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Research Article

Impact of supplementary cementitious materials on life cycle cost of high-strength concrete in coastal environments

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Abstract

This research investigates the application of Life Cycle Cost (LCC) analysis in the construction industry, focusing on reinforced concrete structures. LCC analysis goes beyond initial building costs, encompassing all expenses throughout a structure's service life. Among various service life prediction models, Life-365 and DURACON are noteworthy. Life-365, a specialized computer program, predicts the life cycle cost of reinforced concrete exposed to chlorides. This paper presents a case study using Life-365 to compare the LCC of two concrete mixes, TM1 and TM2, in Mumbai, a location with conditions conducive to chloride exposure. The study uses average monthly temperatures and location-specific input parameters to evaluate the LCC of M70-grade concrete mixes with different compositions, including Fly Ash, GGBS, and Micro Silica as partial cement replacements. Results indicate that quaternary blended M70 grade concrete, incorporating supplementary cementitious materials (SCMs), not only enhance durability but also offers economic benefits, reducing overall life cycle costs. These findings provide valuable insights for engineers and decision-makers, promoting durable, cost-effective, and sustainable concrete structures.

1. Introduction

Uncontrolled urban development poses significant challenges in both developing nations like India and developed countries globally. Unplanned expansions frequently lack adequate infrastructure, resulting in substantial maintenance, rehabilitation, and reconstruction costs that often exceed initial estimates. Addressing this issue necessitates the integration of all life-cycle costs (LCC) into the structural analysis [1]. The primary objective of this research is to apply Life Cycle Cost (LCC) analysis to reinforced concrete structures, particularly focusing on the use of quaternary blended concrete mixes. By employing Life-365 software, the study aims to compare the LCC of different concrete compositions and provide insights into their economic and durability performance.

The study investigates the comprehensive costs associated with reinforced concrete structures exposed to chlorides, including initial construction and long-term maintenance expenses [2].The research utilizes Life-365, a specialized service life prediction model, to analyse the economic viability and durability of concrete mixes in chloride-exposed environments [3].A comparative analysis between two trial mixes, TM1 and TM2, is conducted to determine the most cost-effective and durable option for M70 grade concrete in a coastal setting like Mumbai [4]. Despite the extensive use of LCC analysis across various fields, its application in the construction industry, particularly in predicting the

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long-term costs and performance of reinforced concrete with supplementary cementitious materials (SCMs), remains limited [5]. Existing literature lacks comprehensive studies that integrate LCC analysis with service life prediction models like Life-365, particularly for high-performance concrete mixes in chloride-rich environments [6]. This study addresses this gap by providing a detailed analysis of the economic and durability benefits of quaternary blended concrete, incorporating Fly Ash, GGBS, and Micro Silica [7].

The contemporary application of LCC analysis provides a holistic assessment of costs from initial construction to the end of a structure's service life [8]. This approach is increasingly important for optimizing construction costs while reducing energy expenses through innovative solutions. Unlike traditional emphasis on architectural and structural design, modern LCC analysis extends to operational costs over a structure's lifespan, facilitated by advancements in computer technology [9]. The concept of limit state design, incorporating ultimate strength and serviceability limits, further underscores the safety and longevity of structures [10]. LCC terminology varies globally, with terms such as 'Life Cycle Cost,' 'Cost in Use,' 'Whole Life Costing' (WLC), and 'Whole Life Appraisal' (WLA) being used interchangeably [11]. Despite these differences, the core principle remains the same: a holistic examination of a building's entire life cycle. This paper adopts LCC as equivalent to WLC, acknowledging the comprehensive approach necessary for accurate cost analysis [12].

While minimizing initial construction costs is a common objective, this study emphasizes that achieving the lowest cost does not guarantee optimal performance over a structure's lifetime [13]. Higher initial costs may, in fact, reduce total life cycle costs by enhancing durability and reducing long-term maintenance needs [14]. This research underscores the importance of demonstrating to clients the relationship between design choices and lifetime costs, incorporating energy analyses early in the design phase to ensure sustainable and cost-effective construction solutions [15].

2. Literature Review

The concept of LCC originated in the mid-1960s with the U.S. Department of Defence, later evolving with contributions from institutions such as the Royal Institution of Chartered Surveyors and the British Ministry of Industries. Flanagan and Norman's work in 1983 introduced data collection methods, while subsequent studies, including those by Abraham and Dickson, considered disposal costs in LCC [8, 9]. In 1992, British standards formally accepted the LCC concept, defining it as a technique enabling comparative cost assessments over a specified period, considering all relevant economic factors. Internationally, the Common European Methodology for Life Cycle Costing project by Davis Longdon addressed LCC, yet despite its advantages, LCC's utilization remains limited in the construction industry due to incomplete understanding among professionals [10]. Buyers often prioritize purchase costs without considering structural design, building architecture, and energy systems, neglecting future operation and maintenance costs. Recognition of life cycle costs, encompassing construction costs and subsequent expenses, allows for more effective decision-making [15, 16].

