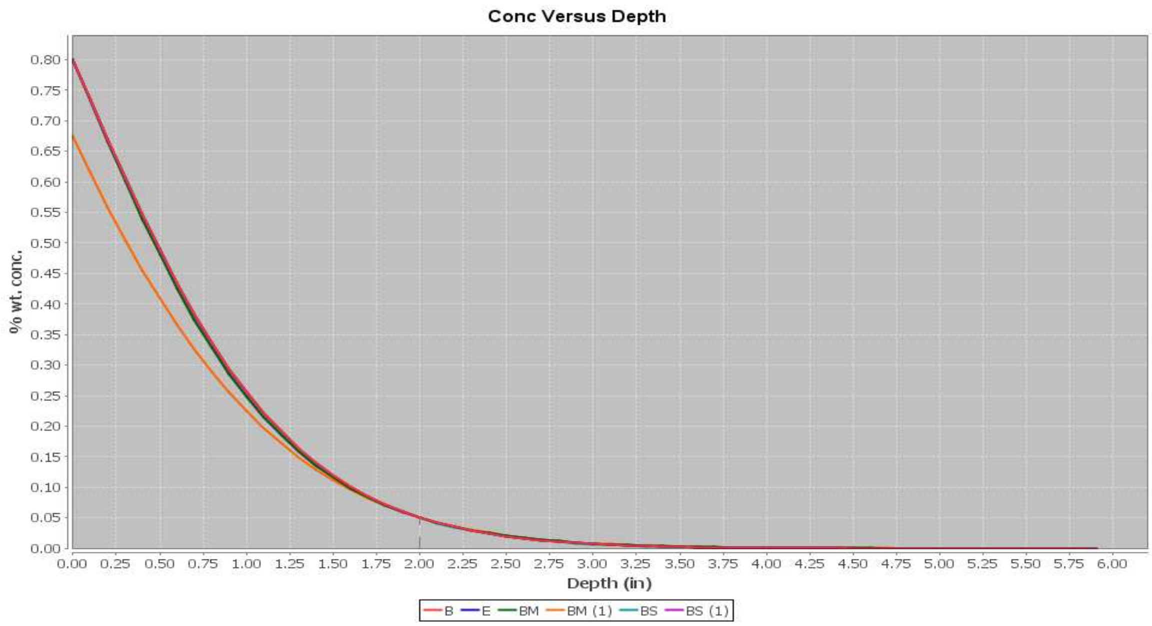

Figure B.26: Chloride concentration percentage as weight of concrete versus total slab depth for case 5 "cover of 2in.and w/cm of 0.3" (plotted by Life-365 software)

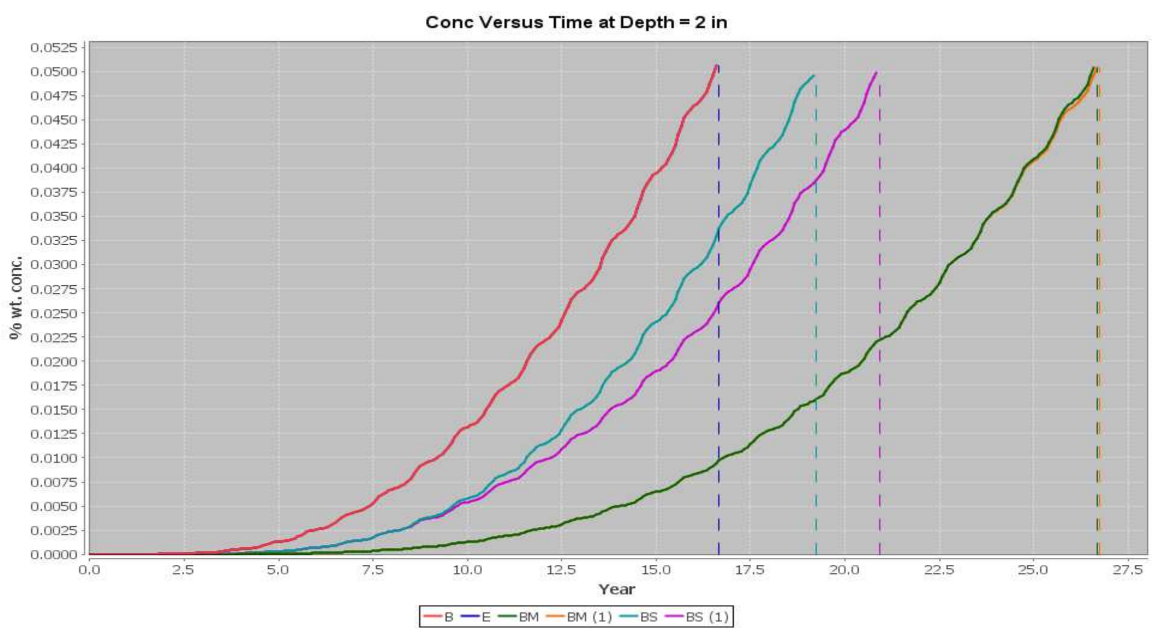

Figure B.27: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 5 "cover of 2in.and w/cm of 0.3" (plotted by Life-365 software)

B.1.6 Case 6, Concrete cover =2 in. & w/cm=0.3

The estimated service life, which is initiation period plus propagation period, in different alternatives for case 6 is shown in Table B.6. The alternatives that will have the barrier, either Membrane ”M” or Sealer “S”, are 2, 4 and 6.

Table B.6: Service life estimation for case 6

	Supplementary Cementitious Materials “SCMs”			**Reinforcement**	
Alternative or mix #	**Fly ash “Class F” %**	**Slag Cement %**	**Silica Fume %**	**Black steel “B”**	**Service life “years”**
1	0	0	5	B	38.3
2 “with M”	0	0	5	B	48.7
3	0	35	0	B	45.6
4“with M”	0	35	0	B	58.4
5	20	0	0	B	38.5
6“with M”	20	0	0	B	50.6
1	0	0	5	B	38.3
2“with S”	0	0	5	B	41
3	0	35	0	B	45.6
4“with S”	0	35	0	B	49.4
5	20	0	0	B	38.5
6“with S”	20	0	0	B	41.8

B.1.6.1 Concrete mixtures with black steel “Membrane in alternatives 2, 4 and 6”

Figure B.28 shows the results of the estimated service life for different alternatives with and without membrane in case 6. In addition, Figure B.29 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.30 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

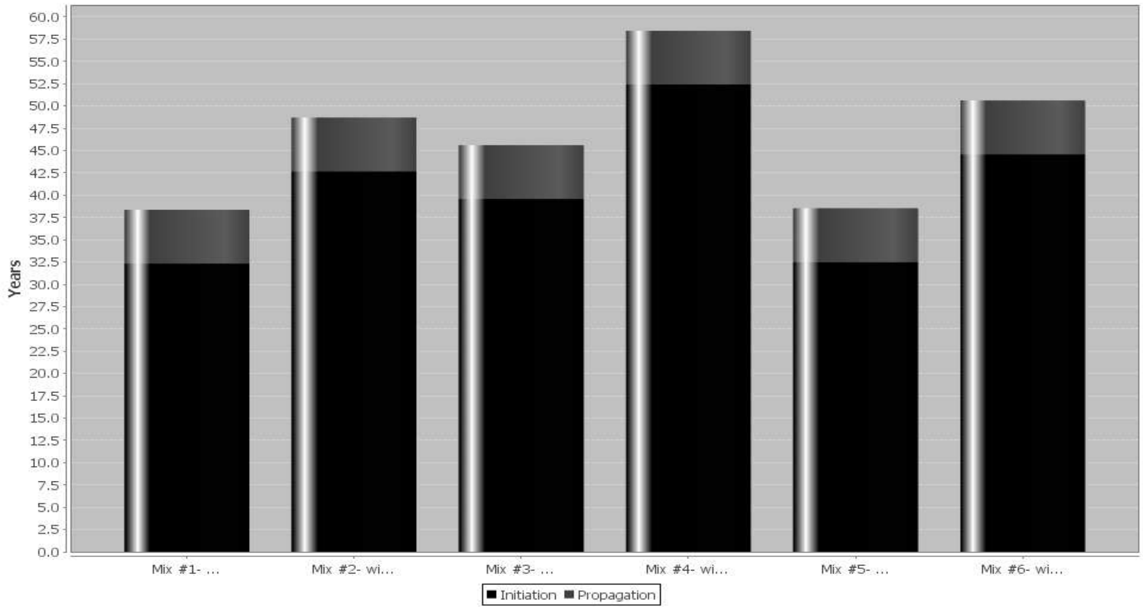

Figure B.28: Service life estimation for case 6 with membrane in some alternatives “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

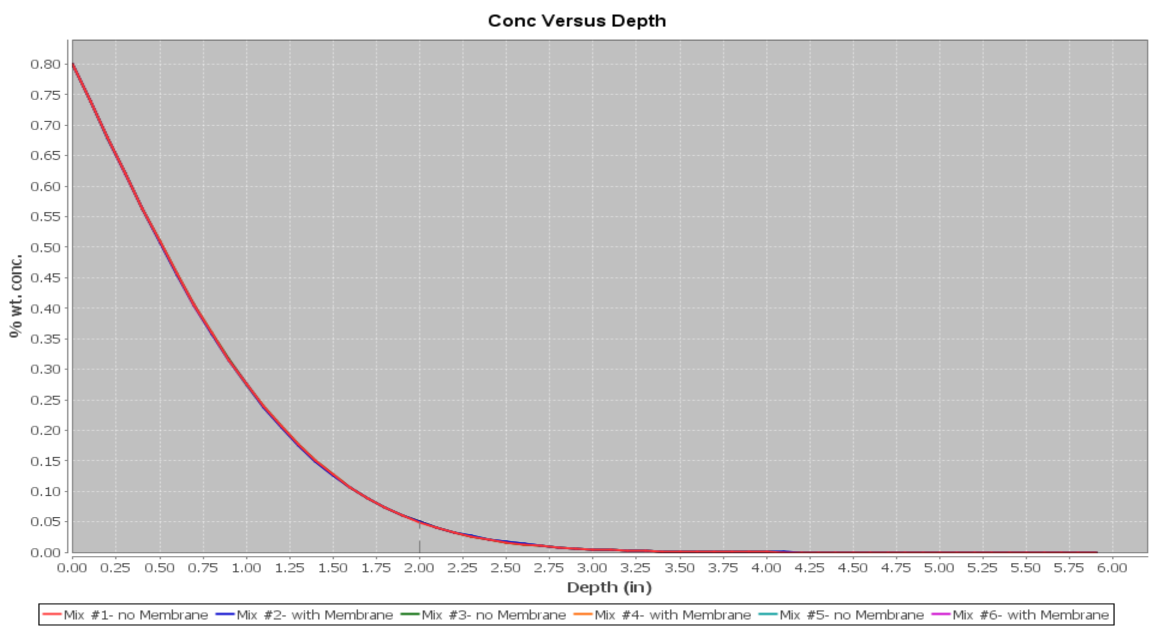

Figure B.29: Chloride concentration percentage as weight of concrete versus total slab depth for case 6 with membrane in some alternatives “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

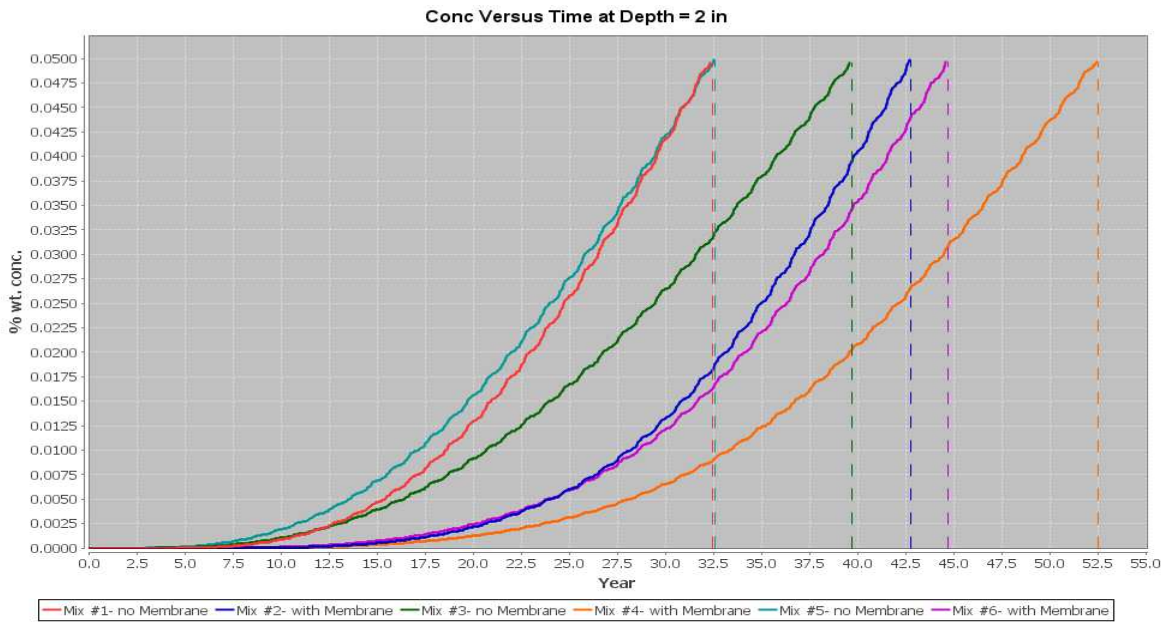

Figure B.30: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 6 with membrane in some alternatives “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

B.1.6.2 Concrete mixtures with black steel “Sealer in alternatives 2, 4 and 6”

Figure B.31shows the results of the estimated service life for different alternatives with and without sealer in case 6. In addition, Figure B.32 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.33 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

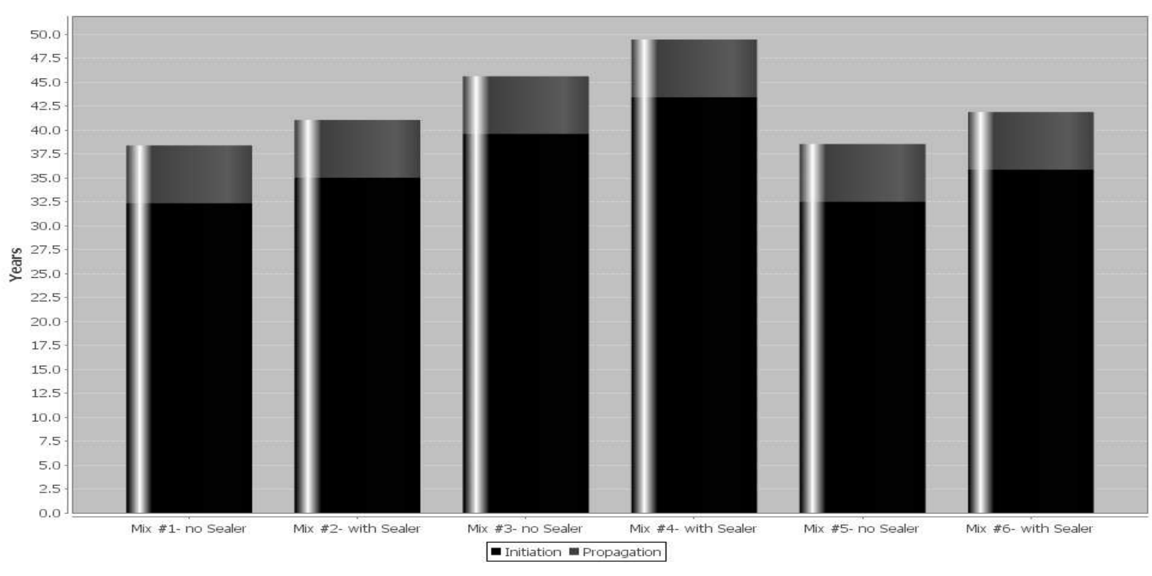

Figure B.31: Service life estimation for case 6 with sealer in some alternatives “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

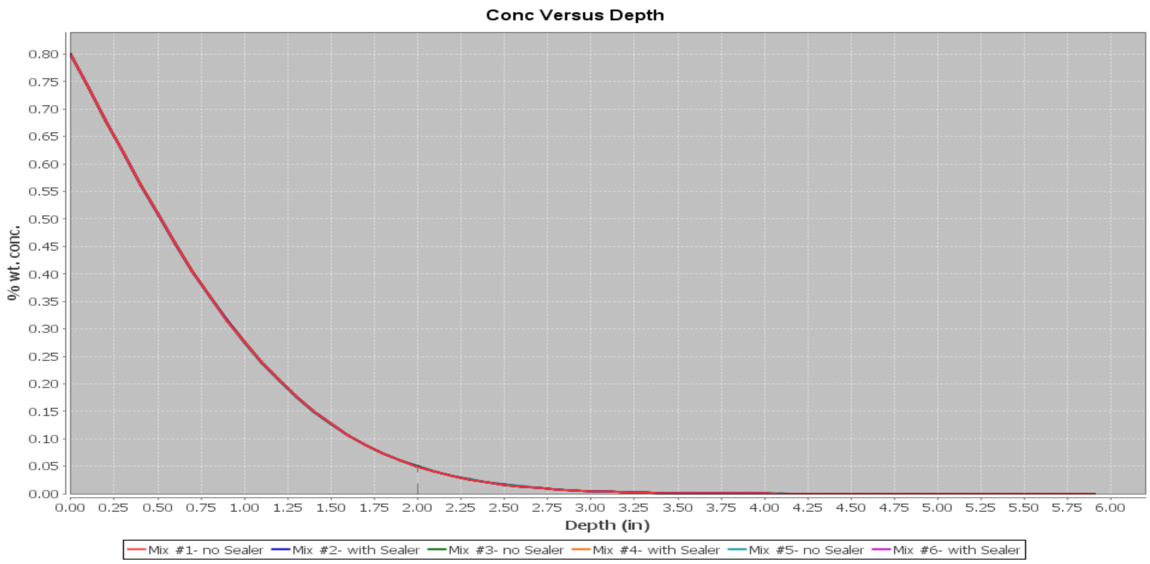

Figure B.32: Chloride concentration percentage as weight of concrete versus total slab depth for case 6 with sealer in some alternatives “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

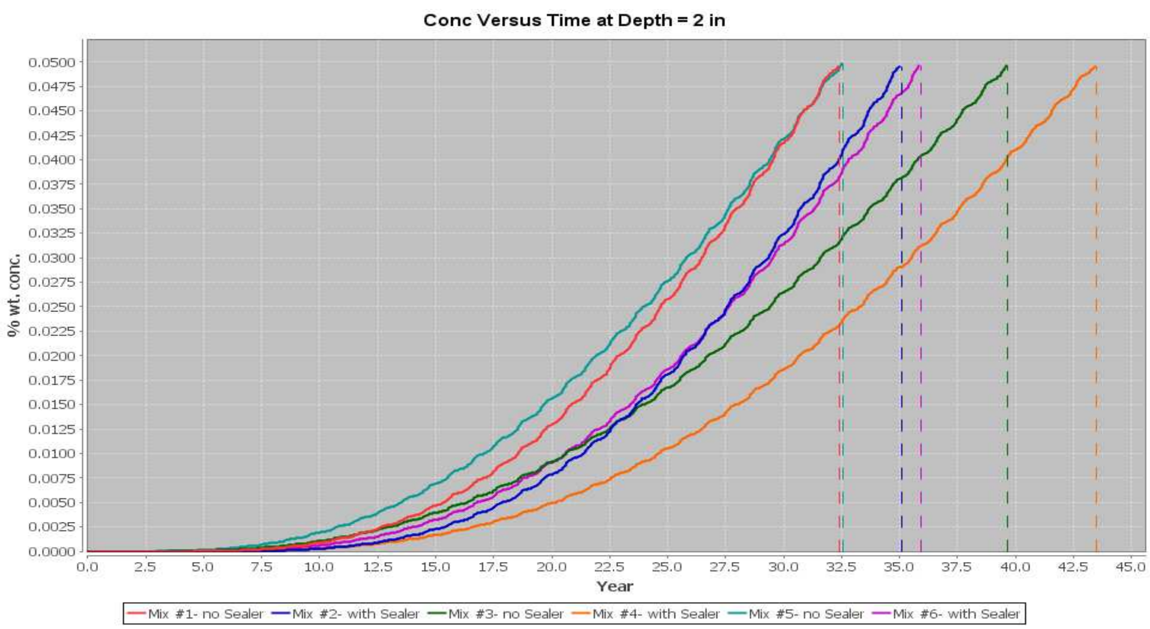

Figure B.33: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 6 with sealer in some alternatives “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

B.1.7 Case 7, Concrete cover =2 in. & w/cm=0.3

The estimated service life, which is initiation period plus propagation period, in different alternatives for case 7 is shown in Table B.7.

