Project 2447 | May 2025

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Strategized Reduction of Greenhouse Gas Emissions Through Predicting and Extending the Service Life of Concrete Pavements and Bridges

Fariborz M. Tehrani, PhD, PE, ENV SP, PMP, SAP, F. ASCE

California State University Transportation Consortium

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Report 25-11

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May 2025

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.
25-11

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Strategized Reduction of Greenhouse Gas Emissions Through Predicting and Extending the Service Life of Concrete Pavements and Bridges

5. Report Date
May 2025

6. Performing Organization Code

7. Authors
Fariborz M. Tehrani, https://orcid.org/0000–0002–7618–8009

8. Performing Organization Report
CA-MTI-2447

9. Performing Organization Name and Address
Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

10. Work Unit No.

11. Contract or Grant No.
SB1-SJAUX_2023-26

12. Sponsoring Agency Name and Address
State of California SB1 2017/2018
Trustees of the California State University
Sponsored Programs Administration
401 Golden Shore, 5th Floor
Long Beach, CA 90802

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplemental Notes
10.31979/mti.2025.2447

16. Abstract
Strong, durable concrete is key to resilient, long-lasting transportation infrastructure—especially in the face of climate change. This project explores innovative strategies for predicting and enhancing the service life of concrete in pavement and bridge systems, addressing the pressing need for sustainable transportation infrastructure. As concrete is pivotal to the durability and resilience of such structures, its environmental impact demands urgent attention. This project aims to reduce greenhouse gas emissions throughout their lifecycle by extending the service life of concrete pavements and bridge decks. A significant focus of the research is on the indications of chloride ion penetration in concrete, which is critical in controlling corrosion of steel reinforcing bars and keeping the infrastructure reliable. This project proposes the integration of lightweight aggregates, which have shown promise in improving the impermeability and resistance to chloride ion penetrations, which can occur through external sources such as seawater and de-icing salts. The findings provide the transportation industry with best practices and guidelines for implementing sustainable material choices while optimizing the performance of concrete structures, thereby contributing to more resilient and environmentally friendly practices that keep American infrastructure safe for moving people and goods.

17. Key Words
Concrete, service life, pavement, bridge, greenhouse gas emissions, lightweight concrete, lightweight aggregate, internal curing, transport properties.

18. Distribution Statement
No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	113	

Form DOT F 1700.7 (8-72)

10.31979/mti.2025.2447

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ACKNOWLEDGMENTS

The California State University Transportation Council and Fresno State Transportation Institute funded this project. The author acknowledges materials donated by Arcosa Lightweight, Buildex, Carolina Stalite, and Holcim Utelite. The author also appreciates the editorial services of the Mineta Transportation Institute (MTI) staff. Any opinions, findings, conclusions, and recommendations expressed in this material are those of the author and do not necessarily reflect the views of these institutes.

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Executive Summary

Considering ongoing challenges related to infrastructure sustainability and environmental impact, this project critically examines innovative strategies to enhance the service life of concrete used in pavement and bridge systems. Funded by the California State University Transportation Council and the Fresno State Transportation Institute, this research addresses pressing environmental issues associated with traditional concrete practices, mainly focusing on the substantial carbon footprint of cement production. Extending the service life of concrete structures, the initiative seeks to mitigate greenhouse gas emissions throughout their lifecycle, aligning with contemporary sustainability objectives.

Goals and Objectives

The primary goal of this research is to devise and evaluate methods that effectively predict and improve the durability of concrete materials in transportation applications. Specific objectives include:

1. Assessment of Lightweight Aggregates: Investigate the feasibility and benefits of incorporating rotary-kiln manufactured lightweight aggregate—that is, expanded shale, clay, and slate—in concrete mixes to enhance hydration processes, improve interfacial transition zone, control shrinkage, and mitigate early-age cracking.

2. Experimental and Analytical Investigations: Conduct comprehensive experimental investigations alongside analytical assessments to predict service life and lifecycle performance of improved concrete formulations.

3. Developing Best Practices: Formulate guidelines and best practices for the transportation industry to adopt sustainable material choices while optimizing the performance of concrete structures.

Literature Review and Environmental Context

The literature review underscores the critical role of concrete durability in infrastructure longevity. It highlights the severe environmental impacts stemming from traditional concrete materials, particularly cement, which is responsible for a significant share of global carbon emissions.

Innovative techniques such as internally cured concrete (ICC) are explored, showcasing their capability to enhance concrete performance and extend service life. This project broadens the scope to include various concrete containing lightweight aggregates. Furthermore, it delves into cracking, permeability, and diffusion issues. These challenges compromise concrete resilience against environmental challenges, including chemical attacks and freeze-thaw cycles.

Methodological Framework

The research methodology blends experimental and analytical approaches to evaluate the efficacy of lightweight aggregates thoroughly. Samples included all lightweight, sand lightweight, internally cured, and high-strength sand-lightweight concrete. Witness samples included normal-weight with normal and high strengths. Samples represented lightweight aggregates and concrete sourced from six ESCS plants nationwide.

Experimental investigations involved laboratory tests to assess the physical, mechanical, and transport properties of concrete containing various ratios of lightweight aggregates. Physical and mechanical properties included fresh and hardened concrete characteristics, such as density, workability, compressive strength, and splitting tensile strength. Transport properties addressed water absorption rate, surface and bulk electrical resistance, and chloride penetration represented by electrical and chemical indicators.

Analytical investigations utilized established models and simulations to examine the predicted service life and potential lifecycle performance of these concrete formulations under varied environmental conditions. Cost and greenhouse gas emissions represented economic and environmental lifecycle measures.

Key Findings and Insights

The preliminary findings reveal promising evidence supporting the use of lightweight aggregates in improving the resistance of concrete to chloride ion penetration while maintaining or improving physical and mechanical properties. By enhancing the hydration process and improving the interfacial transition zone (ITZ) within the concrete, these aggregates facilitate reduced permeability and increased resistance to cracking, presenting significant implications for infrastructure durability. Concrete containing ESCS significantly contributed to the reduction of permeability and the diffusion and enhancement of electrical resistance, indicating the resistance of the concrete to chloride ion penetration.

Moreover, the research indicates that the overall performance of pavements and bridge decks can be markedly improved by addressing common issues associated with concrete, such as shrinkage and permeability. All forms of ESCS concrete provided extended service life and reduced lifecycle cost and emissions compared with normal-weight concrete. These lifecycle reductions surpassed the initial increase in cost and emissions by several orders of magnitude.

Conclusion and Future Directions

This project contributes vital insights into the future of sustainable civil engineering practices, providing a roadmap for the transportation industry to integrate innovative materials, such as expanded shale, clay, and slate, and techniques, such as internal curing. The findings aim to serve as a foundation for developing best practices that enhance the performance of concrete structures and address the urgent need for sustainable infrastructure considering climate change.