Service life prediction becomes crucial for LCC analysis, with models like fib (Model Code) and ISO being commonly used. In seismic zones, LCC incorporates earthquake-related damages, influencing future building ownership costs. Researchers like Takahashi et al. and Frangopol and Liu have explored seismic risk costs in LCC, considering both initial and expected damage costs [17,18,19,20]. Studies on LCC extend beyond traditional structures, with Frangopol and Liu analyzing bridges, and Kappos and Dimitrapoulos evaluating the feasibility of strengthening reinforced concrete buildings. Notably, Oberg emphasizes the substantial and enduring investments in buildings, both financially and in terms of resources [21,22]. In regions with cold climates, indoor design gains prominence for property buyers spending a significant portion of their time indoors. Despite this, reports by Bakis et al. and Flanagan and Jewell highlight the limited application of LCC, revealing that maintenance and other expenses can triple the initial capital cost of construction over a building's first 25 years [04, 23]. Kotaji et al. stress the importance of demonstrating the relationship between design choices and lifetime costs for effective decision-making [24].

Consideration of all aspects is imperative during structural design to ensure the fulfillment of functions throughout the designed service life. While predicting the service life for shorter periods, such as 20 to 50 years, is feasible, determining service life for extended durations, like 100 or 150 years, presents a significant challenge [25].

Service life design involves predicting the behaviour of a structure over an extended period. While current service life models are adequately predictive, challenges arise due to variations in construction quality across different sites. The prevalent use of prescriptive designs in many countries poses a significant problem for quality assessment and service life prediction. Thus, there is a pressing need to adopt a performance-based approach for accurate prediction of service life [26]. For structures in mild or non-aggressive environments, a minimalist approach may be sufficient. However, site engineers should pay attention to good construction practices, including optimal mix design, compaction, and curing, to ensure adequate durability.

A performance-based approach is implemented following ISO – 13823. This standard, based on the limit-state method, covers various service life design approaches. The fib Model Code (2010) [27] adopts the methodology outlined in ISO-13823, offering advantages over current simplistic approaches.

3.Materials and Method

3.1. Concrete Mix Design Trials: TM1 and TM2 Composition Analysis

In this study, M70 Grade concrete mix design trials are conducted and designated as TM1 and TM2. Trial Mix 1 (TM1) is formulated with a primary component of Ordinary Portland Cement (OPC), constituting 90% of its composition. This OPC is sourced from Ambuja, a renowned provider of 53 Grade cement. Unlike TM2 and subsequent trial mixes, TM1 does not incorporate Ground Granulated Blast Furnace Slag (GGBS) in its composition, making it solely reliant on OPC for its binding properties. Additionally, TM1 does not include Micro Silica or any other supplementary cementitious materials apart from a minor inclusion of Pulverized Fly Ash (PFA) at a ratio of 10%. This PFA is sourced from Adani-Dahanu. Moreover, TM1 utilizes a Super Plasticizer, specifically Sika Viscocrete 5210 N, at a proportion of 0.8% to enhance its workability and reduce water content, thereby potentially improving its overall strength and durability

In contrast, Trial Mix 2 (TM2) exhibits a different composition, aimed at exploring alternative materials and proportions for enhanced concrete properties. TM2 incorporates a lower percentage of OPC, accounting for 57% of its composition, still sourced from Ambuja 53 Grade Cement. However, TM2 introduces GGBS, sourced from JSW and certified for quality, constituting 25% of the mix. This addition of GGBS aims to improve the long-term durability and strength characteristics of the concrete. Moreover, TM2 includes 8% Micro Silica, further enhancing its strength and reducing permeability. Similar to TM1, TM2 also includes 10% PFA sourced from Adani-Dahanu, providing additional benefits in terms of sustainability and durability. Finally, both TM1 and TM2 utilize the same Super Plasticizer, Sika Viscocrete 5210 N, at a consistent ratio of 0.8%, ensuring uniformity in workability and strength enhancement across the trial mixes.

3.2. Manufacturing Cost of Concrete:

- **Material Costs:** The primary components of concrete—cement aggregates, water, and admixtures—contributed to the manufacturing cost. The prices of these materials are taken in to account for determining the initial manufacturing cost (All costs in INR). The initial cost of production is taken as an input value for calculating the Life Cycle cost over 70 years.
- **Equipment and Energy Costs:** The use of machinery, transportation equipment, and energy resources during the manufacturing process contributed to the overall cost. The total manufacturing cost of 1 m3 concrete for TM1(Control sample) & TM2.