Table B.7: Service life estimation for case 7

	Supplementary Cementitious Materials "SCMs"			Reinforcement	Barrier	Service life "years"
Alternative or mix #	Fly ash "Class F" %	Slag Cement %	Silica Fume %			
1	0	0	5	Black steel	No application	38.3
2	0	0	5	Epoxy-coated steel	No application	52.3
3	0	35	0	Black steel	No application	45.6
4	0	35	0	Epoxy-coated steel	No application	59.6
5	20	0	0	Black steel	No application	38.5
6	20	0	0	Epoxy-coated steel	No application	52.5

Figure B.34 shows the estimated service life in case 7 for different alternatives with different types of reinforcement. In addition, Figure B.35 shows the decline in chloride concentration as it penetrates the concrete from the surface through the slab thickness. Besides that, Figure B.36 shows the chloride concentration at the upper embedded reinforcement level during the analysis period of the reinforced concrete slab for all alternatives.

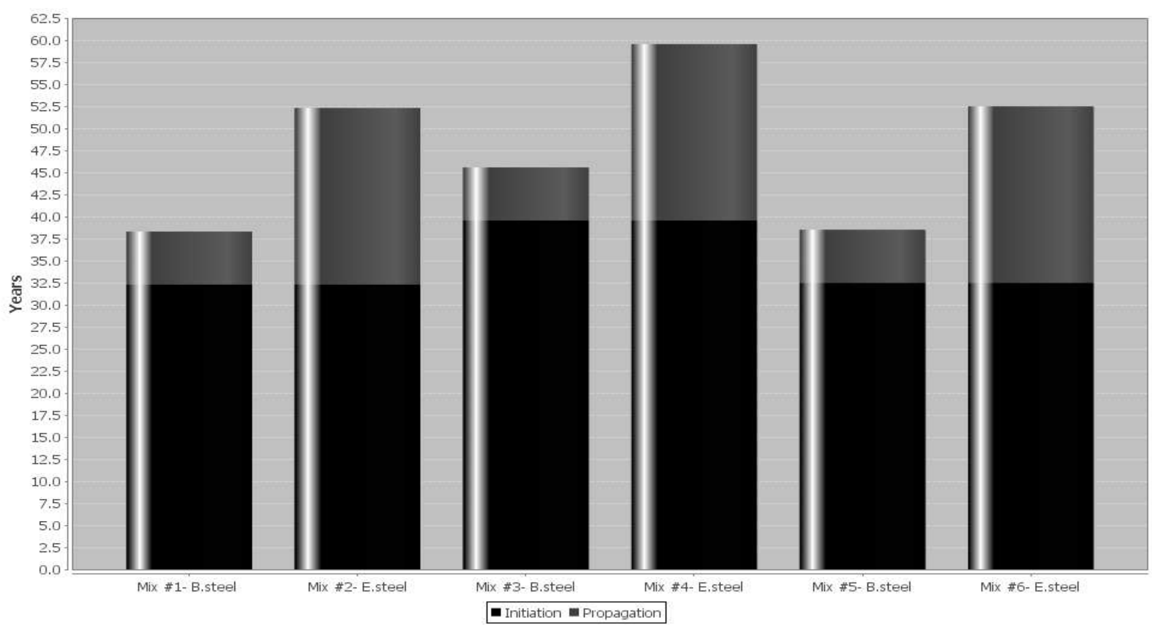

Figure B.34: Service life estimation for case 7 "cover of 2in.and w/cm of 0.3" (plotted by Life-365 software)

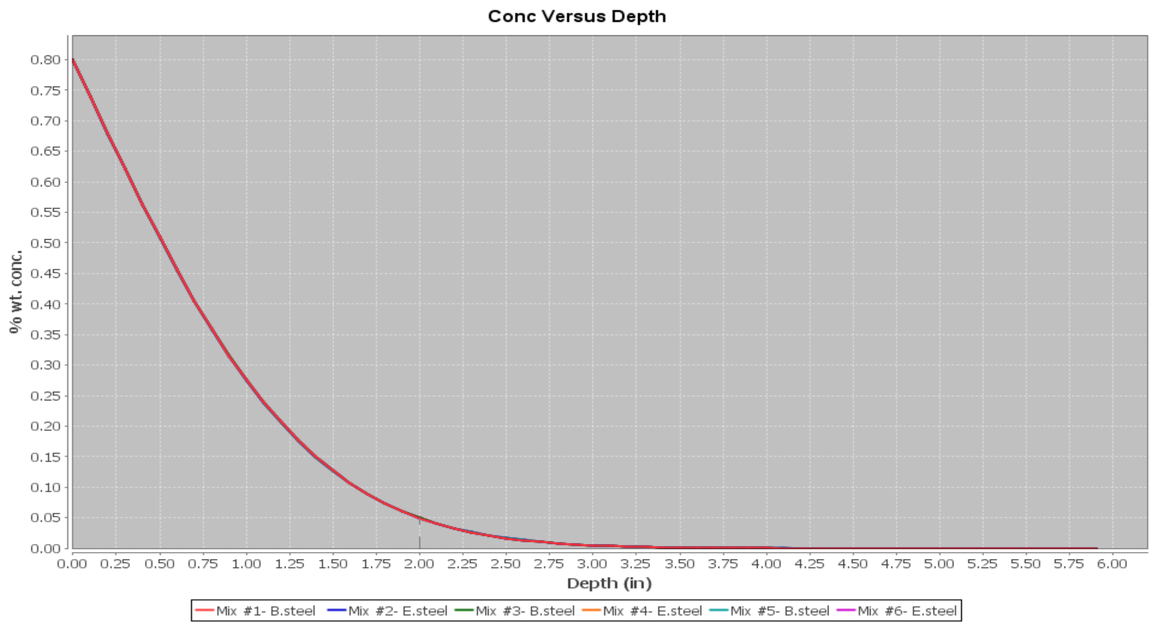

Figure B.35: Chloride concentration percentage as weight of concrete versus total slab depth for case 7 “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

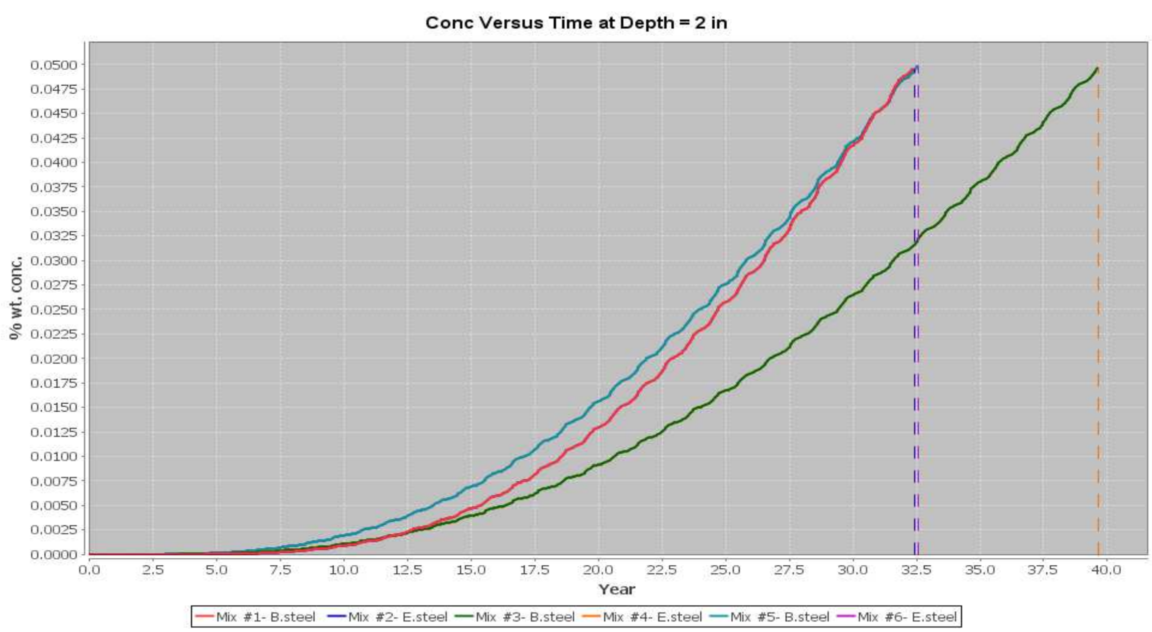

Figure B.36: Chloride concentration percentage as weight of concrete at upper embedded steel level versus time in years for case 7 “cover of 2in.and w/cm of 0.3” (plotted by Life-365 software)

B.2 Life Cycle Cost "LCC"

B.2.1 Case 1, Concrete cover =2 in. & w/cm=0.3

The life cycle cost in case 1 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.8. Life cycle cost is the sum of construction cost, barrier cost and repair cost.

Table B.8: Life cycle cost for case 1

	Alternative or mix #	Construction phase cost	Barrier phase cost	Repair phase cost	LCC "$/Sq.ft"
Black steel and membrane "BM"	1"Base mix"	3.02	2.15	27.44	32.61
	2	3.34	2.15	25.05	30.53
	3	2.81	2.15	21.46	26.43
	4	2.93	2.15	20.47	25.55
	5	3.22	2.15	9.41	14.77
	6	3.1	2.15	0	5.25
Black steel and sealer "BS"	1"Base mix"	3.02	0.58	31.06	34.66
	2	3.34	0.58	24.03	27.95
	3	2.81	0.58	25.2	28.59
	4	2.93	0.58	24.03	27.54
	5	3.22	0.58	8.97	12.77
	6	3.1	0.58	4.81	8.49

B.2.1.1 Cost for concrete mixtures with black steel and membrane

Figure B.37 compares the life cycle cost for different concrete mixtures with black steel and membrane using the total cost. Figure B.38 compares the life cycle cost based on the phases cost. Figure B.39 shows the constant costs for all alternatives. Figure B.40 shows the cumulative present value for all alternatives.

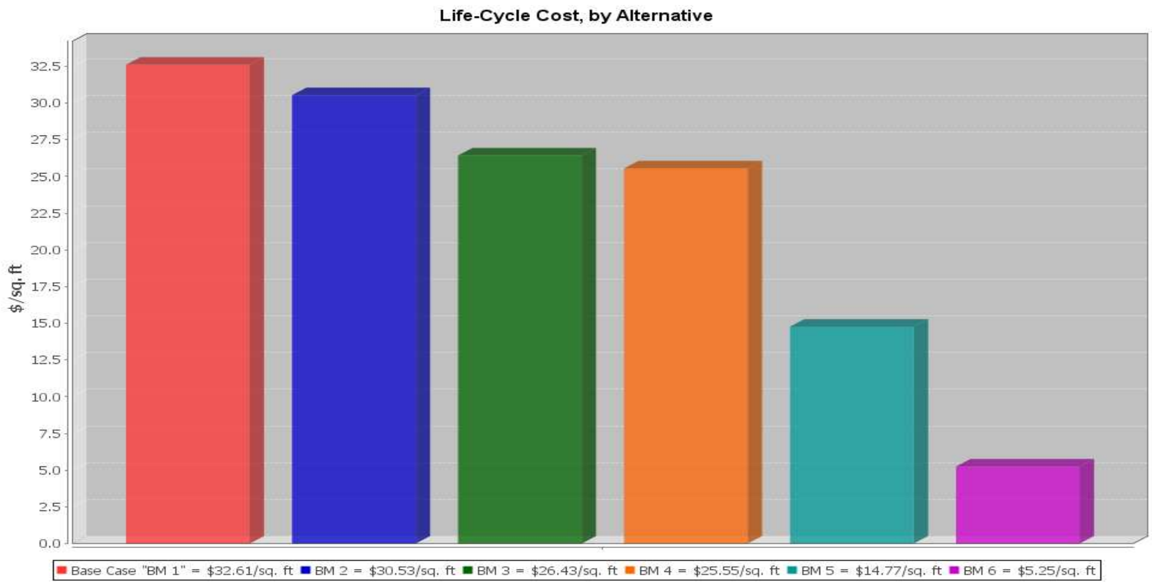

Figure B.37: Life cycle cost by alternatives for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

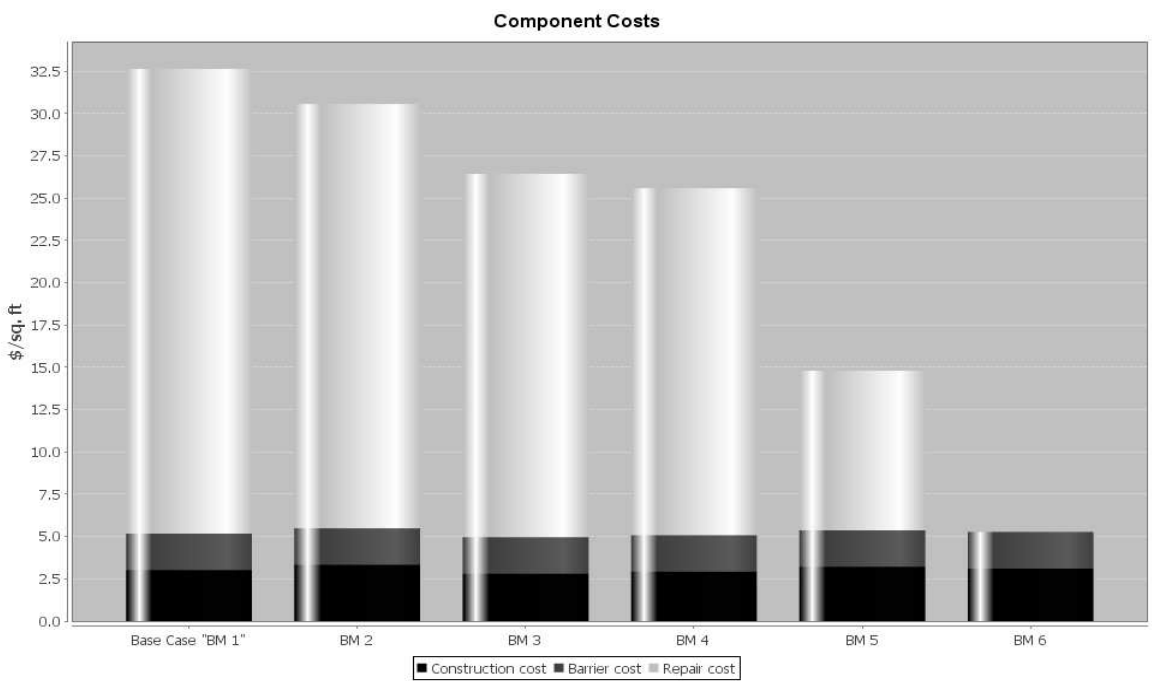

Figure B.38: Life cycle cost by phases cost for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

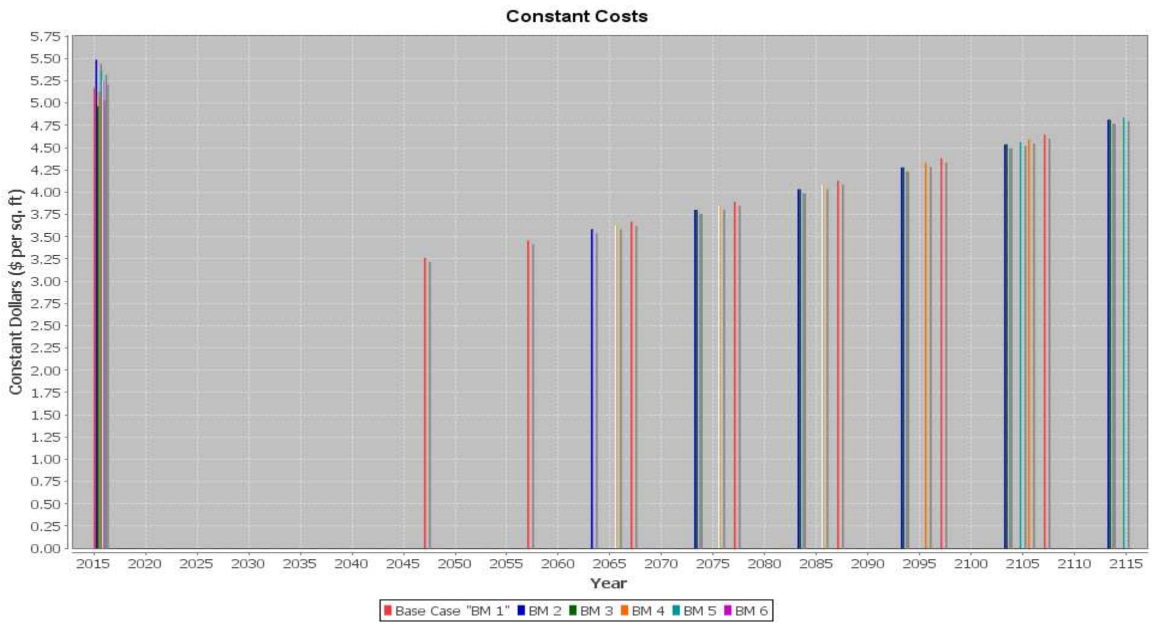

Figure B.39: Cost in constant dollars for all alternatives vs analysis period for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

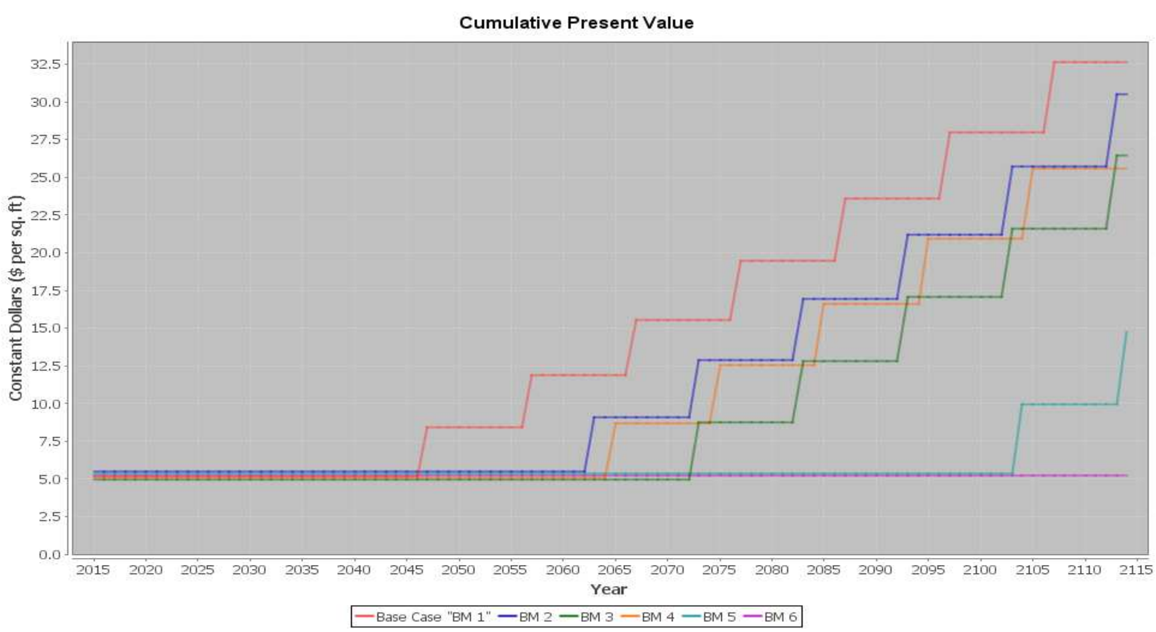

Figure B.40: Cumulative present value vs analysis period for case1 with membrane "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

B.2.1.2 Cost for concrete mixtures with black steel and sealer

Figure B.41 compares the life cycle cost for different concrete mixtures with black steel and sealer using the total cost. Figure B.42 compares the life cycle cost based on the phases cost. Figure B.43 shows the constant costs for all alternatives. Figure B.44 shows the cumulative present value for all alternatives.