As a next step, identifying transportation projects for the application of lightweight and internally cured concrete will be crucial to benefit from the long-term impacts of ESCS across diverse environmental and regulatory contexts, especially within California. Collaboration with industry stakeholders will also be essential to implement these findings in upcoming projects, further solidifying the role of sustainable practices in maintaining infrastructure integrity. Revisions of design specifications and developing durability-based criteria streamline the application of these innovative materials and techniques.

Overall, this research embodies a proactive approach to overcoming the dual challenges of maintaining resilient infrastructure and minimizing environmental impact, underscoring the importance of innovation and sustainability in civil engineering.

1. Introduction

1.1 Background

Concrete

Durable concrete materials are essential for the resilience and sustainability of transportation infrastructure, especially considering the challenges of climate change. Various climate zones influence the service life of concrete structures; for instance, harsher conditions, such as cold climates that use de-icing salts, can significantly reduce durability. By prioritizing durable concrete, we can minimize maintenance costs and enhance long-term performance, which is crucial for critical transportation elements such as bridge decks and pavements (Kalantari et al. 2023).

Implementing updated engineering guidelines and performance-based specifications to optimize durability is essential. These guidelines emphasize key factors such as controlling chloride penetration, ensuring adequate cover thickness, and maintaining quality assurance during construction to prevent deficiencies from compromising structural integrity. Research indicates that adopting a performance-based approach, as demonstrated in various case studies, results in better durability outcomes than traditional prescriptive methods. Focusing on durable concrete is vital for maintaining efficient and long-lasting transportation infrastructure (Forouhi et al. 1996; Kalantari et al. 2023; Kalantari and Tehrani 2024).

Cracking, permeability, and diffusion are common issues in concrete structures that significantly impact the service life of transportation infrastructure, such as concrete pavements and bridge decks. Environmental factors and construction quality often worsen these problems, leading to accelerated deterioration and reduced durability. It is essential to address these concerns through effective design, quality assurance, and regular maintenance to improve the longevity and performance of these structures (Gjørv 2010b 2011).

The properties of concrete, particularly its composition and porosity, are essential in determining its vulnerability to various challenges, including chemical attacks, corrosion, freeze-and-thaw cycles, shrinkage, creep, and thermal effects. These factors can significantly impact the likelihood of cracking when concrete is exposed to unfavorable environmental conditions (Gjørv 2010a).

The cement paste dramatically influences the characteristics of both fresh and hardened concrete. In contemporary concrete mixes, the elevated cementitious materials enhance these effects. The hydration process of these materials and the subsequent chemical bonding between the cementitious elements and water are vital in determining the quality of the cement paste, which in turn affects the overall quality of the concrete. As the mixing water is used up through hydration and evaporation, the cement paste volume diminishes (Neville 2012; Freiesleben Hansen 2009), potentially resulting in shrinkage of the concrete.

The water-cementitious materials (w-cm) ratio is a critical factor in the hydration process, significantly influencing the chemical, physical, and mechanical properties of concrete, including workability, volume changes, and strength. Early deficiencies in cement paste and fresh concrete can lead to uncontrolled volume fluctuations and cracking. These problems can subsequently affect the permeability and durability of hardened concrete over its lifespan. The hydration process that results in the formation of Calcium-Silicate-Hydrate gel is associated with volume changes due to chemical reactions, which are commonly known as chemical shrinkage. Moreover, improving the interfacial transition zone (ITZ) through adequate curing and pozzolanic bonding is crucial for controlling shrinkage, which helps reduce early-age cracking and other related issues (Kosmatka et al. 2021; ACI 231; ACI 308; Schindler and McCullough 2002)

Lightweight Aggregates and Concrete

Rotary-kiln-produced lightweight aggregates, such as expanded shale, clay, or slate (ESCS), contribute to the sustainability and resilience of concrete structures through various channels. These aggregates are created by treating certain minerals, such as clay, shale, and slate, at nearly 1100 degrees Celsius to develop an expanded microstructure (Tehrani 1998; Holm and Ries 2017).

The resulting microstructure decreases the volume weight of the aggregates due to an increased number and volume of voids within a mechanically rigid and chemically stable framework. The expansion process typically increases the volume of the raw materials by 1.5 to 2 times. As a result, the lightweight aggregates industry can reduce the demand for natural resources by one-third to one-half and address contemporary issues, such as the shortage of sand. Additionally, using recycled materials as fuel sources helps minimize environmental footprints and optimize energy use (Tehrani 2023a, b).

Moreover, lightweight materials significantly reduce the energy and emissions of transportation efforts, including hauling raw materials for processing and final products to construction sites. This reduced demand on the transportation system offers more significant advantages for infrastructure in terms of funding and serviceability (Tehrani 1994, 1996).

Expanded shale, expanded clay, and expanded slate aggregates also possess higher absorption capacity, lower thermal conductivity, and reduced sound transmission (Tehrani et al. 2018). These properties enhance fire safety, thermal comfort, and noise reduction in buildings (Tehrani and Ziarani 2010) and improve agriculture's drought resilience and water preservation (Tehrani et al. 2007). They also play a role in waste cleanup in environmental applications (Pouramini et al. 2021).

Concrete materials that use lightweight aggregates have several advantages, including lower thermal expansion and a reduced modulus of elasticity, which help manage thermal cracking (Bohan and Ries 2008; Byard and Schindler 2010). Bridge infrastructures in particular benefit from these aggregates, which enhance seismic performance, improve fire resilience, enhance durability, facilitate accelerated construction, support internal curing, and offer other related benefits (Brown et al. 1995; Tehrani 2021a). Furthermore, the embodied energy and greenhouse gas emissions associated with such applications reduce the environmental footprint of projects (Walter P. Moore 2012; Tehrani 2019a, 2023a).

The literature is rich in applying lightweight structural concrete in corrosive marine environments that affect the durability and service life of bridges and other transportation infrastructure (Holm 1980; Holm and Bremner 2000; Helland 2005; ESCSI 2017). Lessons from other structures such as concrete ships reinforce these studies (Sturm et al. 1999). California also has case studies benefiting from the lower seismic effects on lightweight concrete systems (Roberts 1997).

Internal Curing

The fast-paced nature of transportation projects in California, combined with strict lane-closure regulations, often requires shorter construction times. This demand for rapid completion makes relying on traditional external curing methods impractical, resulting in a need for higher amounts of cementitious contents. Additionally, the limited accessibility in terms of space and time makes internal curing a necessary approach. This concern is especially relevant for transportation projects that cannot afford sufficient closure time for proper external concrete curing (Lane 2010).

The high absorption rate of fine, lightweight aggregates introduces a high potential to preserve water for cement hydration during curing. Thus, utilizing prewetted lightweight fine aggregate for internal curing is an effective and reliable method to reduce early-age shrinkage and thermal cracking in concrete (ACI 213; ESCSI 2006; Tehrani 2019b). Expanded shale, clay, and slate (ESCS) lightweight aggregates have similar absorption and desorption characteristics, allowing these particles to retain water within their pores and release it after the concrete has set (Byard and Schindler 2010). This mechanism ensures adequate moisture for the hydration of cementitious materials throughout the entire concrete mass, making it suitable for various applications. Internal curing is beneficial when traditional external curing methods are insufficient, such as in thick pavement areas, tight construction schedules for overnight slab replacements, or when high amounts of cementitious materials are used in concrete pavements.