Table 1. Comparison of production cost of M70-Grade concrete mix TM1 and TM2 for 1m^3

Material	**Rates (Rs.)**	**Unit**
Cement	7.1	Per Kg.
Fly Ash	3	Per Kg.
Metal	1000	Per MT
Cr. sand	1100	Per MT
SikaViscocrete 5210 NS Admixture	151	Per Kg.
Micro silica	28.50	Per Kg.
GGBS	4.14	Per Kg.
water	0.190	Per Kg.
Diesel	104.8	Per Lit

Grade / Mix	**Material in Kgs.**									**A**	**B**	**C**	**D**	**E**	**F**	**Production cost (E+F)**
										Total Material Cost	Wastage on (A) Cost 2%	Material + wastage A+B	Operation & Plant cost+ Profit	Total Cost (C+D)	GST on E 18%	(Rs.)
TM1 M-70	475.0	0.00	145	460	590	615	6.0	50	147							
Cont.Sam.	3372	0.00	435	460	590	676	910	1425	28	7869	157.3	8026	950	8976	1615	**10593**
TM2 M-70	237.5	237	145	460	590	615	3.8	50	147							
(50:50)	1686	983	435	460	590	676	365	1425	28	6649	132.9	6782	950	7732	1391	**9124**

3.3. Life Cycle Cost Analysis Using Life-365 ver.2.2.3

Life-365 serves as both a Service Life Prediction Model and a Computer Program designed for predicting the Service Life and Life-Cycle Cost of reinforced concrete exposed to chlorides. Initiated in 1998 by the ACI's Strategic Development Council (SDC), a consortium including representatives from various entities developed Life-365 for service life prediction and life-cycle cost analysis (LCCA).

Life-365 predicts the start of corrosion and the time required for corrosion to reach a level necessitating repair. It estimates initial construction costs, predicted repair costs, and costs over the entire design life of a structure. The required inputs include geographic location, construction type, depth of clear concrete cover to the reinforcement, and details of corrosion protection strategies used. The analysis done by Life-365 involves predicting the initiation period of corrosion (ti), the propagation period of corrosion (tp), and the time of the first repair (tr), which is the sum of these two periods (tr = ti + tp). A repair schedule is then calculated for the entire design life after the initial repair of the structure. Estimation of Life-Cycle Cost (LCC) is based on the initial concrete costs, corrosion protection system costs, and future repair costs.

The total life cycle cost is the sum of initial construction costs and discounted future repair costs over the service life of a structure. The initial cost of construction includes the cost of concrete, reinforcing steel, and the cost of surface protection membrane or sealer used, if any. Future repair costs are calculated using software, considering present worth along with the discount rate provided by the user. Life-365 expresses these costs on the unit area of the structure. While the current version has limitations and makes several assumptions to address complex phenomena, the software allows users to run user-defined scenarios by making minor changes to selected values. However, uncertainties in concrete material properties, structural geometry, boundary conditions, and project costs are not fully addressed. Users are encouraged to input data based on exposure conditions and project-specific economic factors.

Life-365 calculates the initiation period using the Fickian diffusion model (One or two-dimensional). Default corrosion propagation times are provided for different types of reinforcement. ASTM E 917 -05, 'Standard practice for measuring Life cycle costs of building and building systems,' is followed in Life-365v2.0, initially setting the design life at 75 years. The most recent model, Life 365v 2.2, allows users to insert the value of Chloride diffusion (Cs) obtained from testing specimens on-site using the ASTM C1556 method of testing, which is similar to NT Build 443 [28].

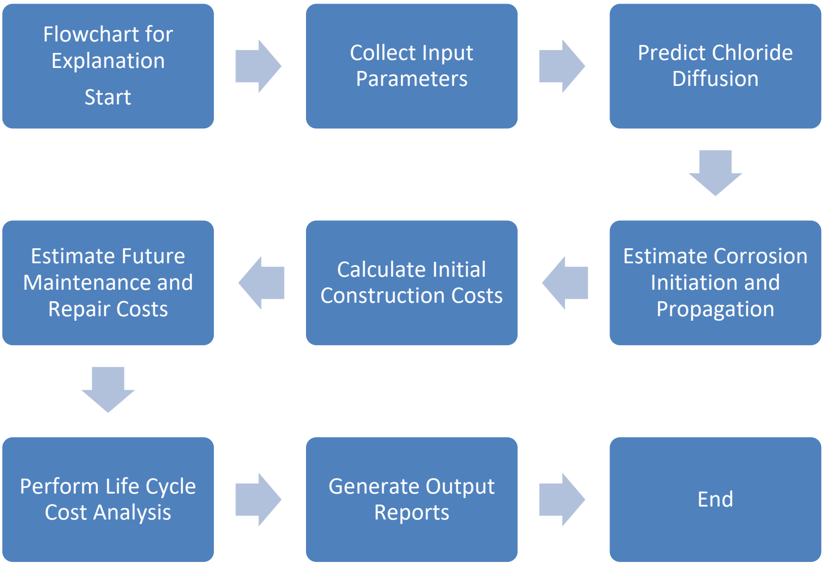
3.4 Data Gathering Procedure

- **Geographic Location:** Data includes average monthly temperatures, humidity levels, and chloride exposure conditions specific to the structure's location.
- **Concrete Composition:** Details on the mix design, including the proportions of OPC, GGBS, Micro Silica, PFA, and any other supplementary cementitious materials.
- **Exposure Conditions:** Information on the environmental conditions the structure will face, such as chloride concentration from seawater or deicing salts.
- **Economic Factors:** Cost inputs for materials, labour, maintenance, and repair activities, as well as discount rates for future cost calculations.