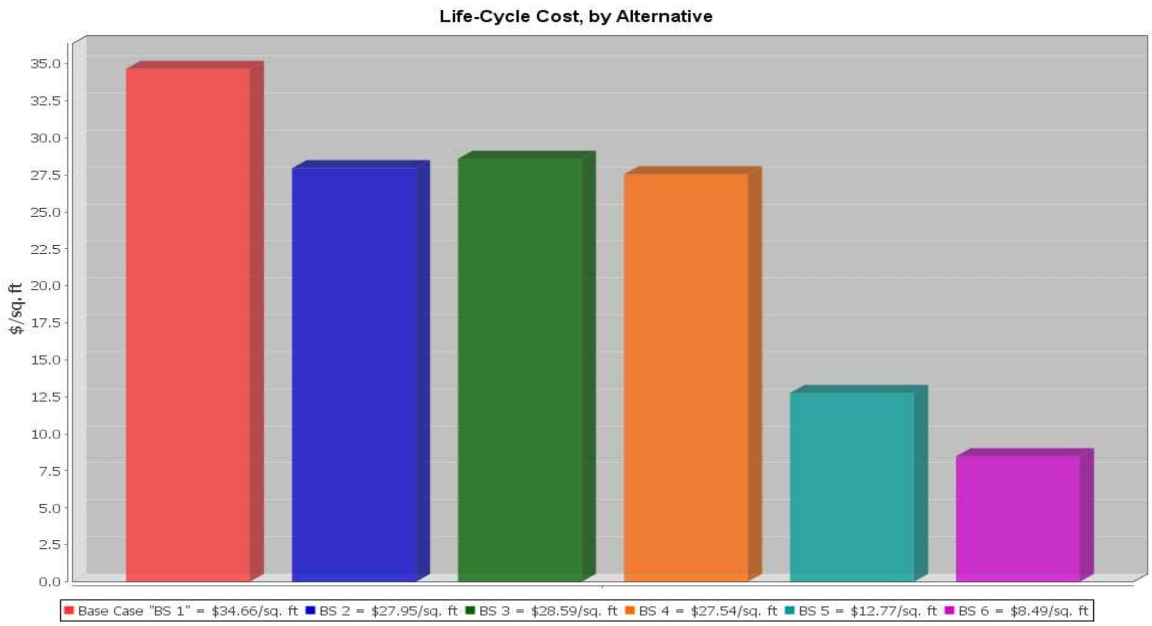

Figure B.41: Life cycle cost by alternatives for case1 with sealer "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

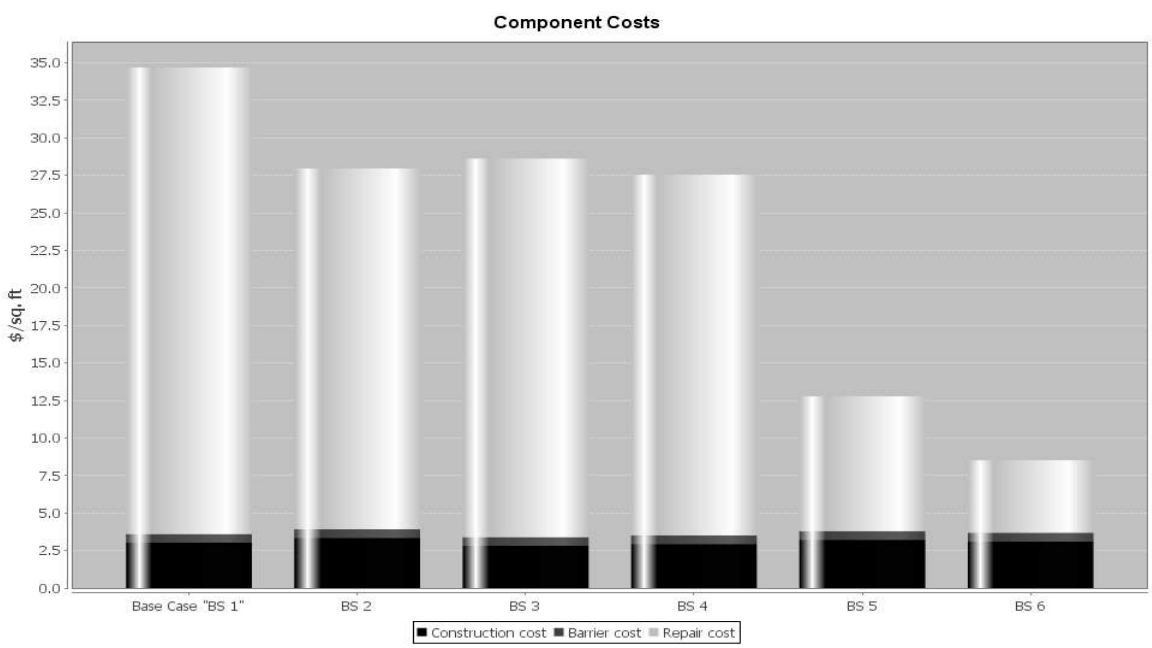

Figure B.42: Life cycle cost by phases cost for case1 with sealer "cover of 2in. and w/cm of 0.3" (plotted by Life-365 software)

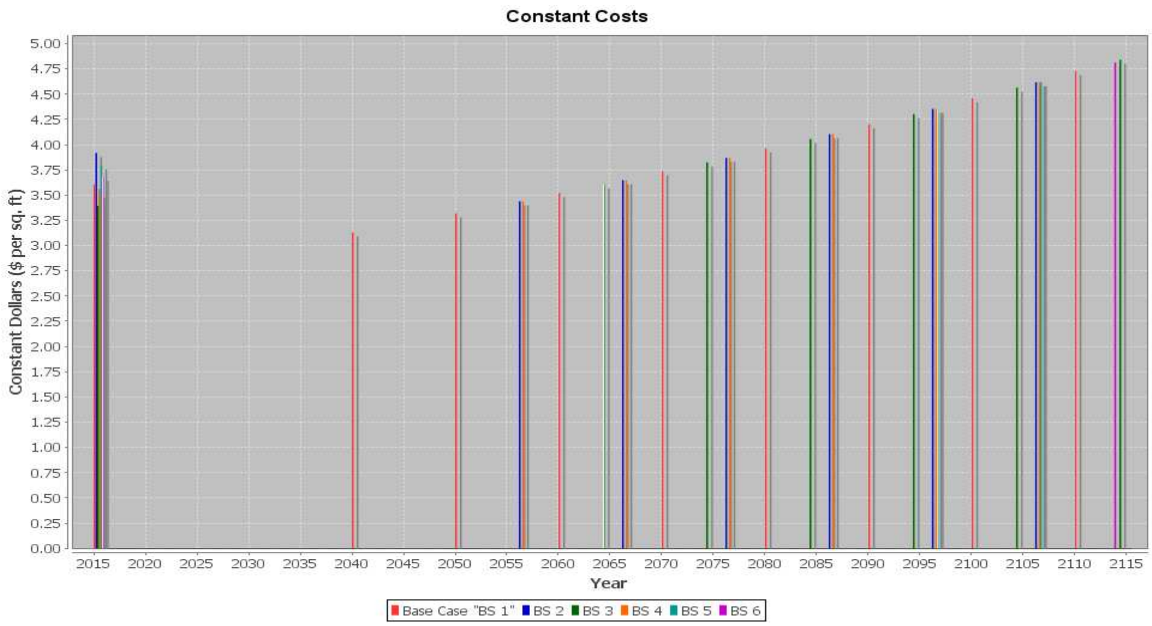

Figure B.43: Cost in constant dollars for all alternatives vs analysis period for case1 with sealer “cover of 2in. and w/cm of 0.3” (plotted by Life-365 software)

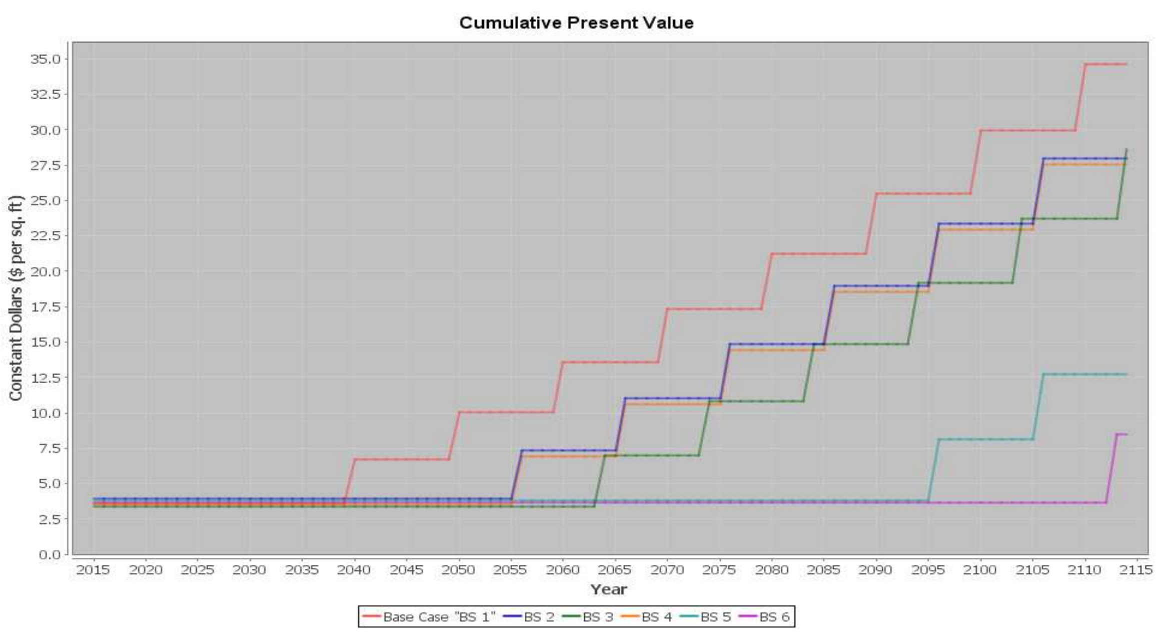

Figure B.44: Cumulative present value vs analysis period for case1 with sealer “cover of 2in. and w/cm of 0.3” (plotted by Life-365 software)

B.2.2 Case 2, Concrete cover =2 in. & w/cm=0.34

The life cycle cost in case 2 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.9. Life cycle cost is the sum of construction cost, barrier cost and repair cost.

Table B.9: Life cycle cost for case 2

	Alternative or mix #	Construction phase cost	Barrier phase cost	Repair phase cost	LCC "$/Sq.ft"
	1"Base mix"	2.9	2.15	31.80	36.85
Black steel and membrane "BM"	2	3.18	2.15	24.32	29.65
	3	2.71	2.15	20.47	25.34
	4	2.82	2.15	24.46	29.43
	5	3.07	2.15	13.47	18.69
	6	2.96	2.15	4.59	9.7
	1"Base mix"	2.9	0.58	30.51	33.99
	2	3.18	0.58	27.93	31.68
Black steel and sealer "BS"	3	2.71	0.58	24.03	27.33
	4	2.82	0.58	27.93	31.32
	5	3.07	0.58	17.56	21.21
	6	2.96	0.58	8.97	12.51

B.2.2.1 Cost for concrete mixtures with black steel and membrane

Figure B.45 compares the life cycle cost for different concrete mixtures with black steel and membrane using the total cost. Figure B.46 compares the life cycle cost based on the phases cost. Figure B.47 shows the constant costs for all alternatives. Figure B.48 shows the cumulative present value for all alternatives.

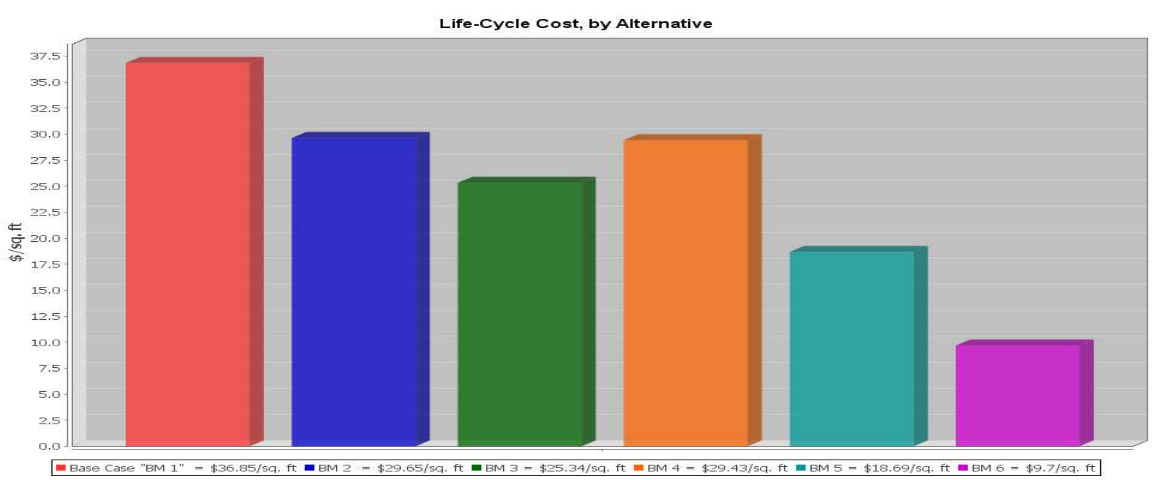

Figure B.45: Life cycle cost by alternatives for case2 with membrane "cover of 2in. and w/cm of 0.34" (plotted by Life-365 software)

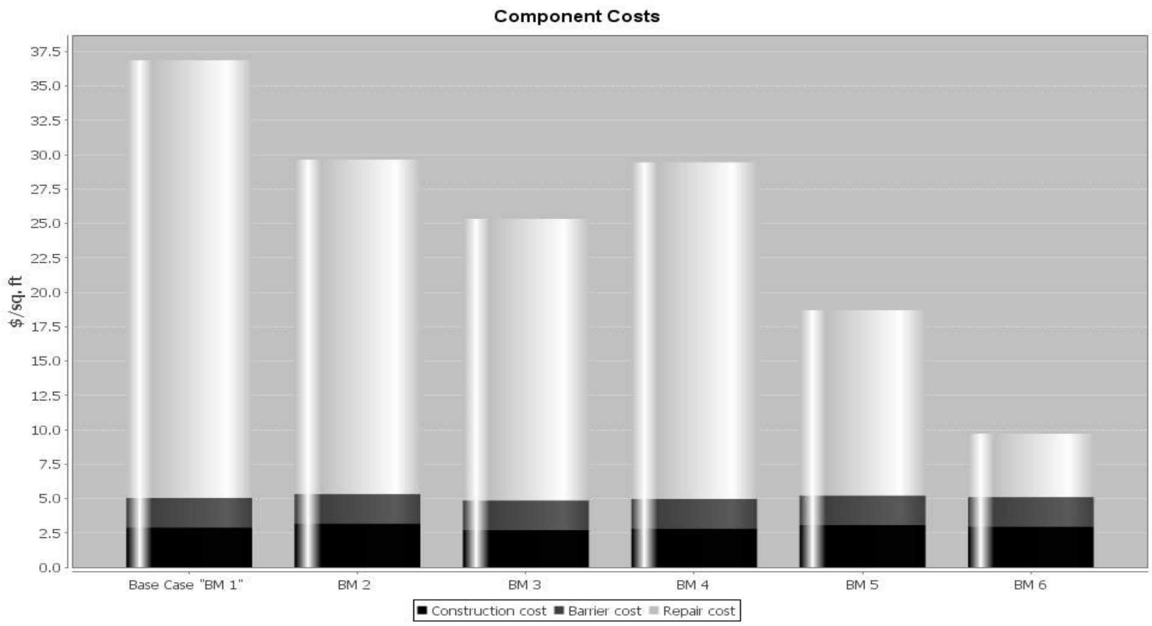

Figure B.46: Life cycle cost by phases cost for case2 with membrane “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

Figure B.47: Cost in constant dollars for all alternatives vs analysis period for case2 with membrane “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

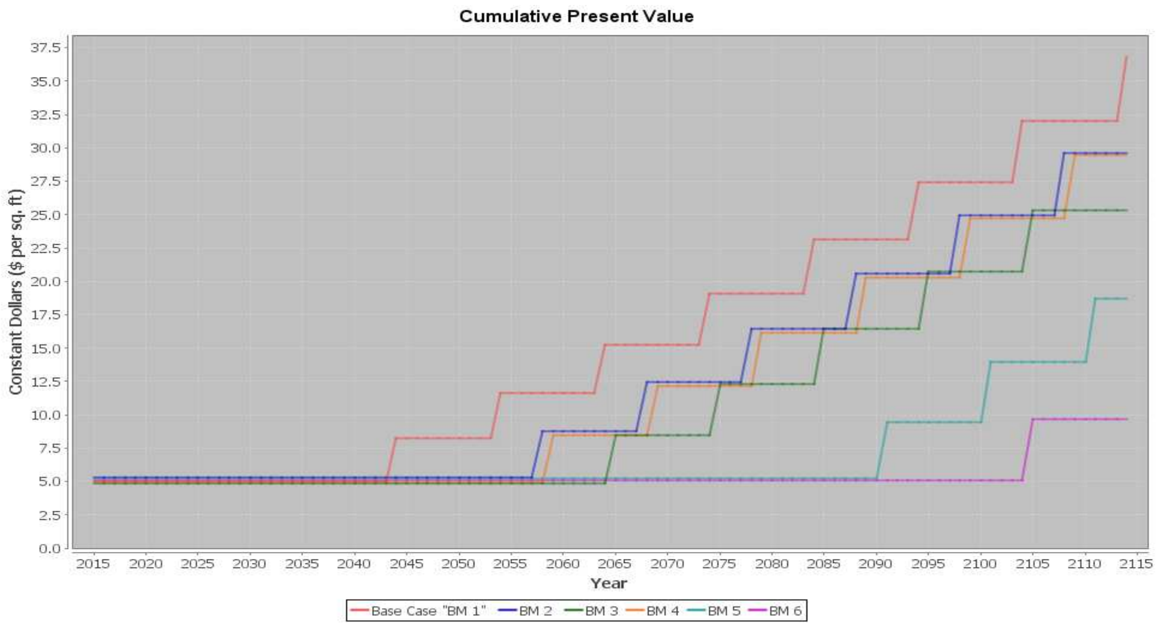

Figure B.48: Cumulative present value vs analysis period for case2 with membrane “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

B.2.2.2 Cost for concrete mixtures with black steel and sealer

Figure B.49 compares the life cycle cost for different concrete mixtures with black steel and sealer using the total cost. Figure B.50 compares the life cycle cost based on the phases cost. Figure B.51 shows the constant costs for all alternatives. Figure B.52 shows the cumulative present value for all alternatives.