Standard specifications and analytical models determine the mixture proportions of internally cured concrete (ICC). The absolute volume of fine lightweight aggregates in an internally cured mixture depends on the amount of cementitious material, the required internal moisture, and the absorption and desorption characteristics of the aggregates. Typically, this volume ranges from 8% to 12% of the concrete volume for conventional concrete (CC) mixtures (ACI 213; Tehrani 2019b; ASTM C1761; Bentz 2000).

Internal curing enables concrete to mature using its internal moisture without external access. It can also supplement external curing, especially when contractors worry about the risks and liabilities of adequately curing concrete. Internal curing offers a dependable method for maintaining appropriate moisture levels in concrete, even in cases of incidental neglect or unpredictable weather conditions, such as hot or windy days (ACI 308-213; Khayat and Mehdipour 2017).

High-performance concrete materials warrant internal curing due to expected substantial early-age shrinkage (ESCSI 2021). Shrinkage stresses are also responsible for cracking and warping concrete surfaces, such as pavements, bridge decks, and slabs on grade (Bentz 2007). Further, permeability plays a vital role in the durability of concrete as it reduces the resistance of concrete to corrosive materials, such as de-icing chemicals in cold climates. Moreover, the pozzolanic properties of porous lightweight aggregate strengthen the Interfacial Transition Zone (ITZ) in concrete (Bentz 2007).

Using prewetted fine lightweight aggregate for the internal curing of concrete helps reduce shrinkage cracking and extends the curing period in the early stages of concrete setting (Bentz et al. 2005). These advantages lower the costs and liabilities related to cracking during construction. The long-term benefits of internal curing include reduced permeability, improved electrical resistivity, enhanced protection against corrosion, extended service life, and decreased life cycle costs of concrete (Henkensiefken 2008). These benefits enhance the sustainability and resilience of concrete infrastructure, contributing to the preservation of natural resources while also reducing energy requirements and emissions associated with concrete applications (Castro 2011).

Internal curing is mainly beneficial for minimizing early-age shrinkage, which can result in cracking. However, research has shown additional advantages, such as a potential increase in compressive strength of up to 20% (Kalantari et al. 2021) and flexural strength by as much as 15% (Mark 2006; Roberts 2004b). Furthermore, studies indicate that internal curing accelerates the maturation of concrete, which is advantageous for pavement projects requiring quick closure times. Small amounts of fine lightweight aggregate might enhance the modulus of elasticity by as much as 10% for 60 kg/m^3, but it could lead to reductions at larger volumes exceeding 150 kg/m^3 (Roberts 2004b). Decreasing crack formation can also lower the permeability of concrete by 25% (Roberts 2004a). Reports indicate long-term declines in chloride permeability of 45% after one year and 30% after three years (Hoff 2006).

Internally cured concrete offers improved durability due to reduced cracking and permeability and enhanced transport characteristics. This results in a longer service life for the material (Thomas 2006). Consequently, the expected lifecycle cost of internally cured concrete is lowered (Tehrani 2020). A longer service life reduces energy input requirements and associated emissions throughout the life cycle of concrete (Vosoughi et al. 2017). Additionally, the decreased permeability of internally cured concrete enhances its chemical resistance against environmental incidents, particularly in extensive surface applications such as pavements. Therefore, internal curing can contribute to project sustainability by improving quality and service duration (ACI 308-213).

1.2 Objective

The performance of structural materials is crucial for enhancing the sustainability and resilience of infrastructure. It plays a significant role in conserving natural resources and reducing environmental impacts. Utilizing high-performance, lightweight materials can extend these benefits across various industries, including transportation, while addressing societal and environmental challenges related to sustainability and resilience.

Concrete materials offer durable solutions and contribute to the resilience of transportation infrastructure. However, the environmental footprint of cementitious materials raises concerns regarding their impact on climate change. Therefore, it is vital to enhance the service life of concrete pavements and bridge decks to reduce embodied energy and greenhouse gas emissions throughout the lifecycle of transportation systems.

This project aims to introduce the application of rotary-kiln manufactured aggregates in lightweight and internally cured concrete to extend the service life of concrete in pavement and bridge systems. The project employs advanced experimental techniques to measure the transport properties of concrete. It uses the results in analytical service life prediction models to assess the lifecycle of transportation elements based on desired environmental and climate characteristics.

This project supports Federal Highway Administration (FHWA) Every Day Count (EDC-7) Innovations, including Integrating GHG Assessment and Reduction Targets in Transportation Planning, Enhancing Performance with Internally Cured Concrete ($EPIC^2$), and EPDs for Sustainable Project Delivery (FHWA 2023; EPD 2025; Tehrani 2023b; 2024a; Tehrani et al. 2024).

1.3 Scope

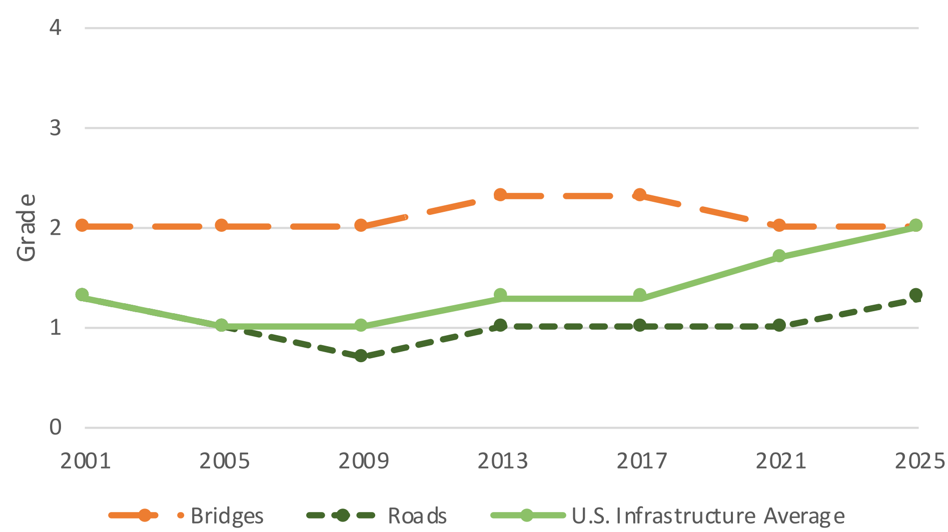
Research has demonstrated the effectiveness of lightweight aggregates in extending the service life of concrete materials, including concrete pavements and bridge decks. However, the adoption of lightweight aggregates has not been uniformed across the United States, particularly in California. This project aims to evaluate the benefits of this innovative solution across various climate zones, environments, and industry practices, including those specific to California, and to introduce best practices to the transportation industry.