3.5 Standardization Followed

Life-365 adheres to several international and industry standards to ensure the reliability and accuracy of its predictions:

- **ASTM Standards**: Life-365 follows ASTM E917-05 for measuring life cycle costs of building and building systems. This standard provides a methodology for cost estimation, ensuring consistency and comparability in LCC analysis.
- **ISO Standards:** The software incorporates methodologies aligned with ISO 15686-5, which focuses on building and construction asset management and service life planning.
- **Testing Methods:** For input parameters such as chloride diffusion, the software utilizes data from standardized testing methods like ASTM C1556 and NT Build 443, which measure chloride penetration in concrete.



Flow Chart 1. The flow chart above explains how the software works

- **Input Parameters:** The software begins with the collection of various input parameters essential for accurate predictions. These parameters include the geographic location of the structure, which influences environmental exposure conditions; the specific composition of the concrete mix, including any supplementary materials; and economic factors such as material costs and maintenance schedules.
- **Service Life Prediction:** Life-365 uses these inputs to predict chloride diffusion into the concrete over time, estimate the time until corrosion initiation, and determine the propagation period until significant damage occurs. This step involves complex modelling of chloride ingress and the resulting deterioration processes.
- **Life Cycle Cost Analysis:** The software calculates initial construction costs based on the concrete composition and other materials used. It then estimates future costs for maintenance and repairs, considering the predicted timing and extent of corrosion-related damage. These costs are discounted to present value to facilitate a comprehensive cost-benefit analysis over the structure’s expected service life.
- **Output Results:** Finally, Life-365 generates detailed reports that include predicted service life, total life cycle costs, and recommendations for cost-effective and durable concrete mix designs. These results provide valuable insights for engineers and decision-makers, helping them to select materials and design strategies that optimize both economic and performance outcomes.

4. Results and Discussions

4.1 Life Cycle Cost of Concrete

The decision-making between manufacturing and life cycle costs hinges on project-specific requirements and constraints. While short-term projects may prioritize minimizing manufacturing costs, long-term projects benefit from life cycle cost analysis. Recognizing that decisions made during manufacturing have far-reaching implications, a holistic approach considers factors like energy efficiency, environmental impact, and maintenance requirements. This report utilizes Life-365 software for a case study, comparing TM1 and TM2 composite mixes over their entire life cycle.

4.2 Average Monthly Temperatures

Life-365 facilitates the analysis of chloride migration's impact on the structure's entire life and the effects of temperature variation on durability. Using Mumbai as a study location, average monthly temperatures are input into the software to assess the life cycle cost of M70-grade concrete mixes. The study employs Life-365 to analyze the impact of temperature variations on life cycle costs, considering different compositions with supplementary materials.

The M70 grade concrete mixes were designed with a base mix containing 450 kg/m^3 of Ordinary Portland cement (OPC), fine and coarse aggregates, and water. Different trial mixes are formulated, incorporating supplementary cementitious materials using Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Micro Silica as partial cement replacement with different proportions. The water-cement ratio is maintained at 0.22 for all mixes. Life-365 software, a comprehensive life-cycle cost analysis tool, is employed to assess the impact of average monthly temperatures on the life-cycle cost of the concrete structure. The software is given inputs on material costs, maintenance, repair, and replacement costs. The average monthly temperatures as input to the software as shown below:

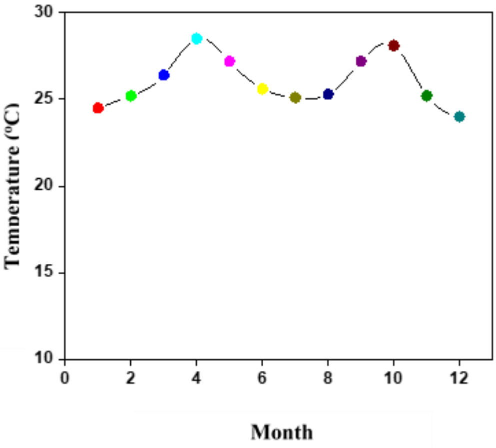


Fig. 1. Shows that the change in average temperature for the period of 12 months

4.3 Cumulative Current Costs

Cumulative current cost graphs visually represent the accumulation of costs over time in life cycle cost analysis. "Life 365" generates these graphs, illustrating cost evolution throughout a project's life cycle. The graph allows stakeholders to understand cost trends over time. For comparison, a cumulative current cost graph is plotted for TM1 and TM2, providing a clear representation of their life cycle costs.