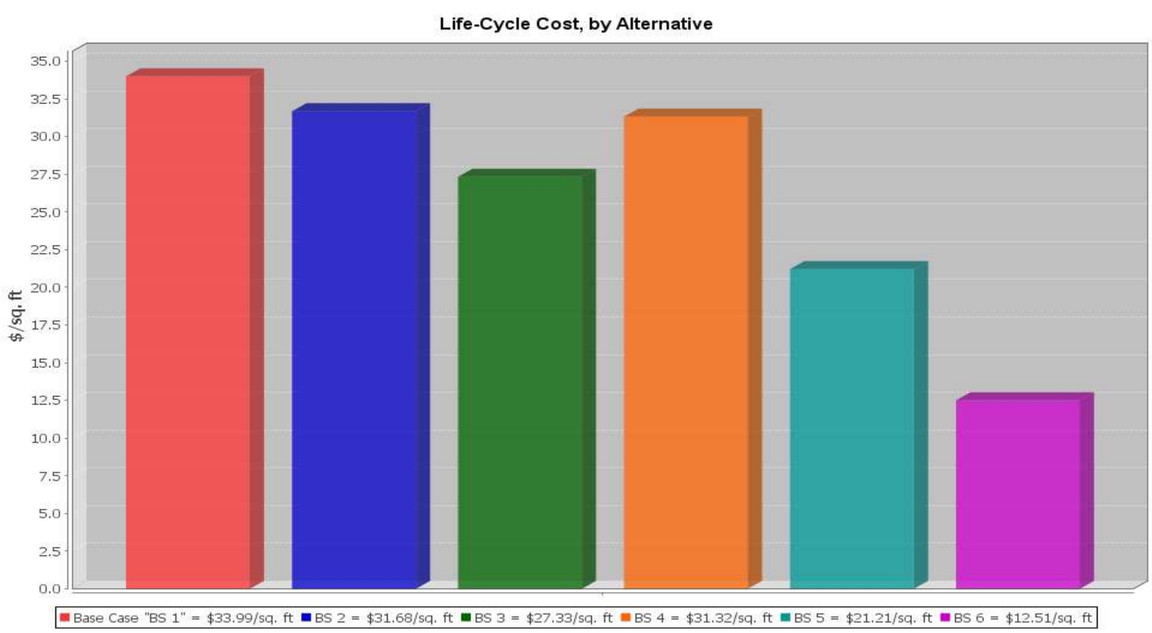

Figure B.49: Life cycle cost by alternatives for case2 with sealer “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

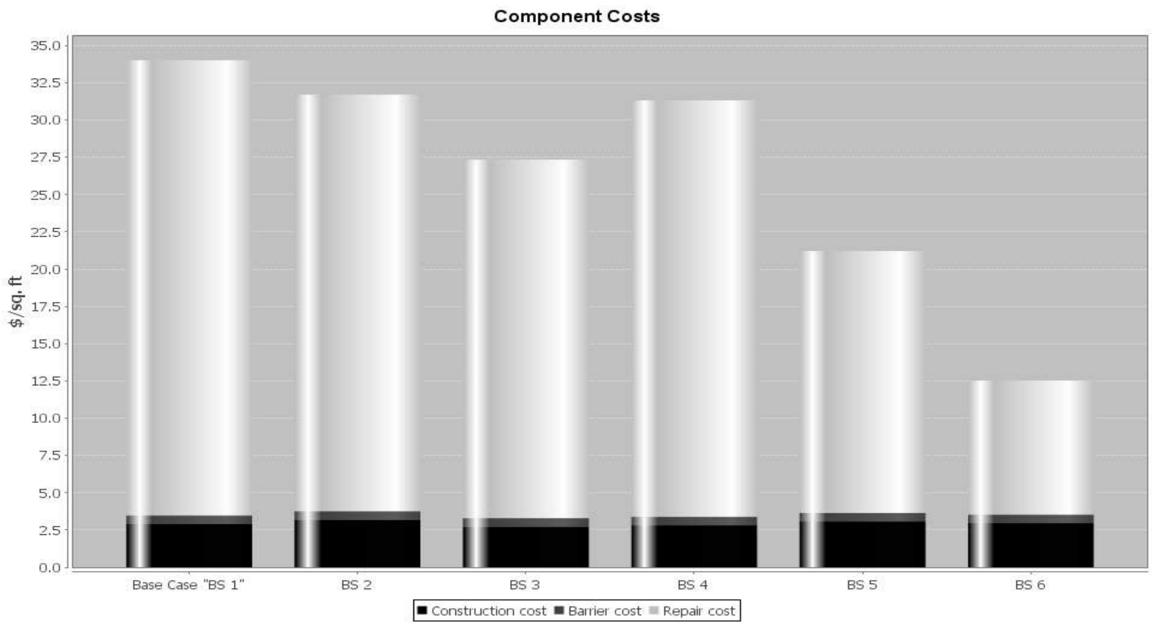

Figure B.50: Life cycle cost by phases cost for case2 with sealer “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

Figure B.51: Cost in constant dollars for all alternatives vs analysis period for case2 with sealer “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

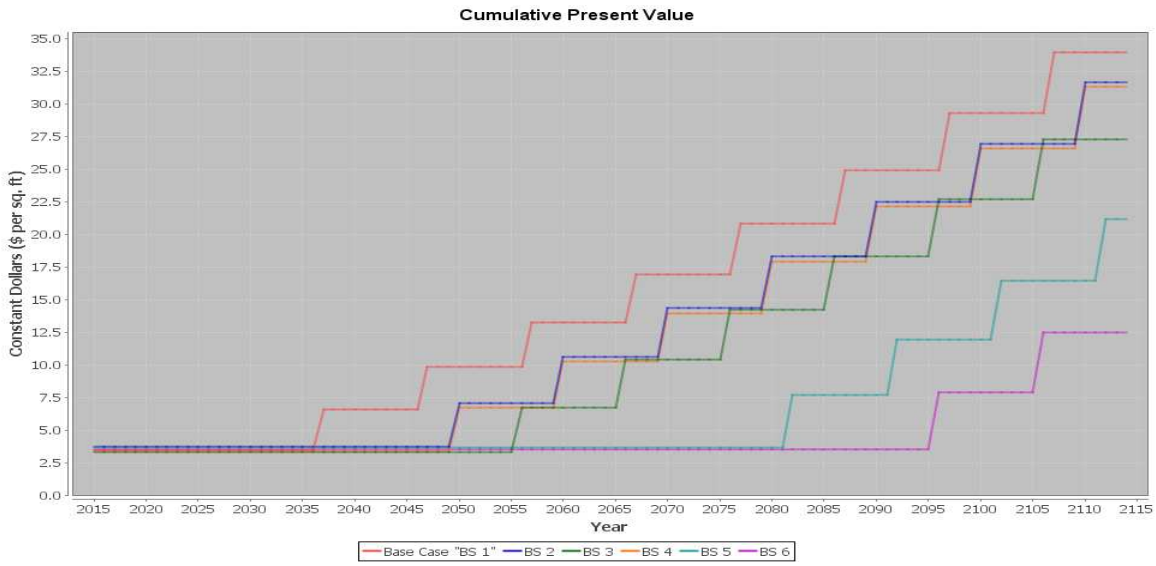

Figure B.52: Cumulative present value vs analysis period for case2 with sealer “cover of 2in. and w/cm of 0.34” (plotted by Life-365 software)

B.2.3 Case 3, Concrete cover =2.5 in. & w/cm=0.3

The life cycle cost in case 3 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.10. Life cycle cost is the sum of construction cost, barrier cost and repair cost.

Table B.10: Life cycle cost for case 3

	Alternative or mix #	Construction phase cost	Barrier phase cost	Repair phase cost	LCC "$/Sq.ft"
Black steel and membrane “BM”	1”Base mix”	3.02	2.15	28.59	33.77
	2	3.34	2.15	17.25	22.74
	3	2.81	2.15	8.92	13.88
	4	2.93	2.15	17.66	22.74
	5	3.22	2.15	0	5.37
	6	3.1	2.15	0	5.25
Black steel and sealer “BS”	1”Base mix”	3.02	0.58	27.44	31.04
	2	3.34	0.58	21.34	25.25
	3	2.81	0.58	13.08	16.47
	4	2.93	0.58	21.59	25.1
	5	3.22	0.58	0	3.8
	6	3.1	0.58	0	3.68

B.2.3.1 Cost for concrete mixtures with black steel and membrane

Figure B.53 compares the life cycle cost for different concrete mixtures with black steel and membrane using the total cost. Figure B.54 compares the life cycle cost based on the phases cost. Figure B.55 shows the constant costs for all alternatives. Figure B.56 shows the cumulative present value for all alternatives.

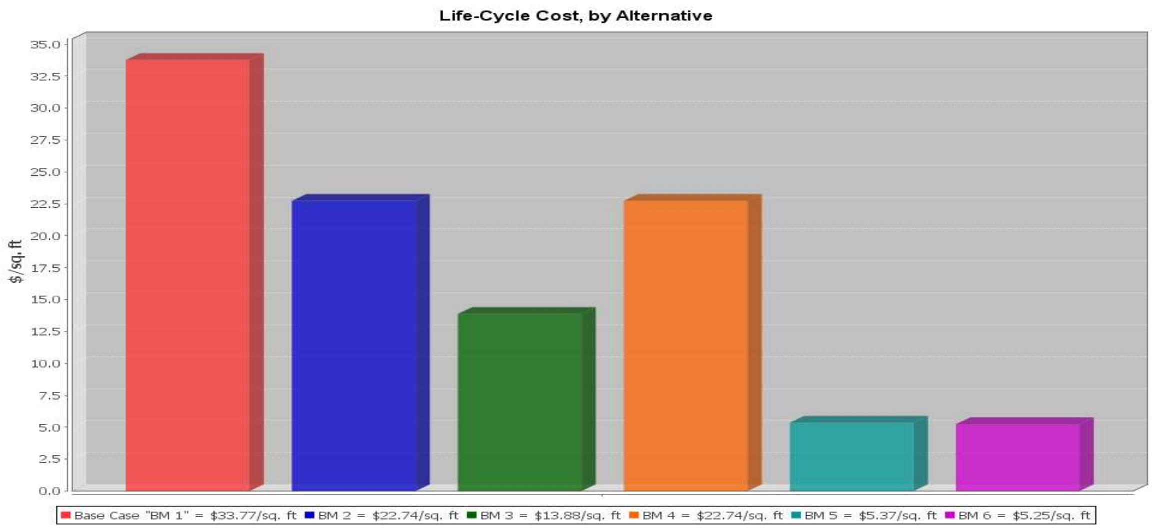

Figure B.53: Life cycle cost by alternatives for case3 with membrane "cover of 2.5in. and w/cm of 0.3" (plotted by Life-365 software)

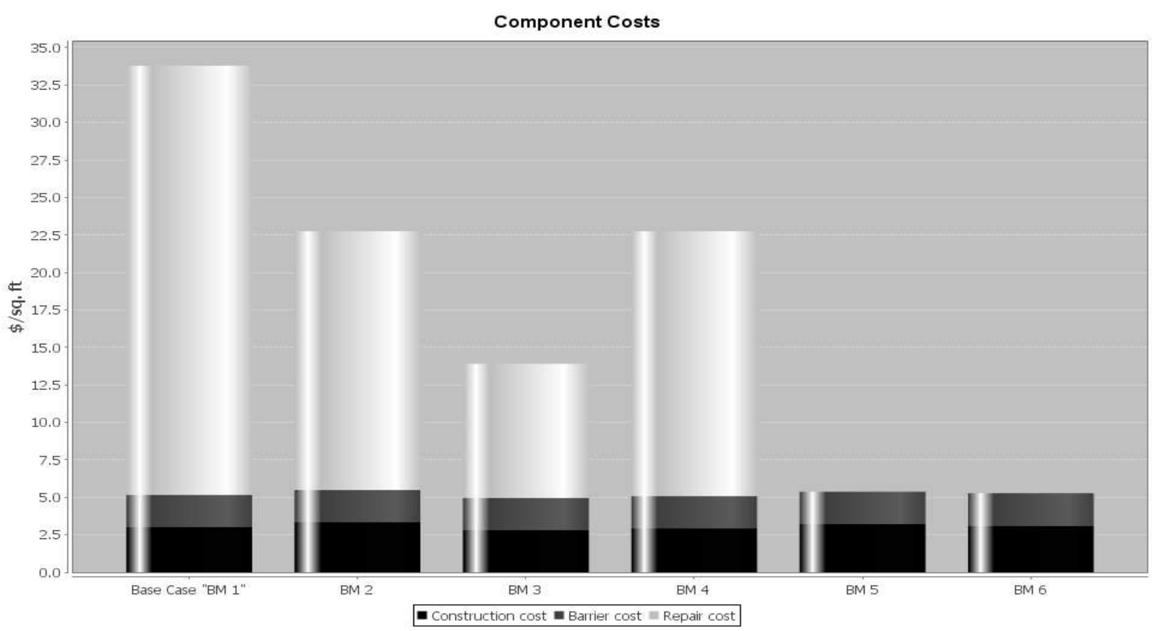

Figure B.54: Life cycle cost by phases cost for case3 with membrane "cover of 2.5in. and w/cm of 0.3" (plotted by Life-365 software)

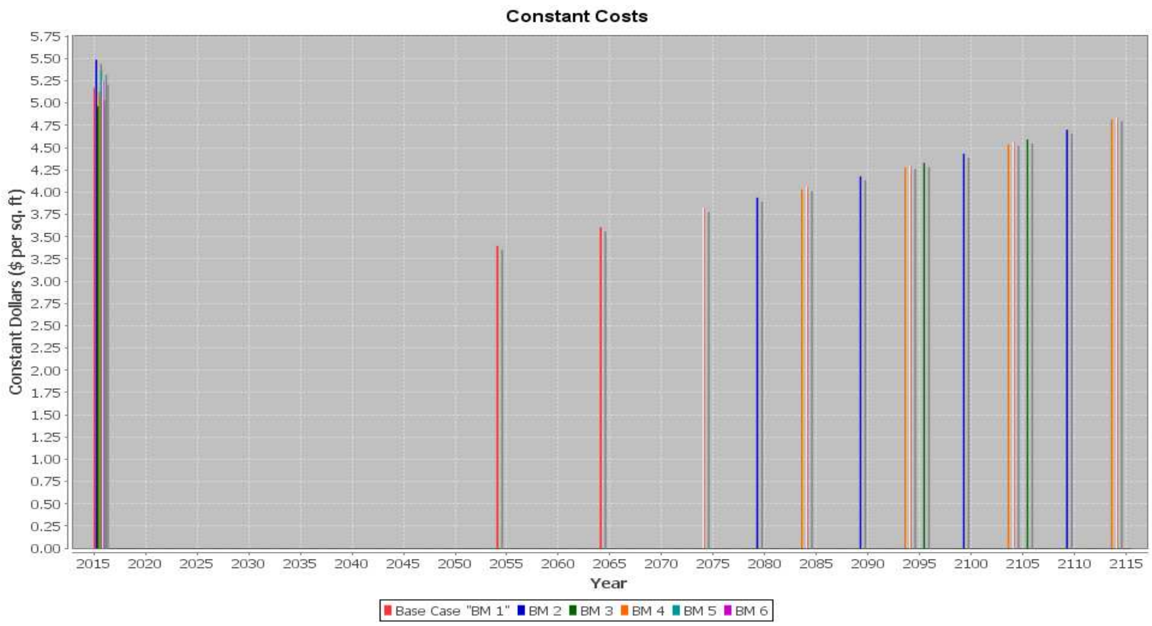

Figure B.55: Cost in constant dollars for all alternatives vs analysis period for case3 with membrane “cover of 2.5in. and w/cm of 0.3” (plotted by Life-365 software)

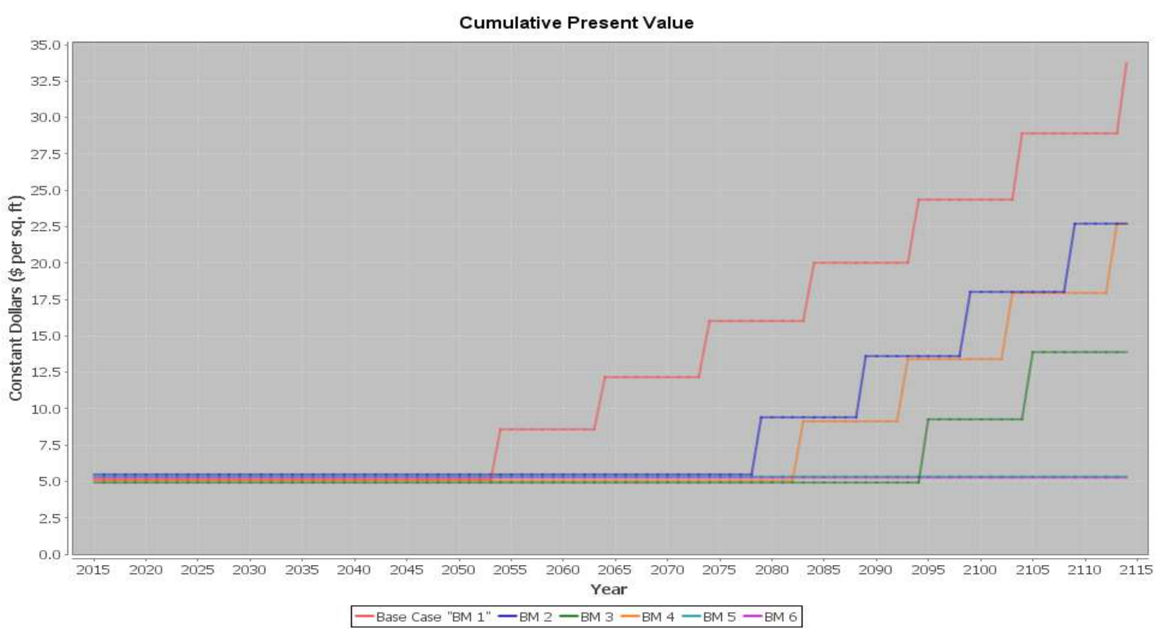

Figure B.56: Cumulative present value vs analysis period for case3 with membrane “cover of 2.5in. and w/cm of 0.3” (plotted by Life-365 software)

B.2.3.2 Cost for concrete mixtures with black steel and sealer

Figure B.57 compares the life cycle cost for different concrete mixtures with black steel and sealer using the total cost. Figure B.58 compares the life cycle cost based on the phases cost. Figure B.59 shows the constant costs for all alternatives. Figure B.60 shows the cumulative present value for all alternatives.