Implementing this solution requires comprehensive assessments at multiple levels, including the performance of materials (lightweight aggregates), methods (curing and transport properties), and infrastructure (pavements and bridges). Experimental investigations will assess lightweight aggregates and concrete specimens according to established standards and specifications. Following these empirical results, analytical investigations will be conducted to predict the service life and life cycle measures of key transportation elements, including cost and environmental impacts.

2. Literature Review

The state of transportation infrastructure in the United States, marked with grade C (2/4) or average (Figure 1), underscores the urgent need for improved sustainability and resilience due to aging structures, funding shortages, and climate-related disasters (ASCE 2021a). Addressing these challenges requires a comprehensive approach that emphasizes performance-based sustainability and resilience measures while connecting technical advancements to these measures. This approach should establish best practices for planning, designing, constructing, and maintaining pavements, bridges, and other transportation elements. Further, it advocates for using lifecycle assessments. Community involvement, resource allocation, and balancing capital investments and operational expenditures are essential for achieving resilient infrastructure. These elements are crucial components of strategic infrastructure planning (Tehrani 2019a).

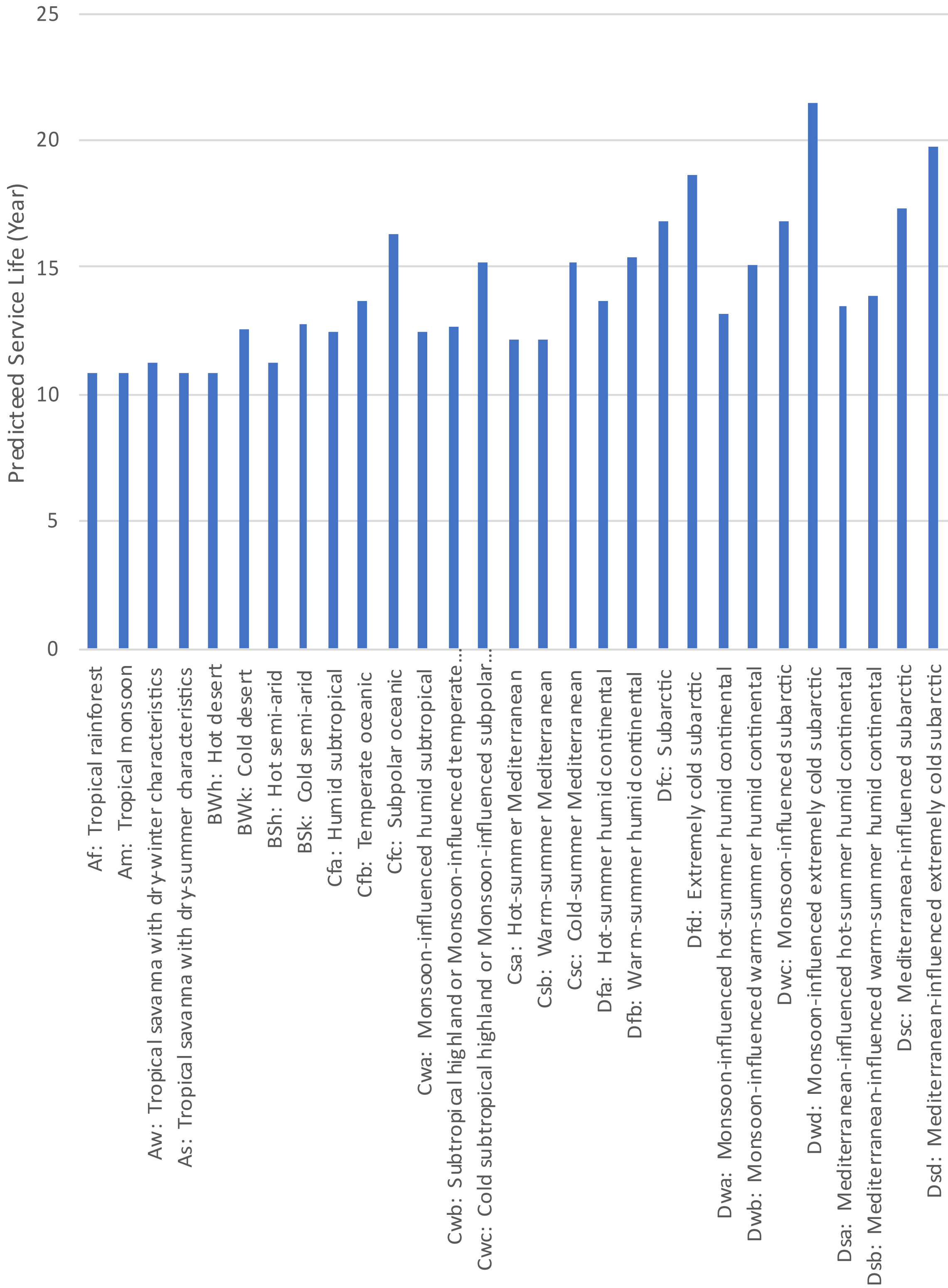
Figure 1. Infrastructure Report Card (after ASCE 2021a)



2.1 Role of Concrete Durability

Durable concrete materials play a crucial role in enhancing the resilience and sustainability of transportation infrastructure, especially considering the challenges posed by climate change (PCA 2019). Different climate zones affect the service life of concrete structures, highlighting the increasing frequency and severity of natural disasters that threaten infrastructure integrity. Service life predictions show how concrete performs under various climatic conditions, indicating that environments with high humidity typically result in longer service lives compared to arid and hot regions. Regardless, the predicted service life of transportation components, such as bridge decks (Figure 2) are far from expected values in standard practice as suggested by ACI, AASHTO, and other professional and official entities (Kalantari et al. 2023).

Figure 2. Predicted Service Life of Urban Bridge Decks in Various Climates
(after Kalantari et al. 2023)



Moreover, studies on concrete applications in essential transportation components, such as bridge decks, reveal that cold climates where de-icing salt is commonly used significantly reduce service life. These findings are particularly relevant for transportation infrastructure, where durability is vital for minimizing maintenance costs and ensuring long-term performance. Environmental factors such as chloride penetration, freeze-thaw cycles, and carbonation significantly deteriorate concrete (ESCSI 2024b; Kalantari et al. 2023).

Concrete Pavements

De-icing salts significantly impact the durability of concrete pavements, highlighting the importance of careful use. Research indicates that concrete specimens exposed to sodium chloride (NaCl) concentrations under freeze-thaw conditions experience issues such as peeling, weight loss, and reduced compressive strength (Figure 3), all of which are correlated with higher salt concentrations when compared to those exposed to freshwater (Pouramini et al. 2021).