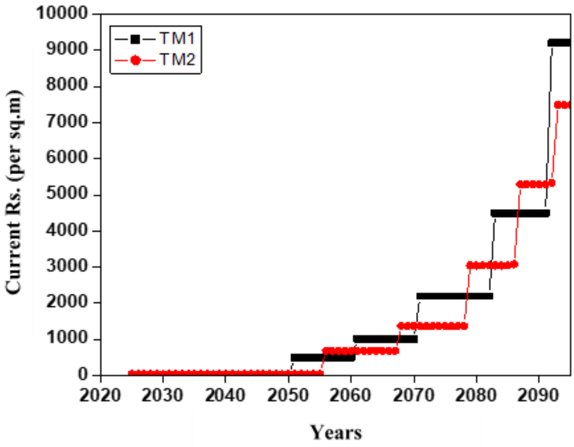


Fig. 2. Shows the cumulative current cost against age of structure in number of years

4.4 Cumulative Present Value

This section assesses the durability of quaternary blended M70 grade concrete, focusing on Cumulative Present Cost. Utilizing Life-365, the study compares two trial mixes over 70 years, incorporating supplementary cementitious materials. Fig. 3 summarizes the cumulative present cost analysis, indicating a positive impact on economic sustainability due to the addition of Fly Ash, GGBS, and Micro Silica in Trial Mix 1 compared to Trial Mix 2.

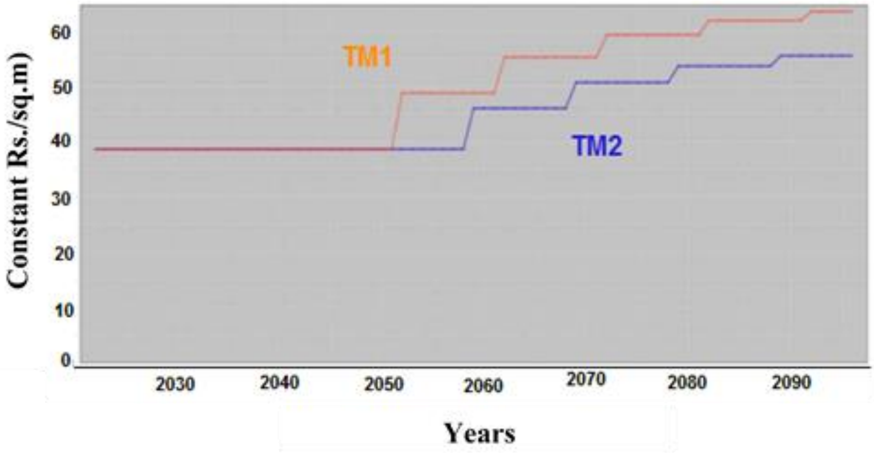


Fig. 3. Shows the cumulative constant cost

Trial Mix 1, which is a control mix, demonstrated a 26.31 % reduction in cumulative present cost compared to Trial Mix 2 when observed at 40 years' age of structure. It is also observed that in Trial Mix 1, the cumulative present cost started increasing at the age of 32 years whereas the same started at 38 years in the case of Trial Mix 2. It is further to be noted that at the end of the life, the cumulative present cost of Trial Mix 1 is 15.68% more than that of Trial Mix 2. This suggests that the addition of Fly Ash, GGBS, and Micro Silica positively influenced the economic sustainability of M70 grade concrete over the 70 years.

4.5 Current Costs

This section focuses on the Current Cost analysis for quaternary blended M70 grade concrete. Figure 4 depicts the outcomes of the current cost analysis for TM1 and TM2, emphasizing the positive influence of supplementary materials on economic sustainability over the total life of the structure.

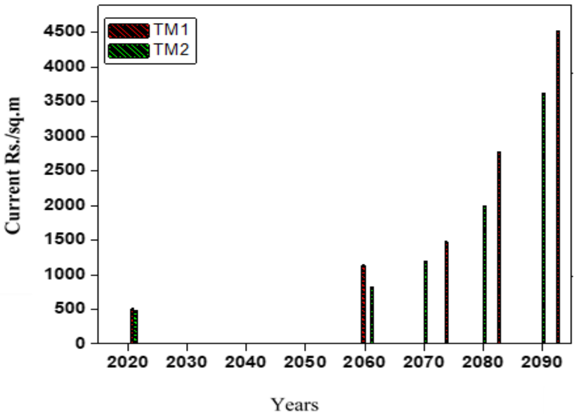


Fig. 4 shows the current cost

It is also observed that in Trial Mix 1, the current cost started adding its value at the age of 32 years whereas the same is started at 40 years in the case of Trial Mix 2. It is further to be noted that at the end of its life current cost of Trial Mix 1 is 24.32 % more than that of Trial Mix 2. This suggests that the addition of Fly Ash, GGBS, and Micro Silica positively influenced the economic sustainability of M70 grade concrete over the total life of the structure i.e. 70-year period [29].