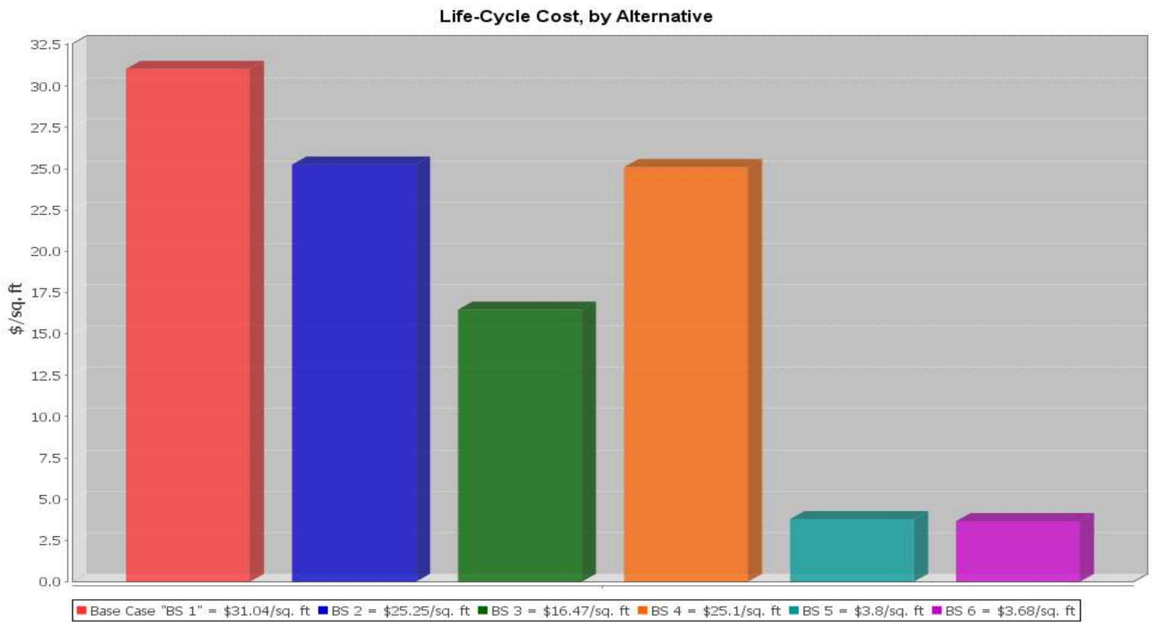

Figure B.57: Life cycle cost by alternatives for case3 with sealer "cover of 2.5in. and w/cm of 0.3" (plotted by Life-365 software)

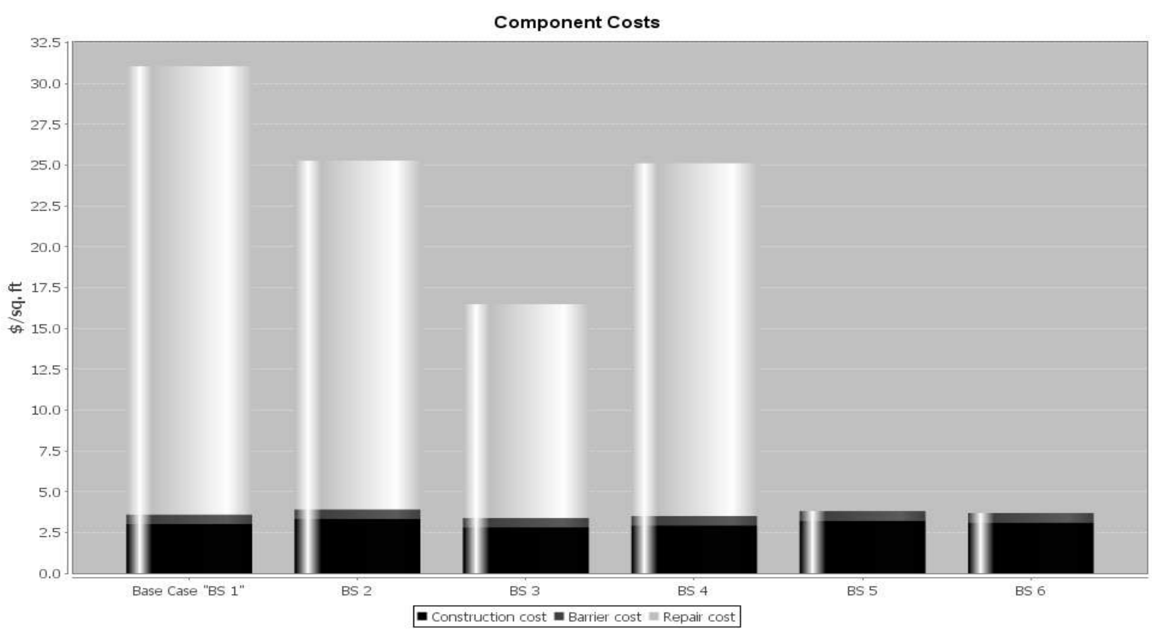

Figure B.58: Life cycle cost by phases cost for case3 with sealer "cover of 2.5in. and w/cm of 0.3" (plotted by Life-365 software)

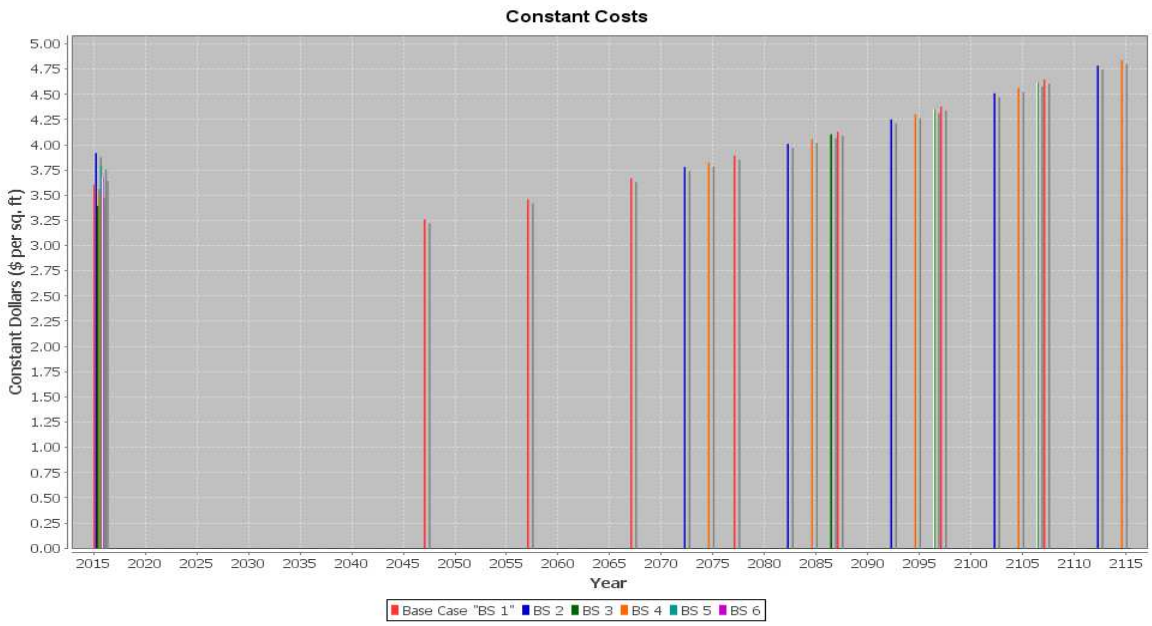

Figure B.59: Cost in constant dollars for all alternatives vs analysis period for case3 with sealer “cover of 2.5in. and w/cm of 0.3” (plotted by Life-365 software)

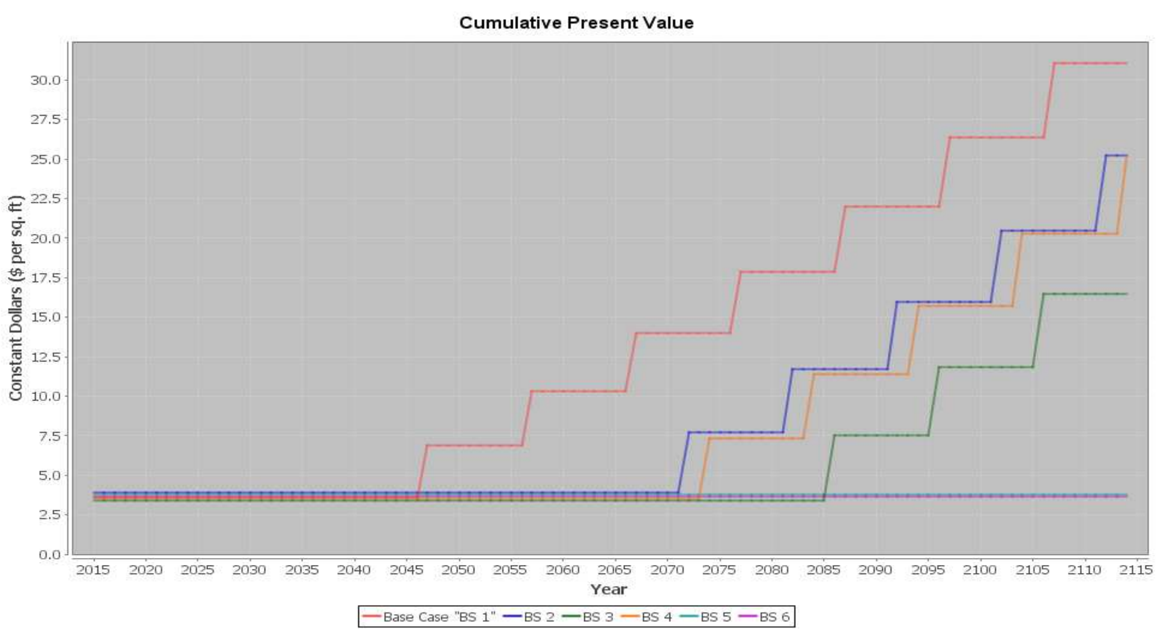

Figure B.60: Cumulative present value vs analysis period for case3 with sealer “cover of 2.5in. and w/cm of 0.3” (plotted by Life-365 software)

B.2.4 Case 4, Concrete cover =2.5 in. & w/cm=0.34

The life cycle cost in case 4 for different concrete mixtures with black steel, membrane or sealer is shown in Table B.11. Life cycle cost is the sum of construction cost, barrier cost and repair cost.

Table B.11: Life cycle cost for case 4

	Alternative or mix #	Construction phase cost	Barrier phase cost	Repair phase cost	LCC "$/Sq.ft"
Black steel and membrane “BM”	1”Base mix”	2.9	2.15	27.93	32.98
	2	3.18	2.15	21.09	26.41
	3	2.71	2.15	17.66	22.53
	4	2.82	2.15	21.46	26.43
	5	3.07	2.15	0	5.22
	6	2.96	2.15	0	5.11
Black steel and sealer “BS”	1”Base mix”	2.9	0.58	31.61	35.09
	2	3.18	0.58	25.05	28.8
	3	2.71	0.58	21.59	24.88
	4	2.82	0.58	25.2	28.59
	5	3.07	0.58	4.84	8.49
	6	2.96	0.58	0	3.54

B.2.4.1 Cost for concrete mixtures with black steel and membrane

Figure B.61 compares the life cycle cost for different concrete mixtures with black steel and membrane using the total cost. Figure B.62compares the life cycle cost based on the phases cost. Figure B.63 shows the constant costs for all alternatives. Figure B.64 shows the cumulative present value for all alternatives.

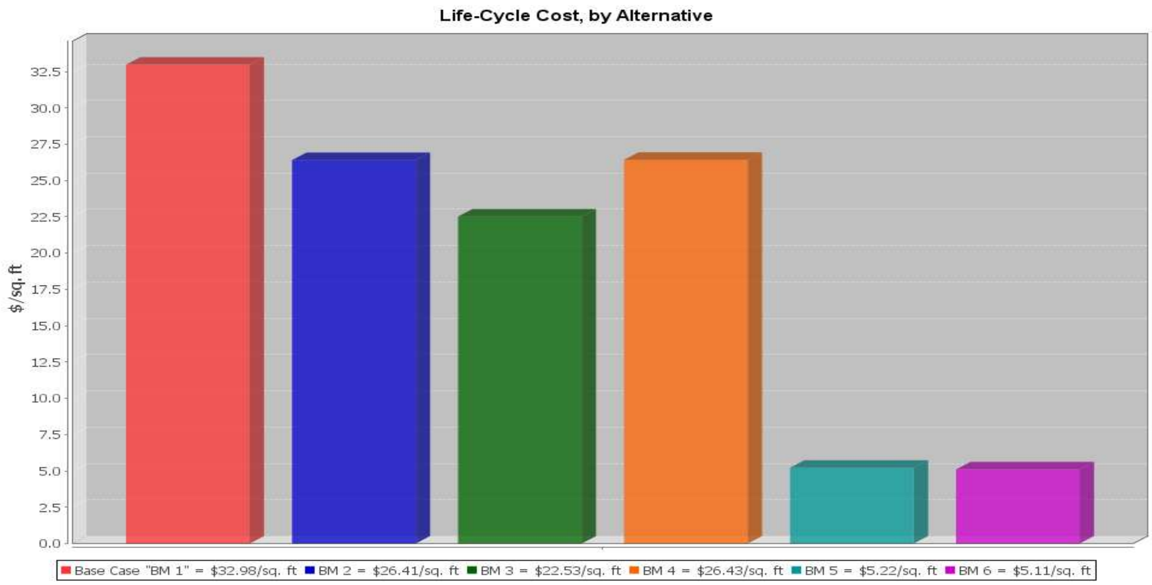

Figure B.61: Life cycle cost by alternatives for case4 with membrane "cover of 2.5 in. and w/cm of 0.34" (plotted by Life-365 software)

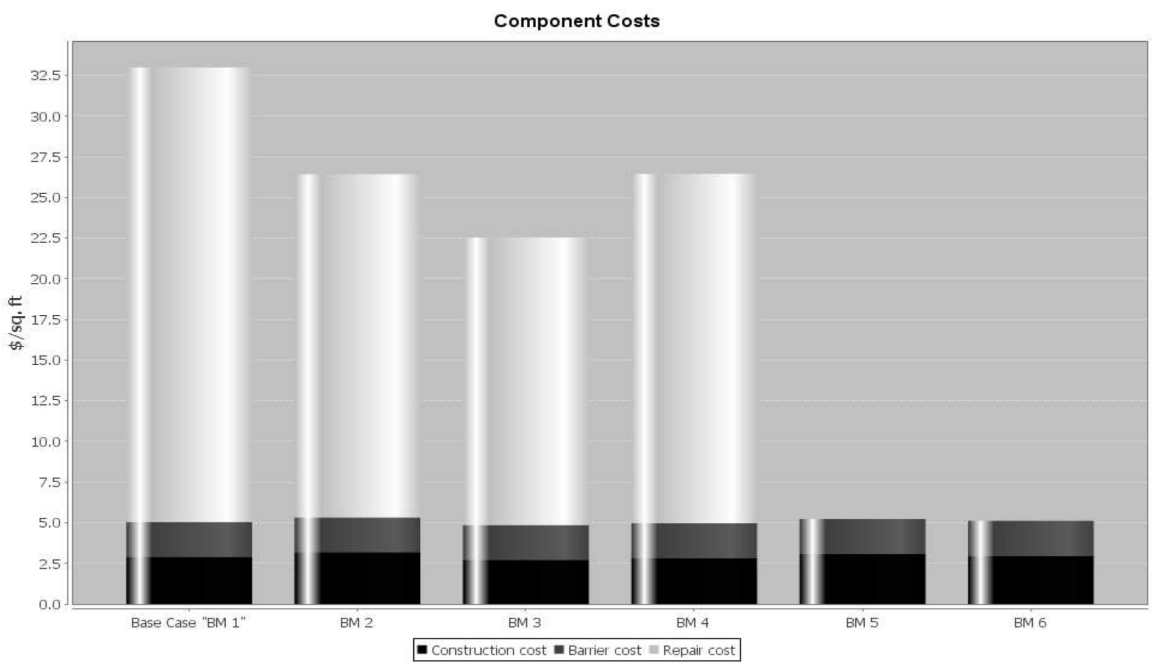

Figure B.62: Life cycle cost by phases cost for case4 with membrane "cover of 2.5 in. and w/cm of 0.34" (plotted by Life-365 software)