Figure 3. Concrete Loss After Freeze-Thaw Cycles with Salt Concentrations Increasing from Left to Right (Courtesy of Pouramini et al. 2021)

Further investigations into concrete deterioration in cold climates reveal that scaling and popout problems are not necessarily linked to insufficient air-void parameters or compressive strength, which remain within acceptable limits. Instead, high chloride levels at varying depths suggest that de-icing salts penetrate the porous concrete surface, likely due to poor finishing practices. This leads to the formation of a weakened layer with a high water-cement ratio that facilitates the intrusion of chlorides and the resulting damage (Issa et al. 1994).

These findings collectively emphasize the detrimental effects of de-icing salts on concrete pavements, especially in cold climates, and underscore the need for additional research to improve concrete performance and longevity in these challenging conditions (ASCE 2021b).

Concrete Bridges

The durability of concrete bridges is a crucial concern due to the aggressive nature of chloride exposure, which can lead to the corrosion of embedded steel reinforcement (Figure 4). Several studies have emphasized the importance of understanding chloride penetration mechanisms and the factors that influence the long-term performance of concrete. Field studies on the Gimsøystraumen and Giske Bridges in Norway (Fluge and Blankvoll 1995; Steen 1995), the Rion-Antirion Bridge Project in Greece (Harikiopoulou et al. 2007; Cussigh et al. 2010), and the Sitra Bridges in Bahrain, Persian Gulf (Hassanain 2010), along with similar studies on bridge columns in Greater Copenhagen, Denmark (Henriksen and Stoltzner 1993), highlight these issues. These bridges represent exposures to marine environments with extreme salts, like the Persian Gulf (Davodijam et al. 2022) or extreme cold, like Scandinavia (ESCSI 2017).

Figure 4. Transverse Cracks on Route 61 Over New River, Salem District, VA (Nair et al. 2016); Courtesy of the Virginia Transportation Research Council (VTRC)

Together, these studies underscore the necessity for a systematic approach to ensure the durability of concrete bridges. They emphasize the influence of environmental factors, material quality, and proactive maintenance in extending service life and preventing deterioration (ASCE 2021c). Furthermore, these studies confirm that chloride penetration tests are valuable tools for investigating concrete structures, allowing for the development of strategies to mitigate damage and enhance the longevity of concrete.

2.2. Environmental Impact of Concrete Materials

The production of cement contributes to the significant environmental impacts of concrete materials. Designing concrete systems with enhanced durability can significantly reduce energy consumption and emissions while keeping costs reasonable. This highlights the urgent need for updated engineering guidelines that consider the effects of climate change on transportation infrastructure. It is crucial to use durable concrete materials to ensure the longevity and efficiency of these vital structures (Kalantari and Tehrani 2024). Consequently, existing research emphasizes the importance of performance-based specifications and lifecycle assessments (LCA), which are essential for improving the durability and sustainability of concrete used in transportation applications (Kalantari et al. 2023; Kalantari and Tehrani 2022, 2024).

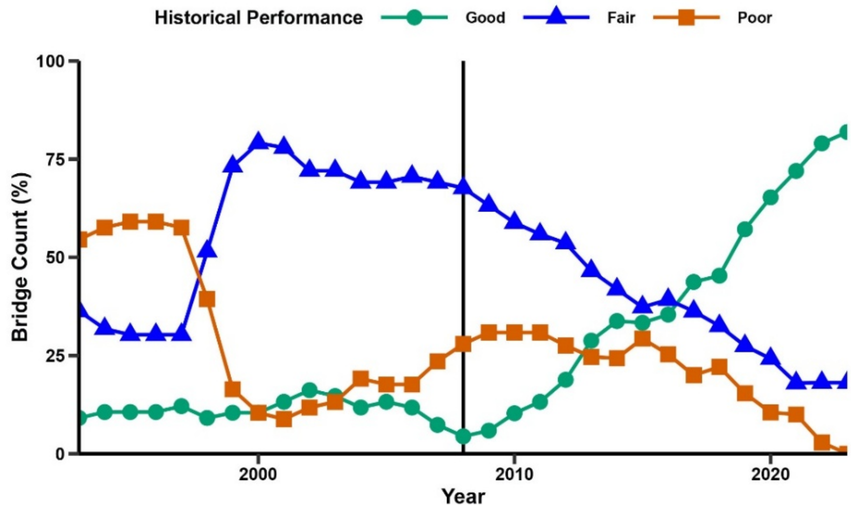
2.3 Innovations and Initiations

Innovative materials are crucial in enhancing concrete transportation infrastructure, primarily due to their potential to improve sustainability, durability, and performance. While widely used, traditional concrete has significant environmental impacts, especially from its production, contributing to nearly 10% of human-caused greenhouse gas emissions (Iacobucci et al. 2024).

Various initiatives, such as the Every Day Counts (EDC) program by the Federal Highway Administration (FHWA 2023), support the integration of innovative materials to tackle these challenges and promote more sustainable infrastructure. The FHWA EDC initiative aims to accelerate the deployment of proven innovations to enhance transportation infrastructure. The seventh round of EDC (EDC-7) focuses on several key areas, three of which motivate the current study: integrating greenhouse gas (GHG) assessments and reduction targets into transportation planning, utilizing environmental product declarations (EPDs) for sustainable project delivery, and enhancing performance with internally cured concrete ($EPIC^2$).

By enhancing the service life of concrete elements, we can reduce the lifecycle greenhouse gas emissions associated with constructing and maintaining transportation infrastructure. Furthermore, predicting the service life of concrete enables the development of environmental product declarations with a lifecycle perspective. Achieving these outcomes requires a comprehensive investigation of proven innovations, such as internally cured concrete using fine lightweight aggregates, as referenced in the $EPIC^2$ initiative (Figure 5). This project expands upon these initiatives by including lightweight concrete that contains coarse or fine lightweight aggregates, in line with efforts to reduce the embodied greenhouse gas emissions from construction materials and products (Tehrani 2024b, 2024c).

Figure 5. Improvements in the State of Bridge Decks Using Internal Curing
(Courtesy of FHWA 2024)



Durability Indicators and Protection

The durability of concrete structures is influenced by several factors, including design, materials, and especially the quality of construction. In harsh environments, any construction deficiencies can quickly become apparent, increasing the vulnerability of these structures. To address this issue, it is essential to implement a strategy that combines probability-based durability design with performance-based quality assurance during construction (Gjørv 2010a, 2011).

Engineering guidelines emphasize the importance of controlling chloride diffusivity and ensuring adequate cover thickness. They also require ongoing verification and documentation of construction quality. After the construction, the collected quality assurance data is utilized for further durability assessments (Gjørv 2010b). This comprehensive approach ensures that the desired durability standards are achieved and maintained, ultimately leading to improved quality and a more controlled environment for the durability of concrete structures (Gjørv 2010b).