4.6 Diffusivity Versus Time

Employing Life-365, the study analyses diffusivity over 70 years for two trial mixes. Figure 5 illustrates the results, showing that Trial Mix 1, incorporating Fly Ash and GGBS, reduces diffusivity.

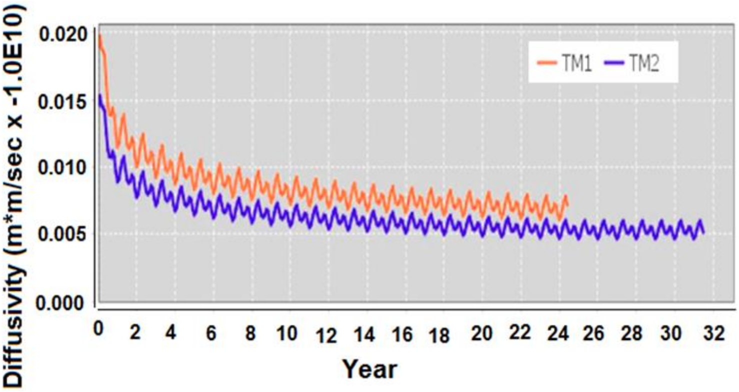


Fig. 5. Shows the change in diffusivity as a function of time

Trial Mix 1, which included Fly Ash and GGBS, demonstrated a 15% reduction in diffusivity compared to the control mix over 70 years. This suggests that the addition of Fly Ash and

GGBS had a positive impact on reducing the diffusion of harmful substances in M70-grade concrete, contributing to enhanced durability. Trial Mix 2, incorporating Fly Ash, GGBS, Silica Fume, and OPC, showed a further 10% reduction in diffusivity compared to Trial Mix 1.

4.7 Comparison of Initiation and Propagation of Chloride Penetration:

The study employed Life-365 software to scrutinize the initiation and propagation of chloride penetration over 70 years for two trial mixes incorporating supplementary materials. Graph 6 visually represents the outcomes of this analysis.

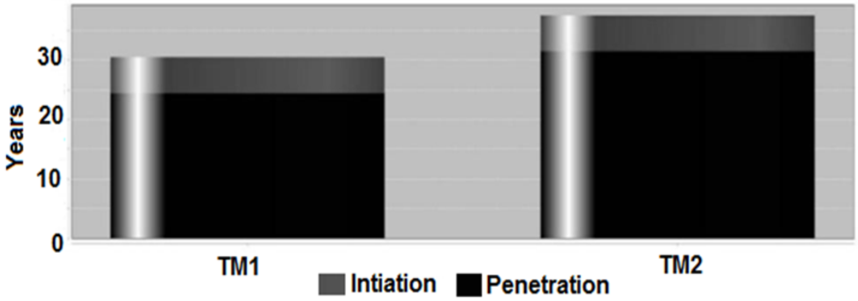


Fig. 6. shows the initiation of chloride penetration

Figure 6 indicates that Trial Mix 2 displayed a delayed initiation of chloride penetration compared to Trial Mix 1, emphasizing the enhanced resistance to chloride ion initiation. Furthermore, the propagation of chloride penetration in Trial Mix 2 exhibited a significantly slower pace than in Trial Mix 1, underscoring the effectiveness of the quaternary blend in preventing chloride ingress [30].

4.8 Chloride Concentration (% Weight) vs. Time in Years at a Depth of 60 mm

The study, utilizing Life-365 software, examined Chloride Concentration (% Weight) vs. Time at a depth of 60 mm over 70 years for two trial mixes with different compositions. The graphical representation of the chloride concentration analysis is presented below.

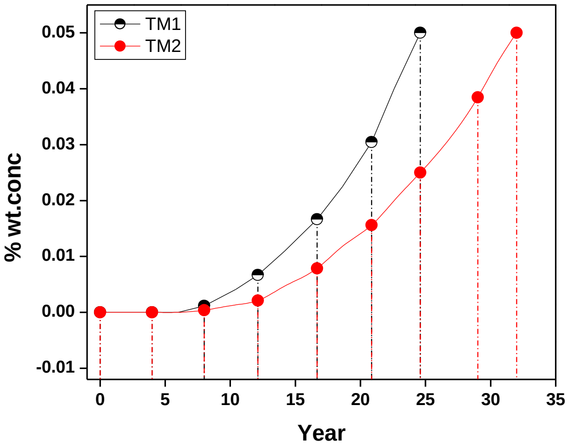


Fig. 7. Shows the effect of chloride concentration as a function of time at the depth of 60 mm

Figure 7 illustrates that Trial Mix 2 exhibited a considerably slower increase in chloride concentration compared to both the control mix and Trial Mix 1. This suggests that the additional inclusion of PFA, GGBS, and Silica Fume enhanced resistance to chloride penetration in Trial Mix 2, highlighting the effectiveness of the quaternary blend [31].