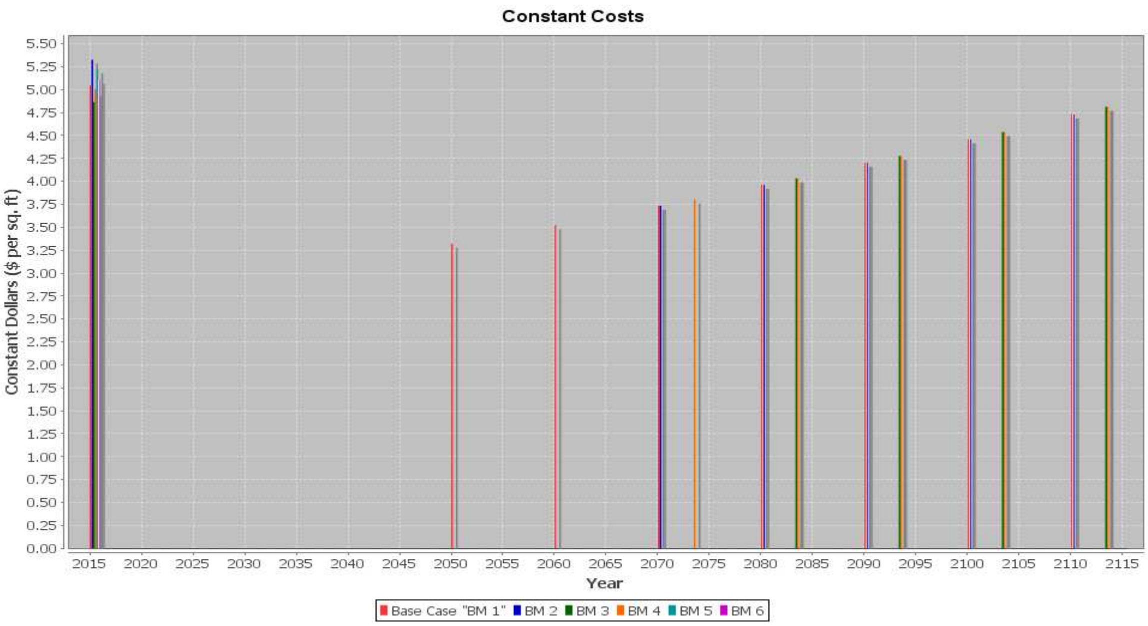

Figure B.63: Cost in constant dollars for all alternatives vs analysis period for case4 with membrane “cover of 2.5 in. and w/cm of 0.34” (plotted by Life-365 software)

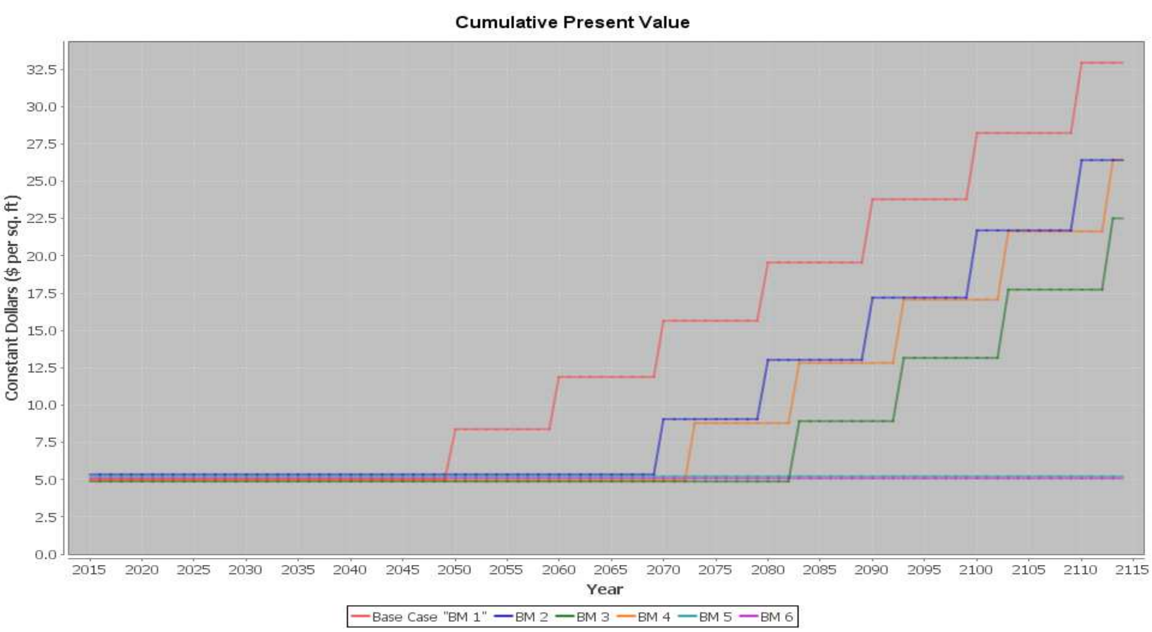

Figure B.64: Cumulative present value vs analysis period for case4 with membrane “cover of 2.5 in. and w/cm of 0.34” (plotted by Life-365 software)

B.2.4.2 Cost for concrete mixtures with black steel and sealer

Figure B.65 compares the life cycle cost for different concrete mixtures with black steel and sealer using the total cost. Figure B.66 compares the life cycle cost based on the phases cost. Figure B.67 shows the constant costs for all alternatives. Figure B.68 shows the cumulative present value for all alternatives.

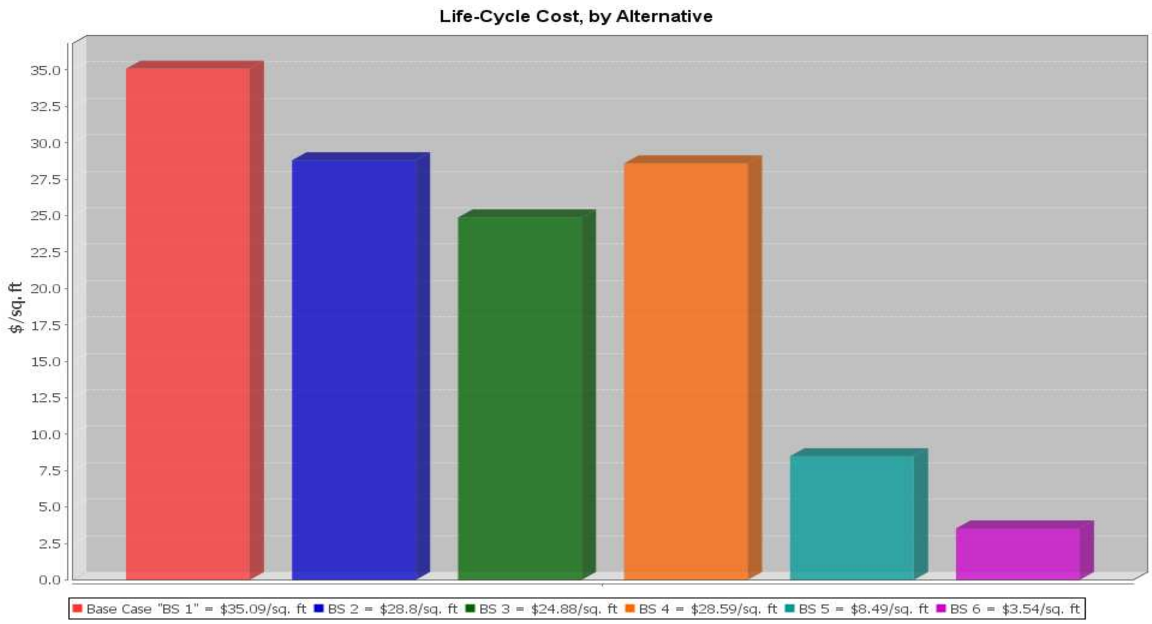

Figure B.65: Life cycle cost by alternatives for case4 with sealer "cover of 2.5 in. and w/cm of 0.34" (plotted by Life-365 software)

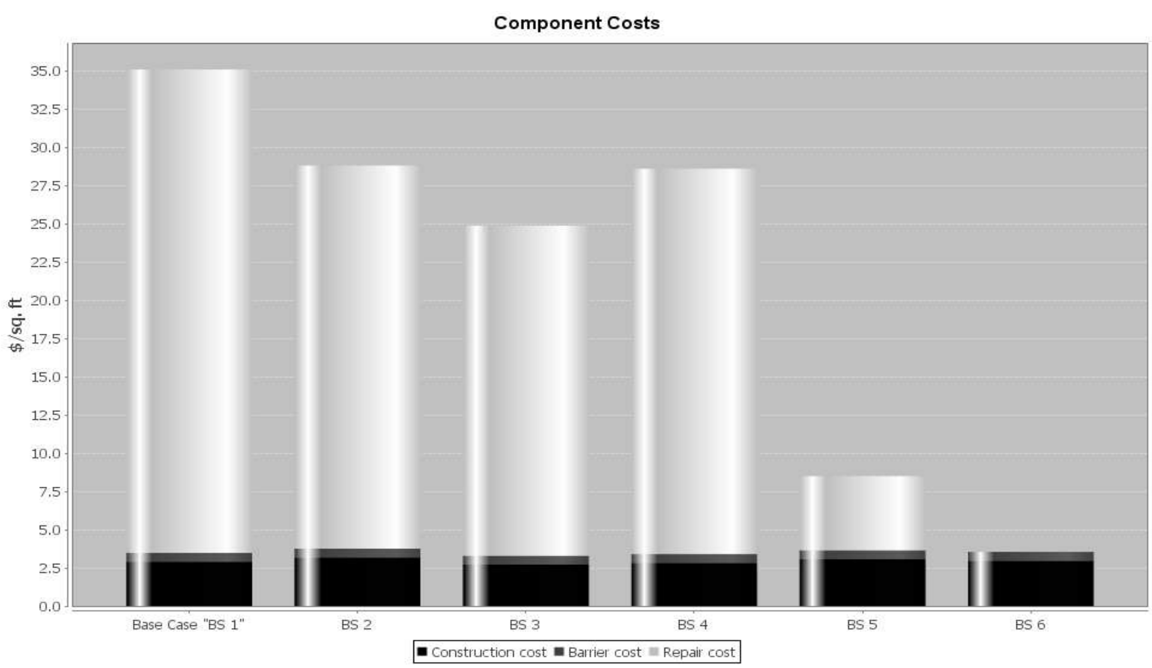

Figure B.66: Life cycle cost by phases cost for case4 with sealer "cover of 2.5 in. and w/cm of 0.34" (plotted by Life-365 software)

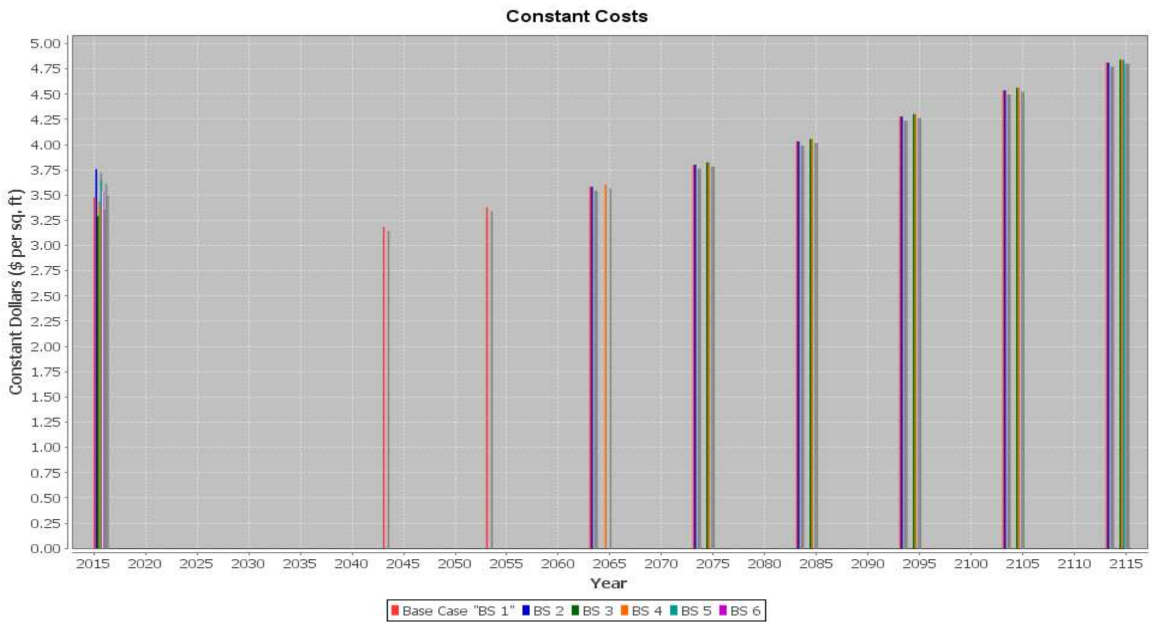

Figure B.67: Cost in constant dollars for all alternatives vs analysis period for case4 with sealer “cover of 2.5 in. and w/cm of 0.34” (plotted by Life-365 software)

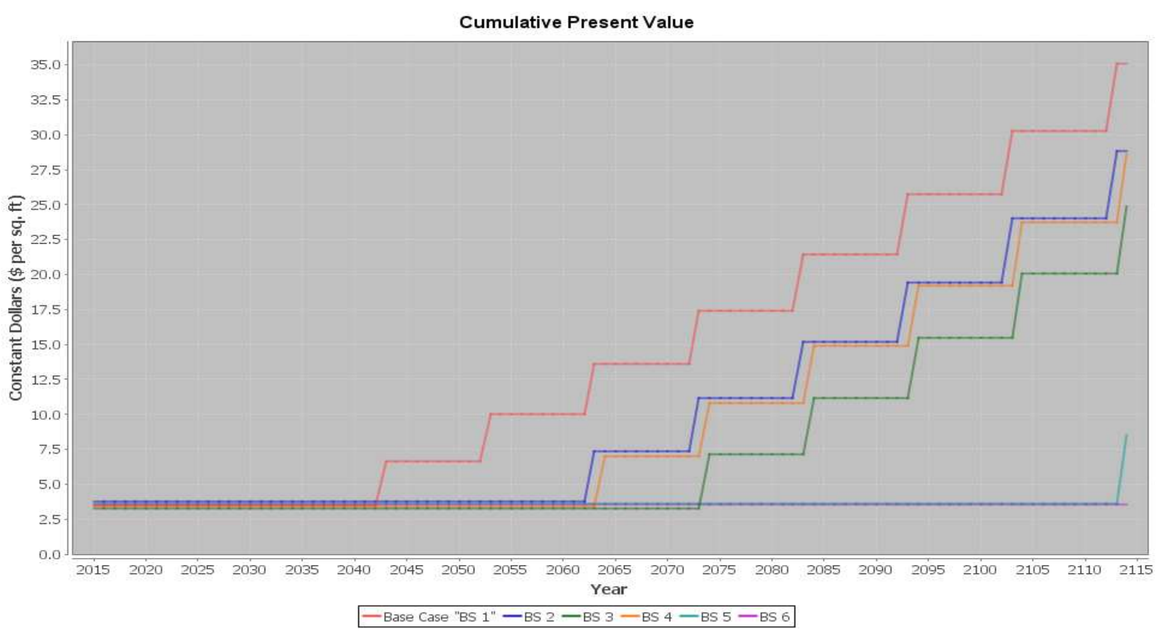

Figure B.68: Cumulative present value vs analysis period for case4 with sealer “cover of 2.5 in. and w/cm of 0.34” (plotted by Life-365 software)

B.2.5 Case 5, Concrete cover =2 in. & w/cm=0.3

The life cycle cost in different alternatives for case 5 is shown in Table B.12. Life cycle cost is the sum of construction cost, barrier cost and repair cost.

Table B.12: Life cycle cost for case 5

Alternative or mix #	Construction phase cost	Barrier phase cost	Repair phase cost	LCC "$/sq.ft"
1	3.02	0	30.51	33.53
2	3.75	0	28.09	31.84
3	3.02	2.15	27.44	32.61
4	3.02	4.57	27.44	35.03
5	3.02	0.58	31.06	34.66
6	3.02	1.18	31.24	35.44

Figure B.69compares the life cycle cost in case 5 for different alternatives using the total cost. Figure B.70 compares the life cycle cost based on the phases cost. Figure B.71 shows the constant costs for all alternatives. Figure B.72 shows the cumulative present value for all alternatives.

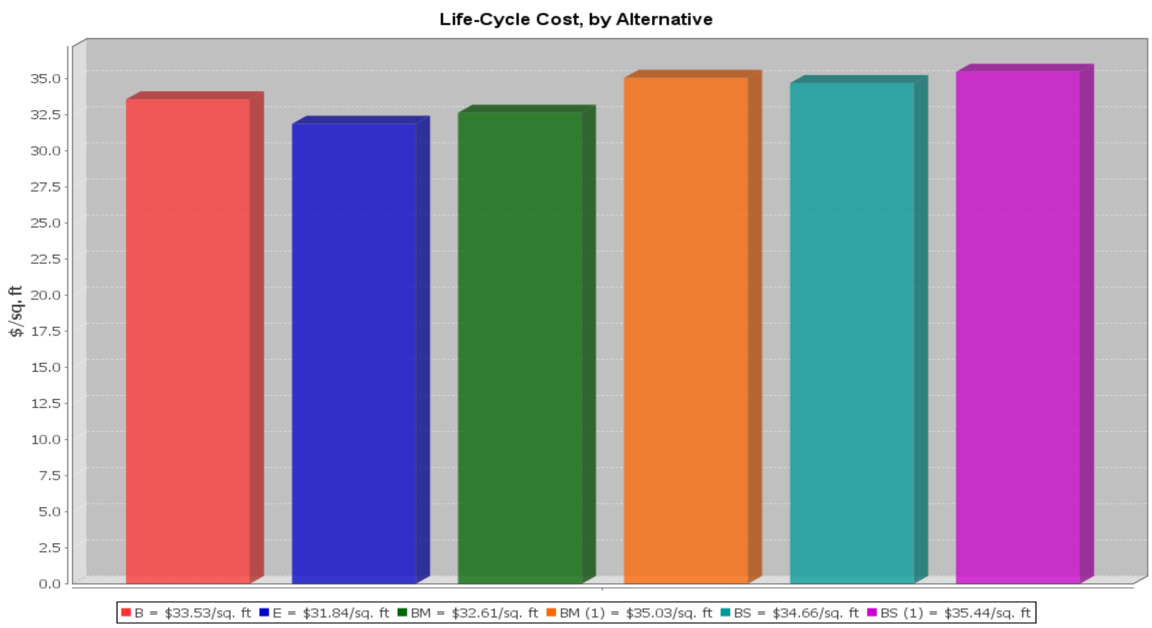

Figure B.69: Life cycle cost by alternatives for case5 "cover of 2 in. and w/cm of 0.3" (plotted by Life-365 software)