Chloride Diffusion

Chloride diffusion is a critical factor in determining the durability of concrete structures, especially those exposed to harsh environments such as marine settings or areas treated with de-icing salts. When chloride ions penetrate concrete, they can damage the protective oxide layer on reinforced steel, leading to corrosion in the presence of water and oxygen (Figure 6). Chloride ingress can occur through contaminated concrete mix materials or external sources such as seawater and de-icing salts. Therefore, it is essential to control chloride penetration by ensuring adequate concrete cover, reducing permeability, and using blended types of cement such as fly ash, slag, and silica fume. These materials improve the concrete's pore structure and resistivity (Neville 1995).

Figure 6. Reinforcing Steel Corrosion in Bridge Columns, Route 91, Los Angeles, CA (Photo by the Author)

The rate of chloride diffusion through concrete is influenced by several factors, including the composition of the concrete, its porosity, and the presence of supplementary cementitious materials like fly ash, slag, and silica fume. These materials refine the pore structure, reducing chloride ion penetrability and enhancing corrosion resistance. Additionally, factors such as curing, temperature, and cracking impact corrosion rates. Various tests are available to assess chloride penetrability, and methods for preventing corrosion include using corrosion inhibitors, epoxy-coated steel, and cathodic protection. A comprehensive understanding of these factors is necessary for designing durable reinforced concrete structures exposed to chlorides (Neville 1995).

Understanding chloride diffusion is vital for assessing the lifespan and durability of concrete structures. Engineers can predict how quickly chlorides might penetrate the material by measuring the chloride permeability of different concrete mixtures and calculating reliable diffusion coefficients. This information is crucial for designing effective corrosion-resistant solutions, such as corrosion inhibitors, epoxy-coated reinforcements, or cathodic protection (Miljoer n.d.).

Moreover, developing probabilistic models incorporating chloride diffusion and varying environmental conditions allows for more accurate service life predictions. Identifying threshold values for chloride concentration specific to different environmental classifications further informs prevention strategies, ensuring structures remain robust and long-lasting even under challenging conditions (Ghosh 2011).

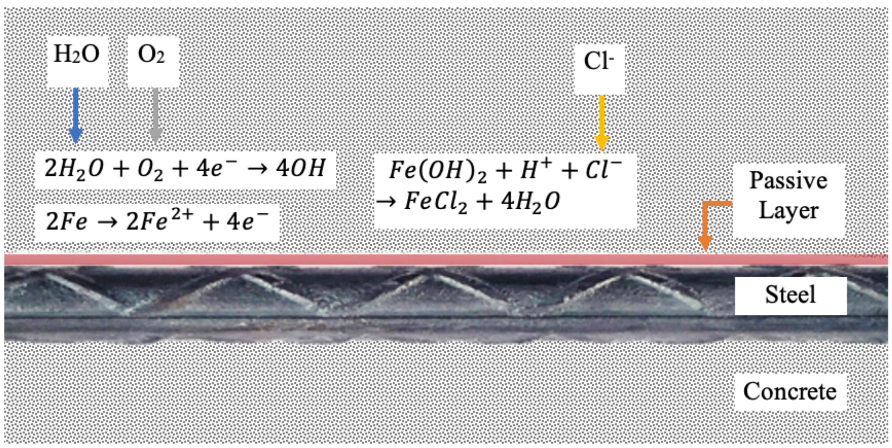
Temperature

Experimental results show that higher temperatures have a direct effect on increasing the chloride diffusion and migration coefficients (Yuan et al. 2009). Standard testing methods account for this influence by using an Arrhenius equation, which can also be applied to measures of electrical conductivity (Julio-Betancourt and Hooton 2004).

Reinforcement

Reinforcing still bars are vulnerable to chloride penetration (Figure 7). Corrosion inhibitors such as calcium nitrite stabilize the passivating layer of steel, controlling corrosion rates (Berke et al. 1988; Berke and Rosenberg 1989; Nmai and McDonald 1999). Other inhibitors may also reduce the initial diffusion coefficient and decrease the surface chloride build-up rate. These effects result from reducing capillary effects of pores (Miltenberger et al. 1999; Miller and Miltenberger 1999).

Figure 7. Schematic Illustration of Steel Reinforcing Bar Corrosion



Gjørv (2011) presents a case study that discusses the comparative effectiveness of performance-based and prescriptive durability requirements for concrete substructures. The project aimed to provide a service life of 300 years for these substructures. In the first phase, performance-based durability requirements were implemented, which included probability-based design and additional protective measures, such as stainless-steel reinforcement. In contrast, the second phase followed prescriptive requirements according to current concrete codes, which specified a 100-year service life. The findings of this study highlighted the superiority of performance-based requirements, combined with rigorous quality control, in achieving more outstanding durability and reducing corrosion probabilities compared to prescriptive methods. This research reinforces the importance of performance-based specifications in ensuring the long-term durability of concrete structures.

Supplementary Cementitious Materials

The durability of concrete, particularly its resistance to chloride ion penetration, has been extensively studied, emphasizing the effective use of supplementary cementitious materials (SCMs). Ozyildirim and Halstead (1988) investigated the effects of fly ash, silica fume, and ground-granulated blast furnace slag on chloride ion intrusion in concrete with low water-to-cementitious material ratios (w/c) ranging from 0.35 to 0.45. Their findings indicated that concrete mixtures with lower w/c ratios and the inclusion of pozzolans or slag significantly enhanced resistance to chloride penetration compared to control samples made solely with Portland cement.

Baroghel-Bouny et al. (2011) further contributed to our understanding of concrete durability by examining transport properties, including electrical resistivity and liquid water permeability, and comparing various measurement methodologies. Additionally, Berke et al. (1988) reviewed using microsilica and calcium nitrite as admixtures to mitigate chloride-induced corrosion in concrete. They found that microsilica reduces concrete permeability and slows down chloride ingress, while calcium nitrite helps stabilize the protective passivating layer of steel, ultimately controlling corrosion rates.

Bouzoubaa et al. (2004) explored the development of ternary blends of high-performance concrete that incorporated fly ash and silica fume. Their results indicated that the combination of fly ash and silica fume significantly improved performance, workability, and resistance to chloride ingress, establishing ternary blends as superior alternatives to binary blends and traditional concrete. Berke et al. (2005) confirm the effectiveness of pozzolans such as fly ash and silica fume in reducing the diffusion coefficient, where fly ash outperforms silica fume over time after the first 28 days.

Ozyildirim (1998) reported reduced permeability at higher curing temperatures. In a related study on applying SCMs, Nadeem et al. (2014) reported that permeability and sorptivity increase at high temperatures, with significant losses occurring above 400°C.

In summary, these studies collectively highlight the crucial role of SCMs in enhancing the durability of concrete and emphasize the necessity for ongoing research to optimize concrete compositions for improved performance in challenging environments.