4.9 Life Cycle Cost Comparison Between Two Alternatives

The life cycle cost comparison analysis results for the two trial mixes are summarized and graphically presented in figure 8.

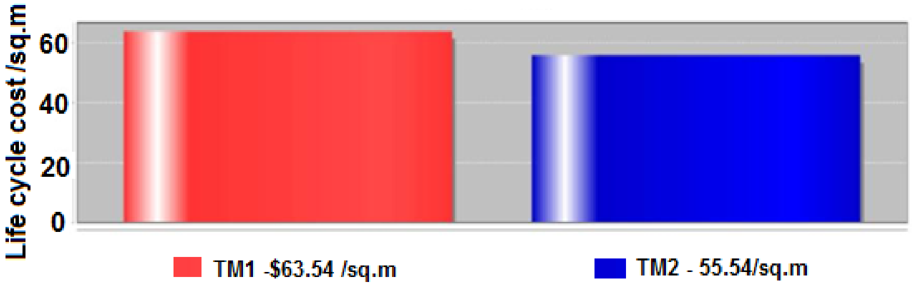


Fig. 8. Shows the comparison of life cycle cost

Figure 8 reveals that Trial Mix 2, incorporating PFA, GGBS, and Silica Fume, achieved a further 10% reduction in life cycle costs per square meter compared to Trial Mix 1. This underscores the cumulative positive impact of supplementary materials in Trial Mix 2, contributing to extended service life and reduced overall costs [32].

4.10 Surface Concentration of Chloride (% Weight) vs. Time in Years

The study utilized Life-365 software to analyse the surface concentration of chloride over 70 years for two trial mixes. The outcomes of the surface concentration of chloride analysis for the two trial mixes are presented graphically below.

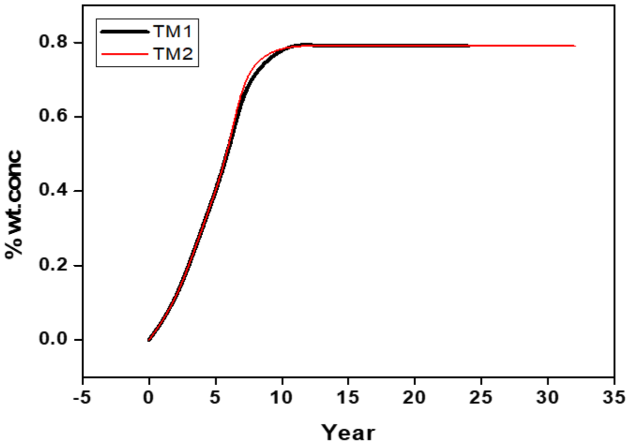


Fig. 9. Shows the surface concentration of chloride as a function of time

Figure 9 demonstrates that Trial Mix 2 exhibited an even slower increase in surface chloride concentration compared to Trial Mix 1. This suggests that the additional inclusion of PFA, GGBS, and Silica Fume further improved the resistance to chloride penetration at the concrete surface, highlighting the effectiveness of the quaternary blend [33].

4.11 Constant Cost Incurred in the Life of a Structure

The study, utilizing Life-365 software, analysed constant costs per square meter over 75 years for two trial mixes. The outcomes of the constant cost analysis for the two trial mixes are summarized and presented graphically below.

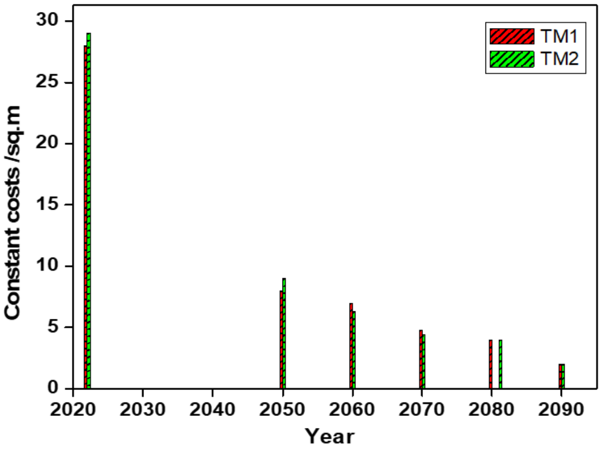


Fig. 10. Shows the constant cost as a function of time

6. Limitation of the Work

6.1 Dependence on Assumptions and Approximations

The Life-365 software relies on several assumptions and approximations for predicting chloride ingress, corrosion initiation, and life cycle costs. These assumptions may not always accurately represent real-world conditions, leading to potential discrepancies between predicted and actual performance.

6.2 Data Quality and Availability

The accuracy of Life-365's predictions heavily depends on the quality and completeness of the input data. In cases where precise data on environmental conditions, material properties, and economic factors are unavailable or unreliable, the software's outputs may be compromised.