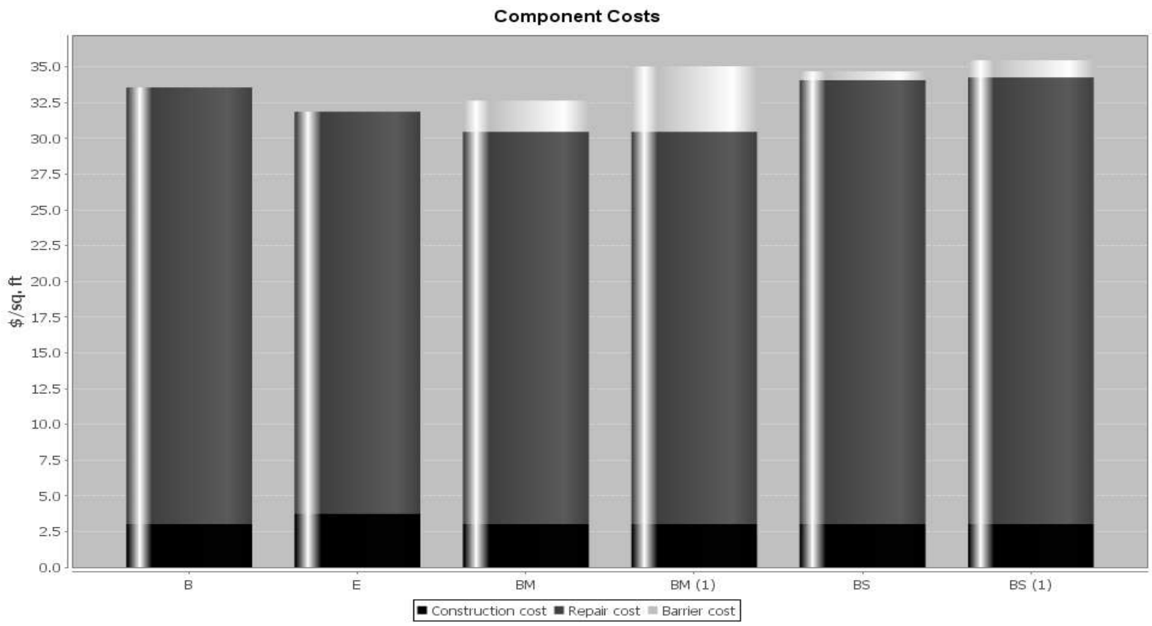

Figure B.70: Life cycle cost by phases cost for case5 “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

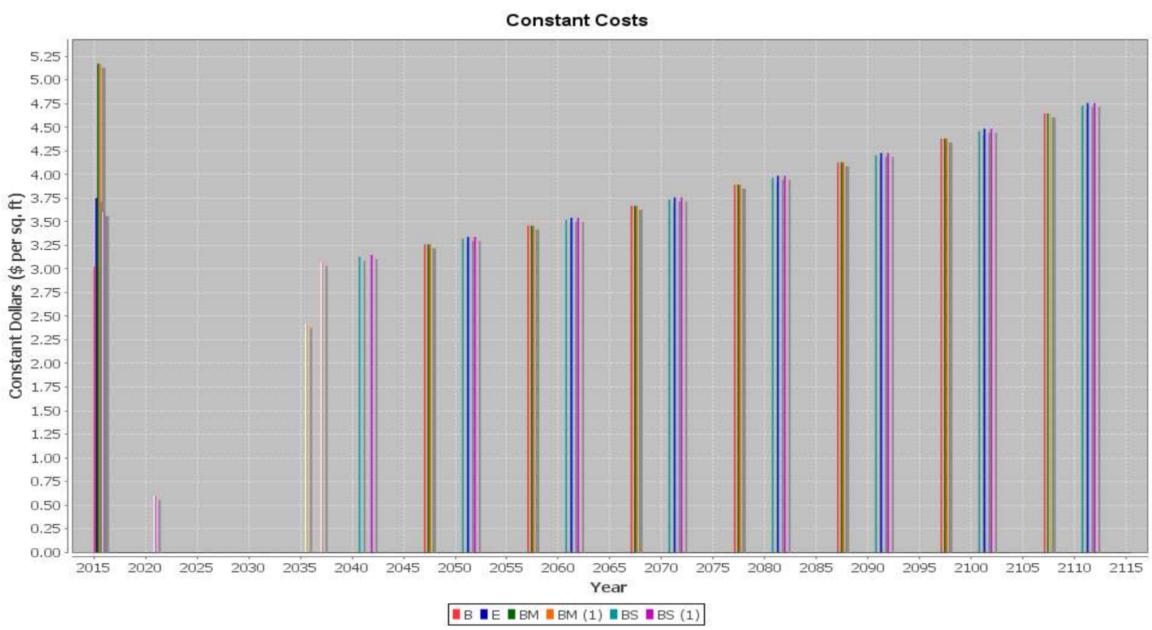

Figure B.71: Cost in constant dollars for all alternatives vs analysis period for case5 “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

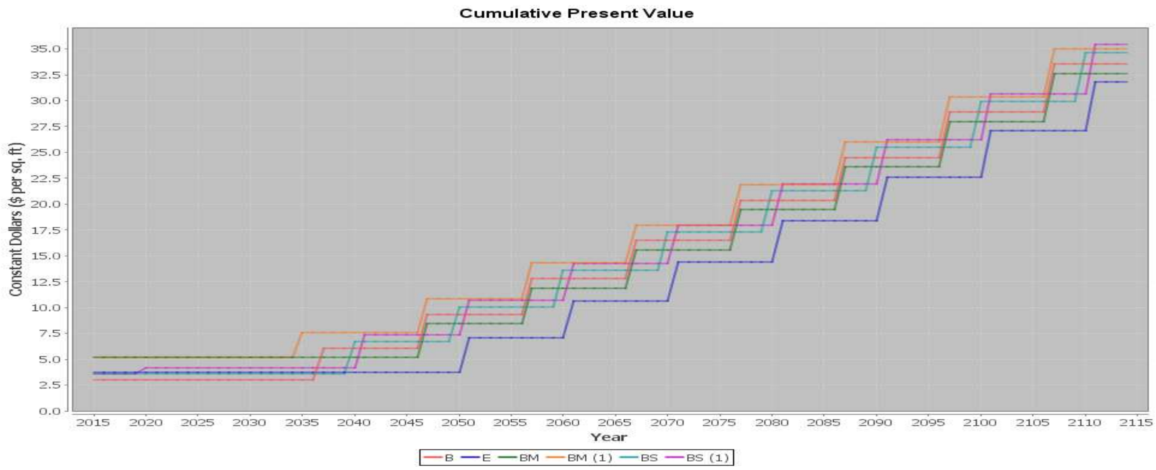

Figure B.72: Cumulative present value vs analysis period for case5 “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

B.2.6 Case 6, Concrete cover =2 in. & w/cm=0.3

The life cycle cost in different alternatives for case 6 is shown in Table B.13. Life cycle cost is the sum of construction cost, barrier cost and repair cost. The alternatives that will have the barrier, either Membrane ”M” or Sealer “S”, are 2, 4 and 6.

Table B.13: Life cycle cost for case 6

Alternative or mix #	**Construction phase cost**	**Barrier phase cost**	**Repair phase cost**	**LCC “$/Sq.ft”**
1	3.34	0	28.43	31.76
2 “with M”	3.34	2.15	25.05	30.54
3	2.81	0	24.61	27.42
4 “with M”	2.81	2.15	21.46	26.43
5	2.93	0	28.43	31.36
6 “with M”	2.93	2.15	20.47	25.55
1	3.34	0	28.43	31.76
2 “with S”	3.34	0.58	24.03	27.95
3	2.81	0	24.61	27.42
4 “with S”	2.81	0.58	25.20	28.59
5	2.93	0	28.43	31.36
6 “with S”	2.93	0.58	24.03	27.54

B.2.6.1 Cost for concrete mixtures with black steel "Membrane in alternatives 2, 4 and 6"

Figure B.73 compares the life cycle cost for different concrete mixtures with black steel, with and without membrane, using the total cost. Figure B.74 compares the life cycle cost based on the phases cost. Figure B.75 shows the constant costs for all alternatives. Figure B.76 shows the cumulative present value for all alternatives.

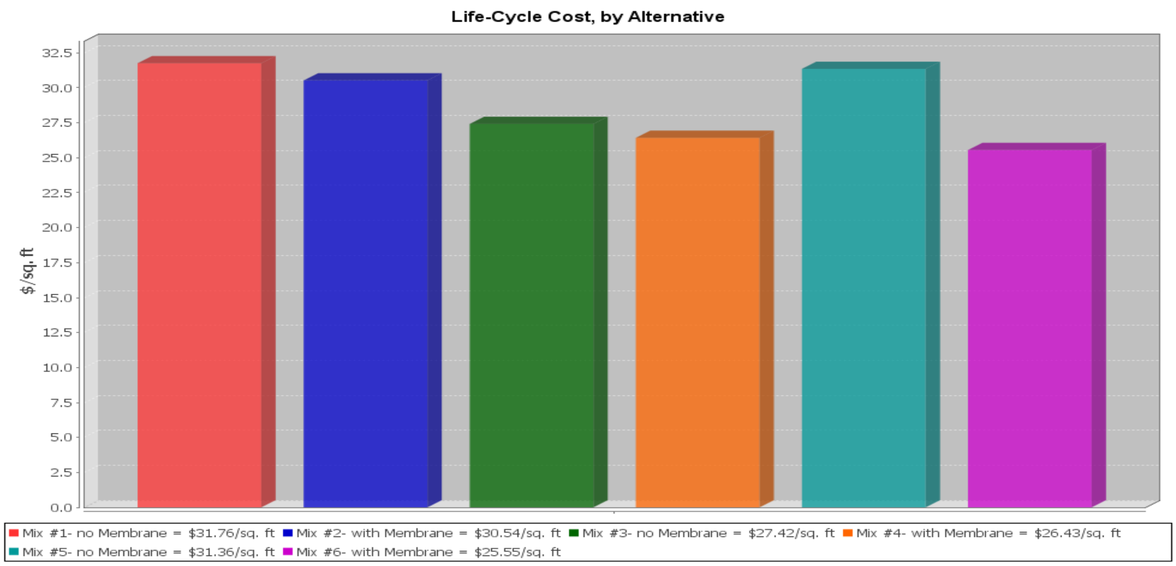

Figure B.73: Life cycle cost by alternatives for case 6 with membrane in some alternatives "cover of 2 in. and w/cm of 0.3" (plotted by Life-365 software)

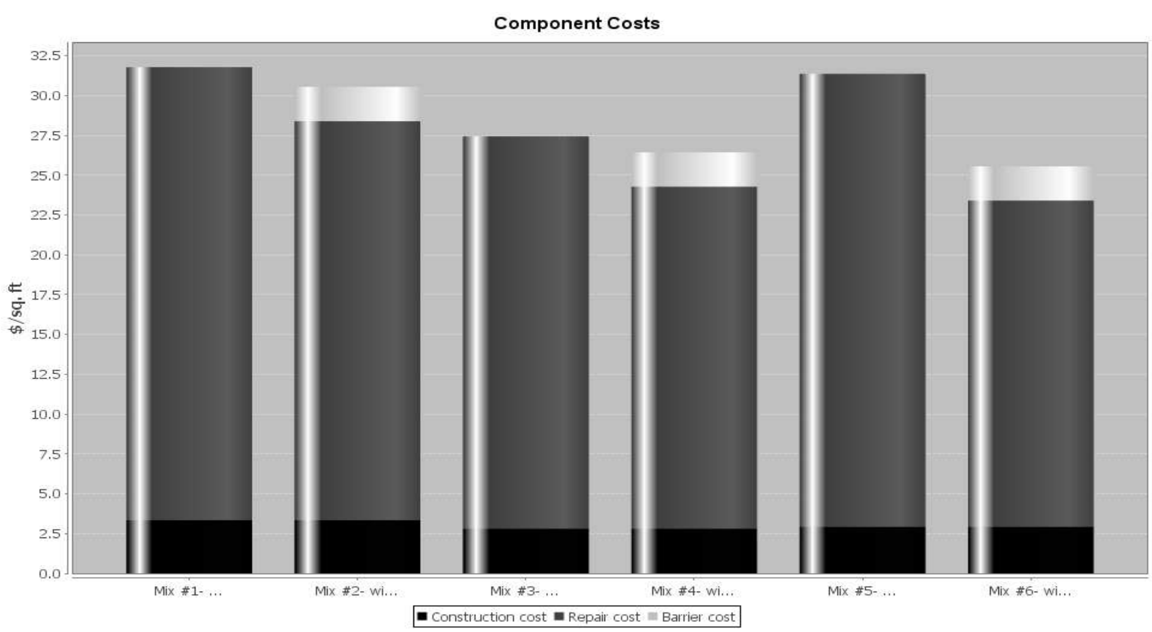

Figure B.74: Life cycle cost by phases cost for case 6 with membrane in some alternatives "cover of 2 in. and w/cm of 0.3" (plotted by Life-365 software)

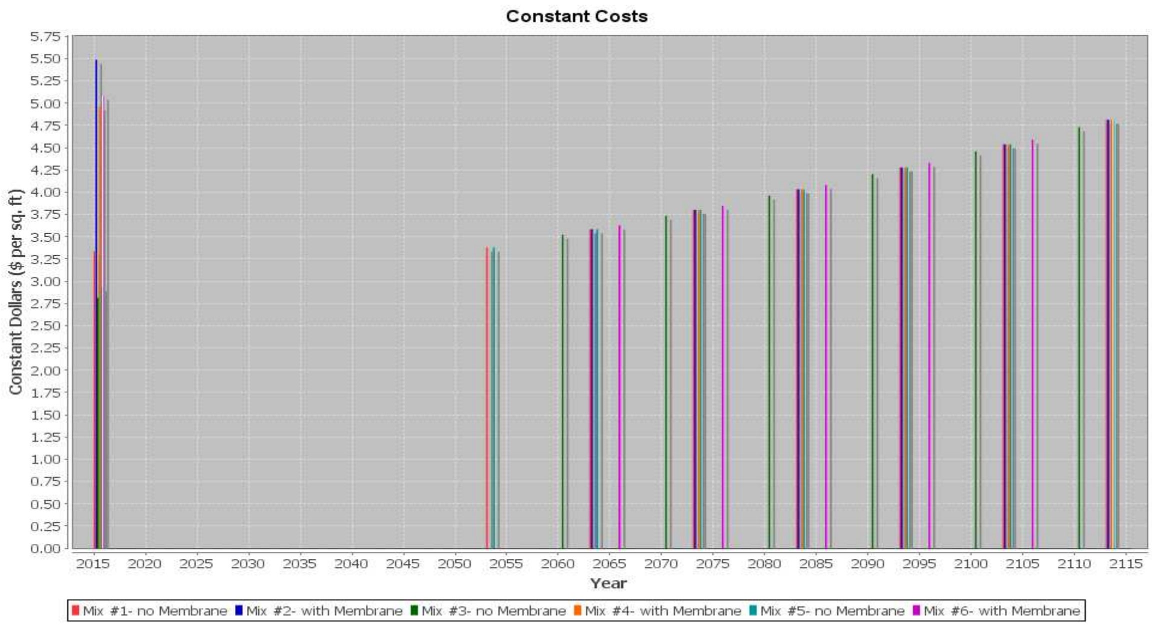

Figure B.75: Cost in constant dollars for all alternatives vs analysis period for case 6 with membrane in some alternatives “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

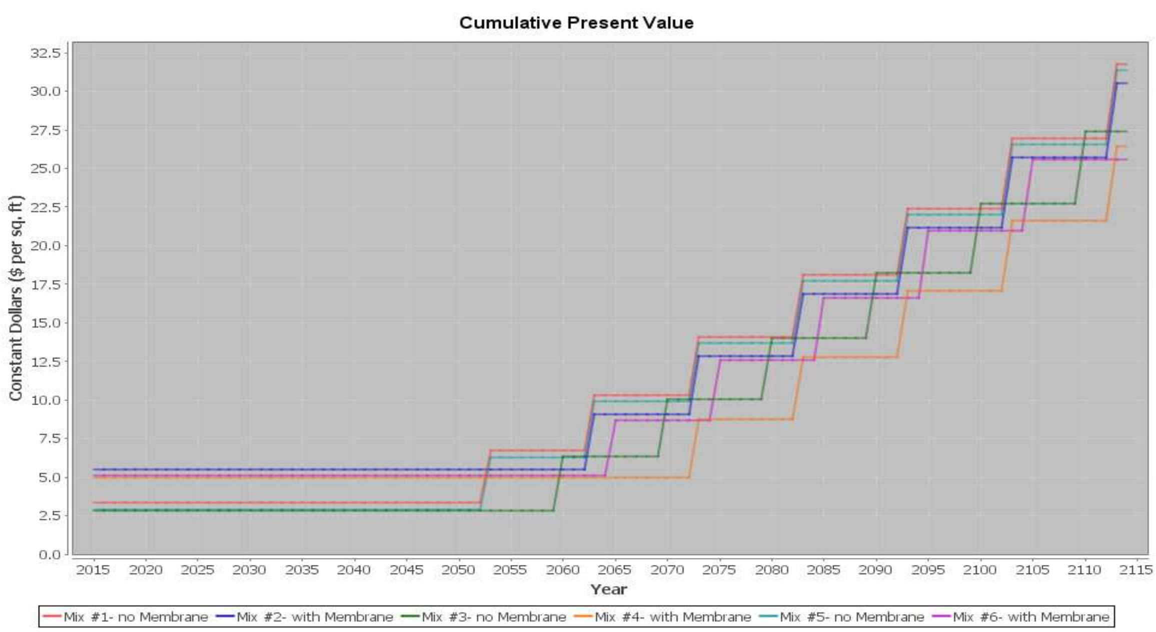

Figure B.76: Cumulative present value vs analysis period for case6 with membrane in some alternatives “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

B.2.6.2 Cost for concrete mixtures with black steel “Sealer in alternatives 2, 4 and 6”

Figure B.77 compares the life cycle cost for different concrete mixtures with black steel, with and without sealer, using the total cost. Figure B.78 compares the life cycle cost based on the phases cost. Figure B.79 shows the constant costs for all alternatives. Figure B.80 shows the cumulative present value for all alternatives.