Lightweight Aggregates

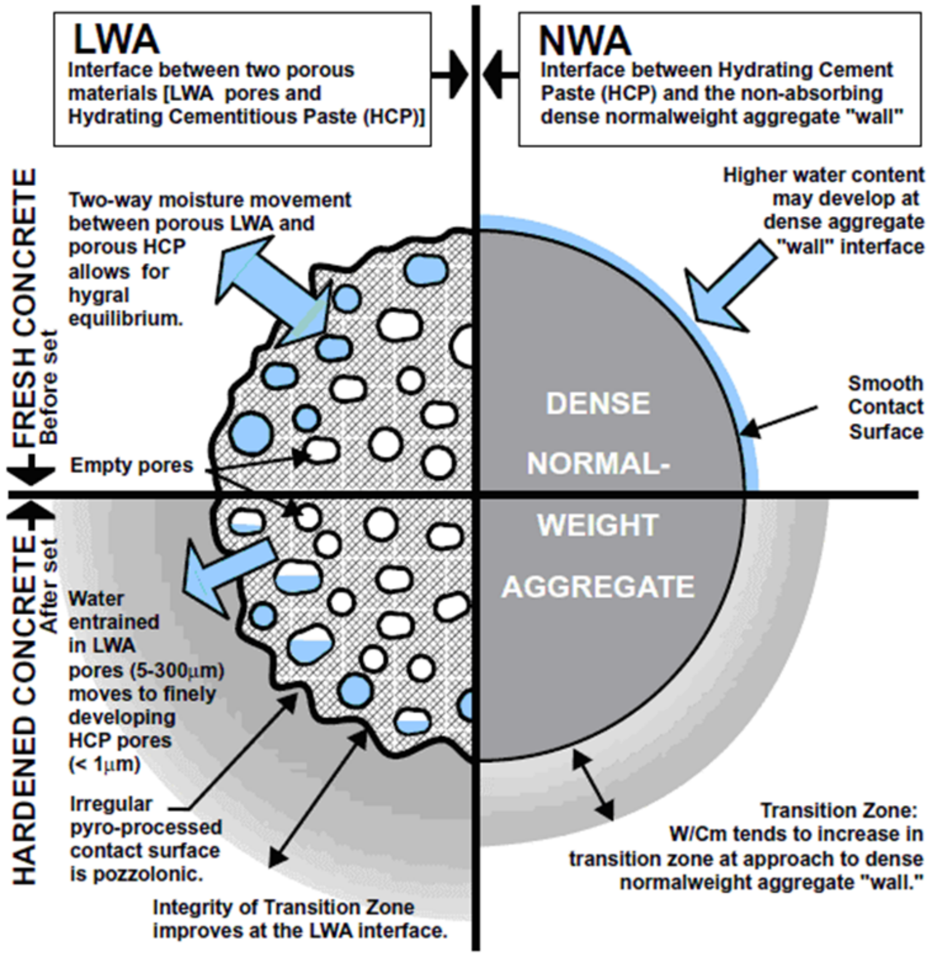
Tehrani (2022) discusses how rotary-kiln-manufactured lightweight aggregates can enhance the sustainability and resilience of bridge infrastructure in the United States. Castrodale (2021) also provides a comprehensive reference of lightweight aggregate applications in bridge design. The benefits of using these aggregates include extending the service life of bridge decks (Kalantari and Tehrani 2021), improving the load-bearing capacity of superstructures, and reducing the demands placed on abutment walls. Case studies, such as the Williams Creek Bridge (Nunley 2018) and the Bayonne Bridge (Wolfe 2017), illustrate the practical advantages of lightweight aggregates, such as reduced material usage, lower environmental footprints, and enhanced durability. The existing literature emphasizes the importance of sustainable practices in addressing the challenges of aging infrastructure and climate change, advocating for integrating these materials into bridge design and maintenance to optimize resource allocation and improve overall infrastructure performance (Tehrani 2022).

The porosity of lightweight aggregates contributes to a reduction in the self-weight of concrete; however, it also affects the tensile strength compared to normal-weight concrete with the same compressive strength. Although reinforced concrete design specifications often overlook the tensile strength of plain concrete, there are conservative approaches for designing lightweight aggregate concrete that consider mechanical performance aspects rooted in the tensile behavior of these aggregates, such as shear and bonding strength (ACI 318; AASHTO 2015; ESCSI 2024c).

Additionally, the porosity of lightweight aggregates decreases the modulus of elasticity, which can reduce strain-induced stresses in dynamic applications such as in pavements and bridges. This reduction can also influence displacements caused by static loads (ESCSI 2022). Recent research has indicated a need to revise design specifications (Graybeal 2014; Greene et al. 2015; Greene and Graybeal 2013; Greene and Graybeal 2019). Furthermore, studies by Kadkhodaie et al. (2024) and Ghavami et al. (2024) demonstrate that concrete made with expanded shale, clay, and slate shows higher values of splitting tensile strength, shear strength, and modulus of elasticity compared to concrete made with other types of lightweight aggregates.

Tehrani (2020) reported on the impact of coarse and fine expanded shale, clay, and slate (ESCS) aggregates on the transport properties of concrete, which are crucial for service life analysis models like STADIUM® and Life 365™. These benefits reflect significant enhancements in the interfacial transition zone between lightweight aggregate and cementitious paste (Figure 8). The study highlights the durability benefits of lightweight aggregates (LWA) in concrete infrastructure. Simulations for a bridge deck in Detroit demonstrated that lightweight mixtures increased the time to corrosion by 22% compared to normal-weight aggregates. Substituting normal-weight sand with lightweight fines improved corrosion resistance by 34% to 88%. Life 365™ analysis indicated similar performance between lightweight coarse aggregates and control mixtures, with lightweight fines showing up to three times improvement. Furthermore, internal curing mixtures with lightweight fines improved strength and reduced shrinkage cracking. The effectiveness of LWA was confirmed across various conditions.

Figure 8. Improving the Contact Zone
(Lura 2003; Courtesy of ESCSI 2006)



Internal Curing

Wet curing provides essential moisture to concrete during its early stages to combat water loss caused by autogenous shrinkage. This process is vital for achieving the desired physical and mechanical properties, including proper setting, resistance to cracking, and overall durability. Experimental studies have indicated that the mechanical properties of concrete—such as elastic modulus, compressive strength, flexural strength, and splitting tensile strength—are sensitive to both the method of curing and its duration (Bonyadi et al. 2022).

Internal curing (IC), which utilizes prewetted fine lightweight aggregates, supports the ongoing hydration of concrete. This approach helps address early-age shrinkage and cracking issues and long-term permeability concerns. Investigations have shown that internally cured concrete reaches higher compressive and flexural strengths than conventionally cured concrete, making it a valuable option for accelerated bridge construction projects, particularly in challenging environments and situations with limited accessibility (Bonyadian et al. 2019, 2024). Additionally, internal curing is a practical choice for high-performance concrete (HPC) applications in bridge decks. Laboratory tests indicate that IC HPC exhibits significantly lower chloride permeability and reduced early-age shrinkage, suggesting a service life of 60 to 90 years, in contrast to just 18 years for conventional concrete (Barrett 2015).