6.3 Simplification of Complex Processes

While Life-365 models the essential aspects of chloride-induced corrosion and concrete deterioration, it simplifies many complex processes. Factors such as varying environmental conditions, load-induced stresses, and interactions between different degradation mechanisms are not fully accounted for, which can affect the robustness of the predictions.

6.4 Geographic and Climatic Variability

The software's performance may vary significantly based on geographic and climatic conditions. While it includes generalized environmental data, local variations in temperature, humidity, and chloride exposure may not be precisely captured, potentially leading to inaccuracies in service life predictions.

6.5 Limited Consideration of Non-Chloride Aggressors

Life-365 primarily focuses on chloride-induced corrosion and does not comprehensively address other potential aggressors such as carbonation, sulfate attack, or alkali-silica reaction. Structures exposed to multiple or combined deterioration mechanisms may require additional analysis beyond the capabilities of Life-365.

6.6 Economic Factor Variability

The economic analysis within Life-365 assumes static costs for materials, labor, maintenance, and repairs. However, these costs can fluctuate due to market conditions, inflation, and regional economic factors, potentially affecting the accuracy of the life cycle cost analysis.

6.7 User Expertise and Interpretation

The effectiveness of Life-365 depends on the expertise of the user. Incorrect input data, improper calibration of the model, or misinterpretation of the results can lead to suboptimal decision-making. Training and experience are essential to maximize the software's potential benefits.

6.8 Software Limitations and Updates

As with any software, Life-365 is subject to limitations in its algorithms and computational capabilities. Additionally, the need for regular updates to incorporate the latest research findings, standards, and technological advancements can be a challenge. Users must ensure they are using the most current version of the software.

6.9 Scope of Applicability

The study primarily focuses on quaternary blended M70 grade concrete. While the findings provide valuable insights for this specific mix design, the applicability of the results to other concrete grades or mix designs with different proportions or supplementary materials may be limited.

6.10 Site-Specific Variability

The performance of concrete structures can vary significantly based on site-specific factors such as construction practices, workmanship quality, and on-site environmental conditions. These factors are not fully captured in the software's predictions, potentially affecting the real-world applicability of the study's conclusions.

These limitations highlight the need for cautious interpretation and application of the study's findings. While Life-365 provides a valuable framework for life cycle cost analysis, supplementary analyses and considerations are necessary to ensure comprehensive and accurate assessments for concrete infrastructure projects.

7. Conclusions

The contemporary construction industry is progressively prioritizing the integration of cost optimization and energy-efficient strategies. This necessitates a comprehensive approach that encompasses both the initial acquisition costs and the long-term service life costs of structures. Life Cycle Cost (LCC) analysis emerges as a crucial tool in this endeavour, providing a holistic framework to evaluate the economic feasibility and sustainability of construction materials and methodologies.

In this study, we conducted a detailed LCC analysis using Life-365 software, focusing on two specific concrete mix design trials: TM1 and TM2, both designed for M70 grade concrete. TM1 consists predominantly of Ordinary Portland Cement (OPC), while TM2 incorporates supplementary cementitious materials such as Ground Granulated Blast Furnace Slag (GGBS) and Micro Silica, reflecting a quaternary blended composition. Our objective was to not only compare their immediate performance but also project their long-term economic and durability implications.

The findings from the Life-365 analysis indicate significant differences in the long-term cost efficiency and durability between TM1 and TM2. TM2 demonstrated a substantial reduction in life cycle costs due to its enhanced resistance to chloride penetration, leading to extended service life and lower maintenance requirements. This underscores the economic advantages of incorporating supplementary materials in concrete mixes, which enhance durability and reduce the frequency and cost of repairs over the structure's lifespan.

One of the critical insights from this study is the necessity of making informed adjustments and considerations when using predictive tools like Life-365. While the software provides valuable approximations, the accuracy of its prediction's hinges on the precise calibration of input parameters based on site-specific conditions and material properties.

Furthermore, the study highlights the broader implications of LCC analysis for sustainable construction. By demonstrating the long-term cost savings and durability benefits of quaternary blended concrete, we provide a compelling case for the adoption of such materials in construction projects, particularly in environments exposed to aggressive conditions like chloride ingress.

For engineers and decision-makers, these insights are invaluable. They emphasize the importance of looking beyond initial construction costs and considering the total cost of ownership over the structure's life. This approach not only promotes economic efficiency but also aligns with the principles of sustainable development by minimizing resource consumption and environmental impact over the long term.

In conclusion, our study reinforces the critical role of LCC analysis in guiding sustainable construction practices. By integrating economic and durability assessments, we can make more informed decisions that ensure the construction of cost-effective, durable, and environmentally friendly infrastructure. The adoption of quaternary blended concrete, as evidenced by the superior performance of TM2, represents a significant step forward in achieving these goals.

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