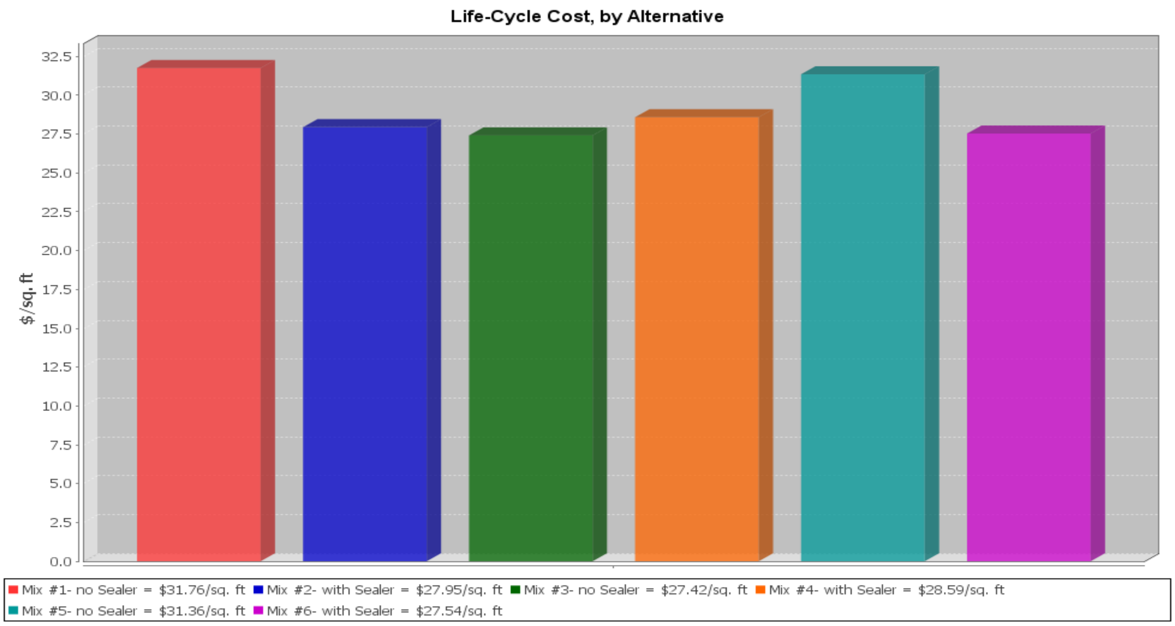

Figure B.77: Life cycle cost by alternatives for case 6 with sealer in some alternatives "cover of 2 in. and w/cm of 0.3" (plotted by Life-365 software)

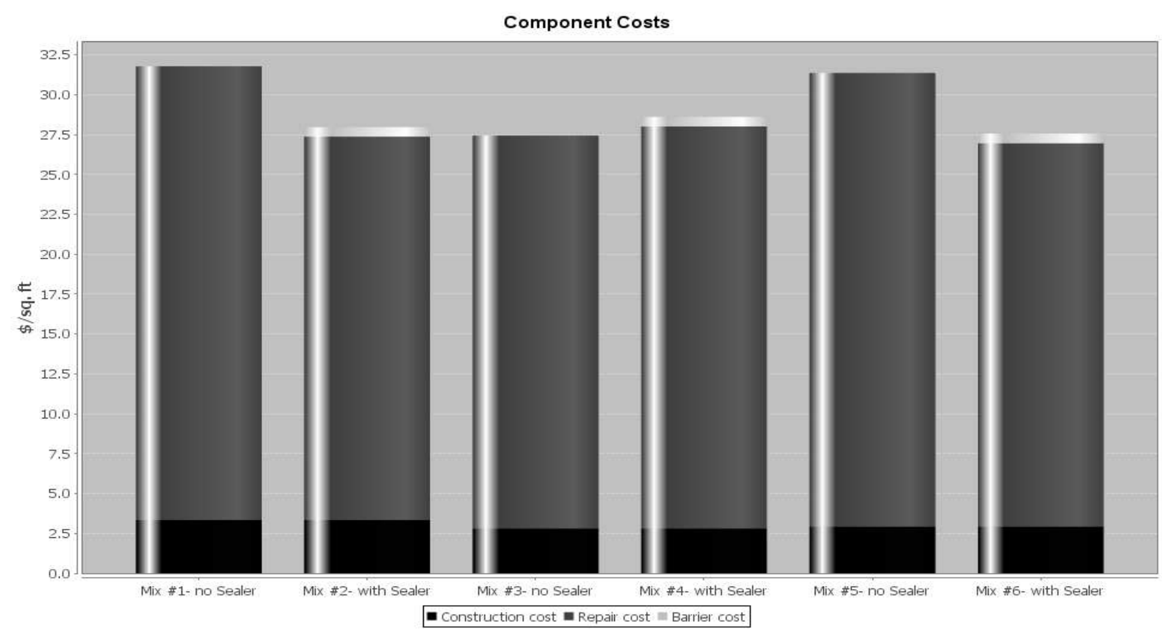

Figure B.78: Life cycle cost by phases cost for case 6 with sealer in some alternatives "cover of 2 in. and w/cm of 0.3" (plotted by Life-365 software)

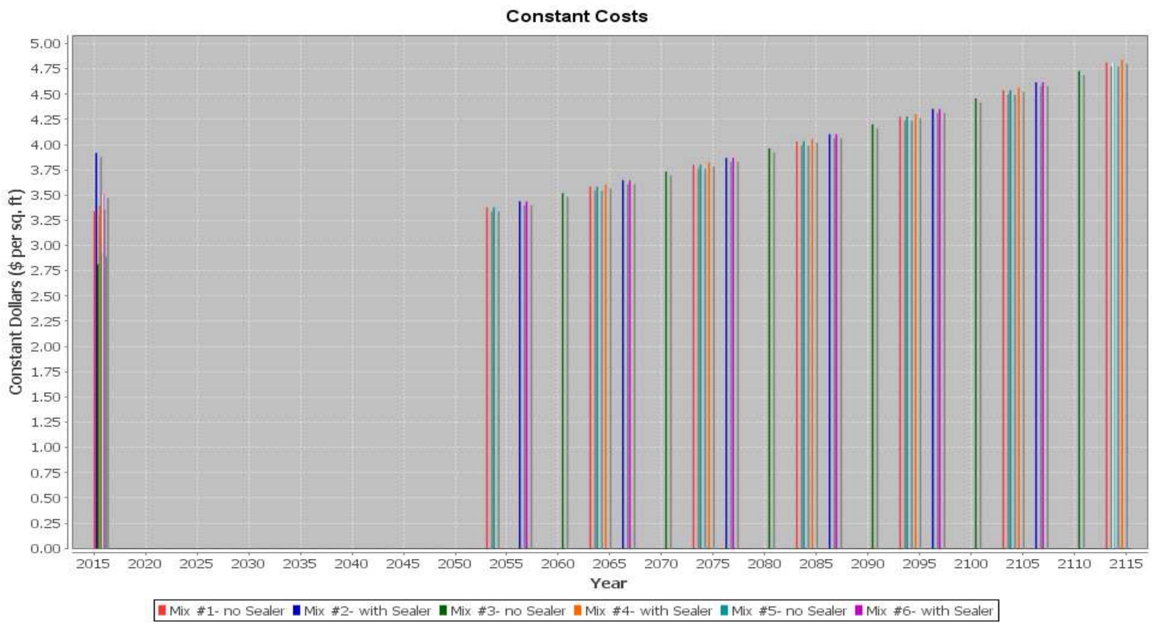

Figure B.79: Cost in constant dollars for all alternatives vs analysis period for case 6 with sealer in some alternatives “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

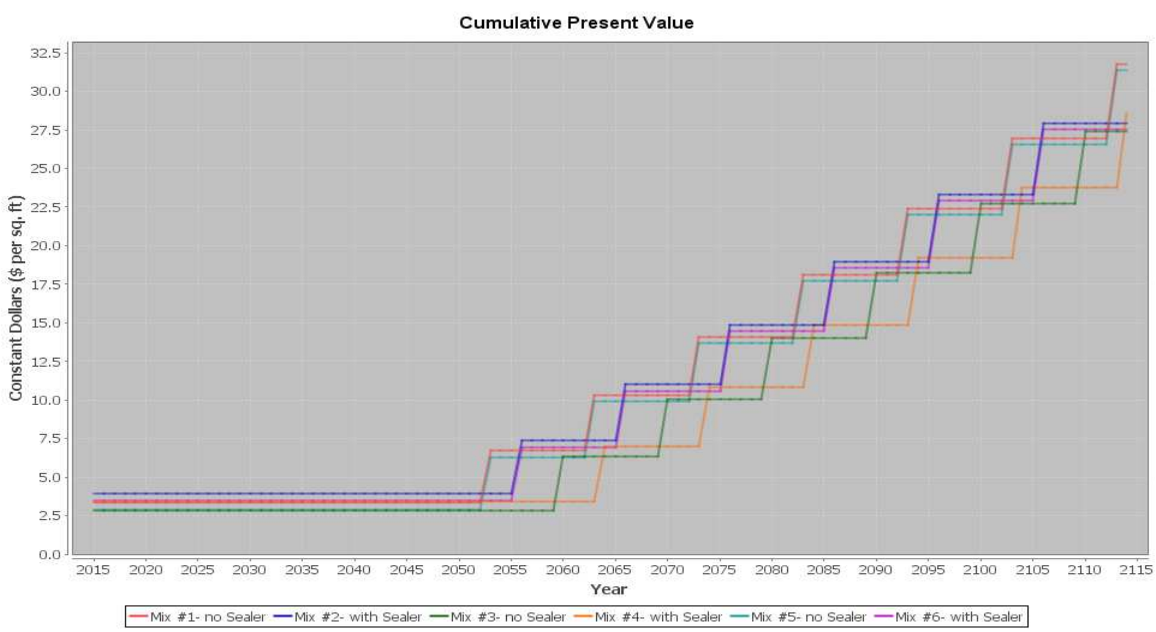

Figure B.80: Cumulative present value vs analysis period for case 6 with sealer in some alternatives “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

B.2.7 Case 7, Concrete cover =2 in. & w/cm=0.3

The life cycle cost in different alternatives for case 7 is shown in Table B.14. Life cycle cost is the sum of construction cost, barrier cost and repair cost.

Table B.14: Life cycle cost for case 7

Alternative or mix #	Construction phase cost	Barrier phase cost	Repair phase cost	LCC "$/sq.ft"
1	3.34	0	28.43	31.76
2	4.07	0	20.72	24.78
3	2.81	0	24.61	27.42
4	3.54	0	21.59	25.13
5	2.93	0	28.43	31.36
6	3.66	0	20.72	24.37

Figure B.81 compares the life cycle cost in case 7 for different alternatives with different types of reinforcement using the total cost. Figure B.82 compares the life cycle cost based on the phases cost. Figure B.83 shows the constant costs for all alternatives. Figure B.84 shows the cumulative present value for all alternatives.

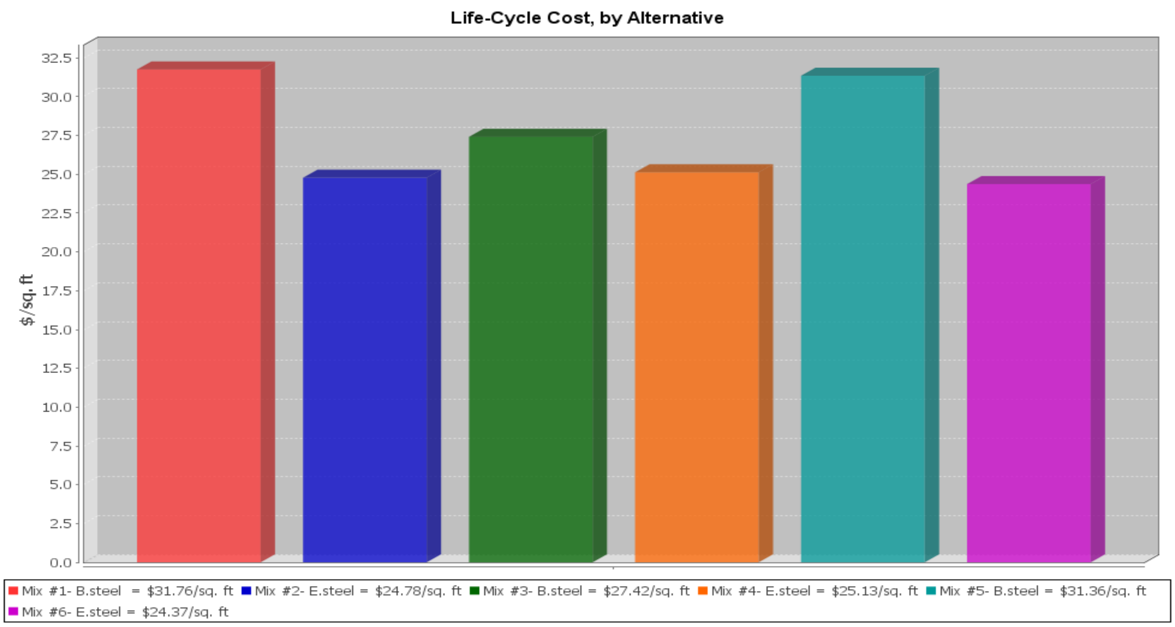

Figure B.81: Life cycle cost by alternatives for case7 "cover of 2 in. and w/cm of 0.3" (plotted by Life-365 software)

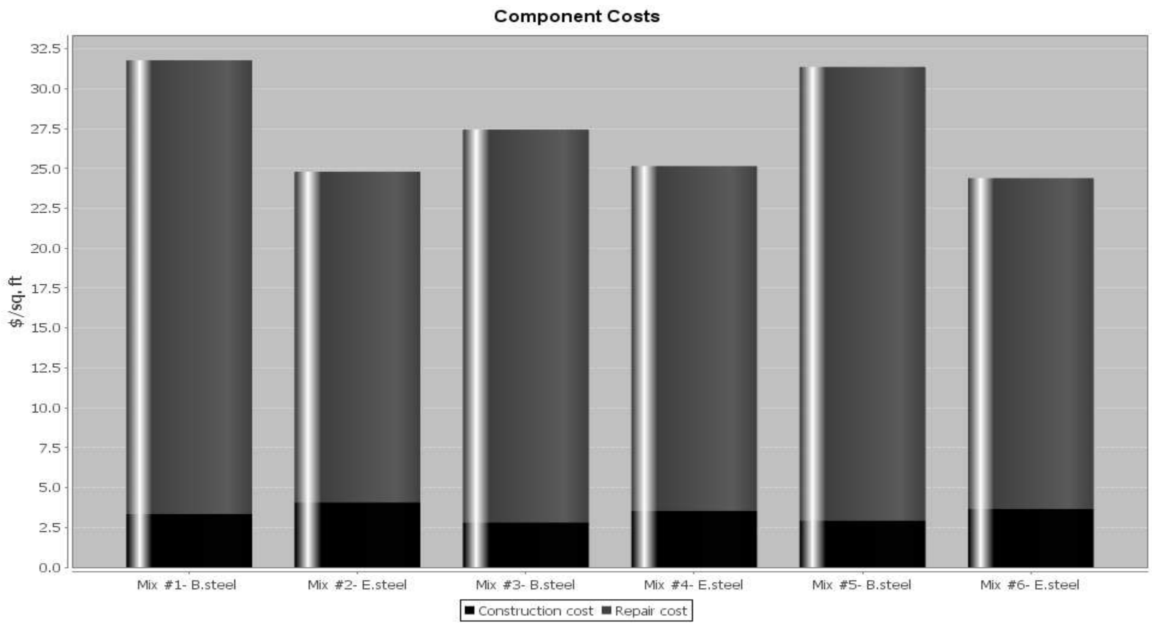

Figure B.82: Life cycle cost by phases cost for case 7 “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

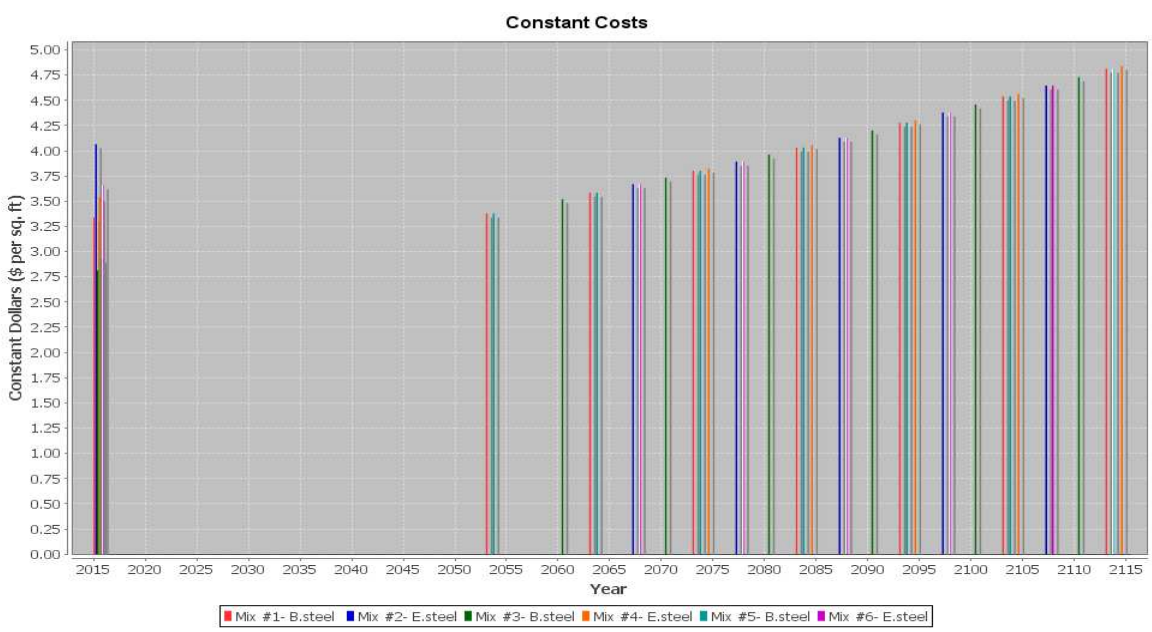

Figure B.83: Cost in constant dollars for all alternatives vs analysis period for case 7 “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)

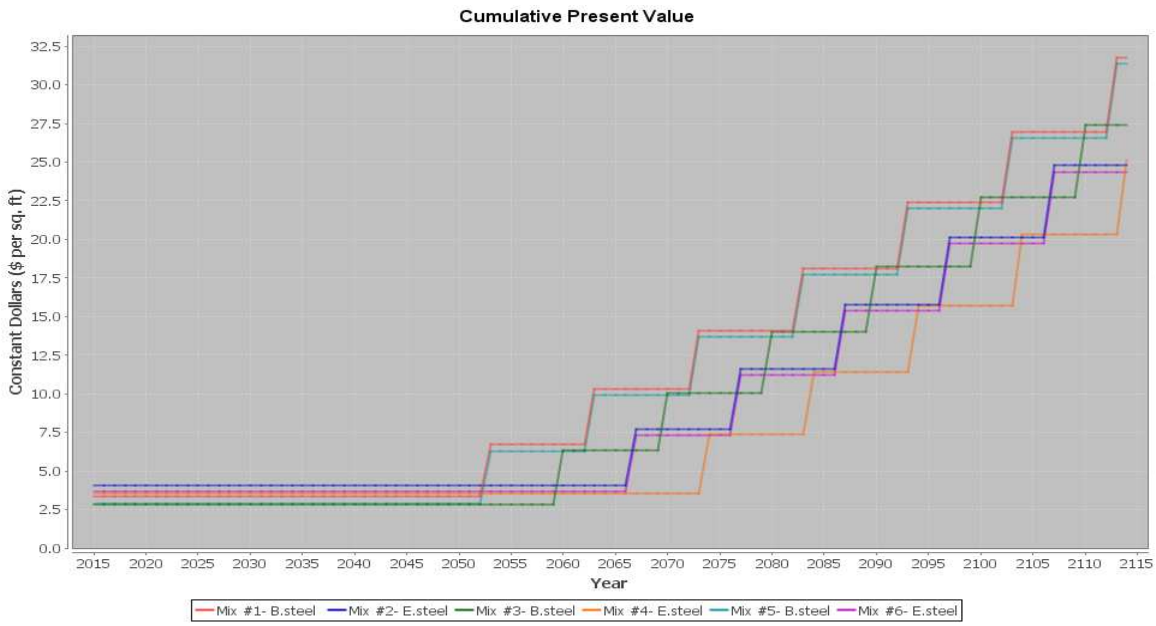

Figure B.84: Cumulative present value vs analysis period for case 7 “cover of 2 in. and w/cm of 0.3” (plotted by Life-365 software)