Predicting the Service Life of Concrete Structures

The prediction of service life depends on the rate of chloride penetration, which is used to simulate the chloride profile through numerical methods. Several ways to estimate this rate include chloride permeability, electrical conductivity, and water sorptivity. The industry generally prefers rapid, reliable, and standardized tests for quality control during construction. While some tests may be time-consuming and primarily used for prequalification, others, such as electrical conductivity tests, can provide quick indicators of the concrete's resistance to fluid penetration. Therefore, it is crucial to understand the limitations of each testing method and examine their correlations (Lane et al. 2010).

Service Life Prediction Models

In recent years, predicting the service life of concrete structures has become increasingly important due to the harmful effects of chloride ingress. Poulsen (1993) developed a foundational model incorporating a time-dependent diffusion coefficient, highlighting the changes in concrete properties, particularly during the early stages after casting. This model is based on Fick's second law of diffusion and enables the prediction of chloride profiles and critical chloride concentrations that affect the durability of concrete structures (Poulsen and Møjlbro 2006).

In later research, Poulsen (1995) expanded on determining and analyzing chloride profiles by detailing advanced sample preparation techniques, including grinding methods for accurately assessing chloride content. This study examined various sources of chlorides and the mechanisms facilitating their ingress while addressing measurement uncertainties. Importantly, it introduced a methodology for distilling chloride profiles into three key parameters when diffusion predominates, thereby enhancing the understanding of the transport mechanisms and environmental influences that affect chloride ingress dynamics.

Building on this foundation, Poulsen (1999) reviewed chloride ingress models specific to marine reinforced concrete structures. Møjlbro (1996) developed a mathematical model that refines predictions by incorporating time-dependent diffusion coefficients and surface chloride content, as outlined by Fick's second law. This model, derived from empirical observations of marine reinforced concrete structures, integrates four primary parameters that capture environmental conditions and concrete responses. Calibration exercises that utilized various concrete types and exposure scenarios have validated the model, reinforcing its utility in predicting service life and optimizing rebar cover.

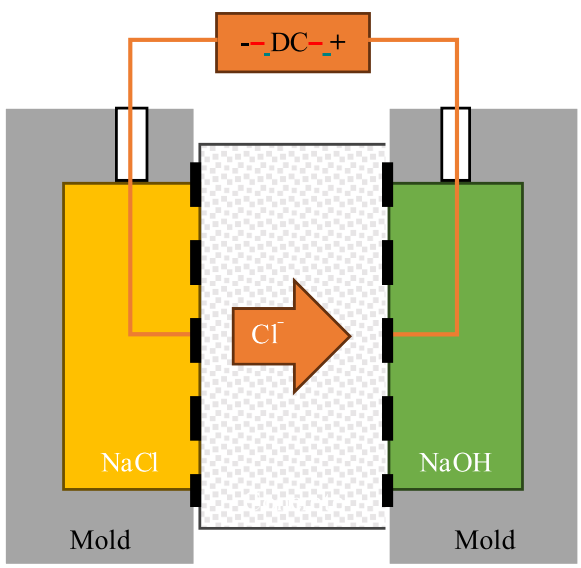
Lu (1997) explored the applicability of the Nernst-Einstein equation for understanding ion diffusivity in concrete. This research emphasized methods for assessing concrete permeability, monitoring reinforcement corrosion, and predicting the longevity of reinforced concrete structures. The findings demonstrated that the diffusivity of aggressive ions, such as chlorides, could be accurately determined using the Nernst-Einstein equation by measuring either the ions' partial conductivity or the concrete mix's overall conductivity. Furthermore, the study established a relationship between concrete permeability assessments and conductivity measurements, suggesting that monitoring changes in conductivity could effectively track corrosion in reinforcement.

Chloride Permeability Testing

Measuring chloride permeability may involve direct chemical detection of chloride ions or indirect indication of ion transport by detecting electrical charges. The industry has continuously supported the development of straightforward and reliable testing systems and particularly portable devices for field investigations that relate these measures to the corrosion of steel reinforcing bars in concrete (Streicher and Alexander 1994; Klinghoffer 1995; Elsner et al. 1997; Luping and Sörensen 1998; Frølund et al. 2000; Frølund et al. 2002; Sørensen and Frølund 2002; Frølund et al. 2003; Bäßler et al. 2001, 2003).

Chloride permeability testing involves applying a direct current (DC) voltage to a section of concrete specimens exposed to ions for a specified duration (Figure 9). The samples can be either cast laboratory specimens or drilled field specimens. Standard methods outline various parameters, such as voltage, duration, conditioning, and the dimensions of the specimen. A typical test spans two days: one day is allotted for conditioning to ensure the correct moisture content, and the other is for the actual testing. The testing phase can last anywhere from 6 to 24 hours.

Figure 9. Schematic of Chloride Penetration Test Setup



A rapid chloride permeability test (RCPT) utilizes the charges passed through the specimen to assess its electrical conductivity or diffusion coefficient. An alternative approach measures chloride penetration depth within the sample to determine a non-steady migration coefficient. Technical specifications classify results into different levels of chloride permeability, ranging from very low to very high (Whiting 1981; Whiting and Dziedzic 1989; Geiker et al. 1991). The Germann instrument is an example of rapid chloride test equipment (Petersen and Hansen 1991).

Feldman et al. (1994) explored the effectiveness of RCPT in measuring the electrical conductance of concrete to evaluate its resistance to chloride ion penetration. Their findings indicate that initial current or resistivity measurements can yield the same ranking of concrete quality as the conventional RCPT, presenting a quicker alternative. This research also highlights that the RCPT may induce physical and chemical changes in the concrete specimens, potentially resulting in an overestimated permeability. Consequently, the study proposes that more straightforward measurements of initial current or resistivity could replace the RCPT for certain concrete types, thereby reducing testing time and avoiding specimen alterations.

Similarly, Snyder et al. (2000, 2003) utilized impedance spectroscopy to assess the rapid chloride test. They found that the total charge passed during the six-hour rapid chloride test is not a reliable indicator of specimen conductivity due to factors like heating and changes in microstructure. However, initial current measurements were noted to provide a more accurate estimate of specimen conductivity. The study suggested that the initial current could offer quantitative insights into diffusivity but emphasized the need to regularly monitor electrode conditions to maintain accuracy.

Support for the appropriateness of rapid tests is echoed by further studies, including those by Luping and Sorensen (1998), Bognacki et al. (2010), and Rupnow et al. (2019). Obla and Lobo (2007) also employed the rapid test to establish performance-based specifications. Conversely, Stanish et al. (2001) examined the relationship between long-term and short-term chloride permeability testing, underlining factors influencing chloride penetration such as concrete pore structure, curing conditions, and chloride binding capacity. Their review concluded that no single test is universally applicable, making it essential to understand the limitations of each testing method and appropriate applications for accurately assessing concrete durability against chloride ingress. In addition, Szweda et al. (2023) highlighted discrepancies in standard methods for measuring diffusion coefficients using a thermodynamic migration model.

Electrical Conductivity or Resistivity Testing

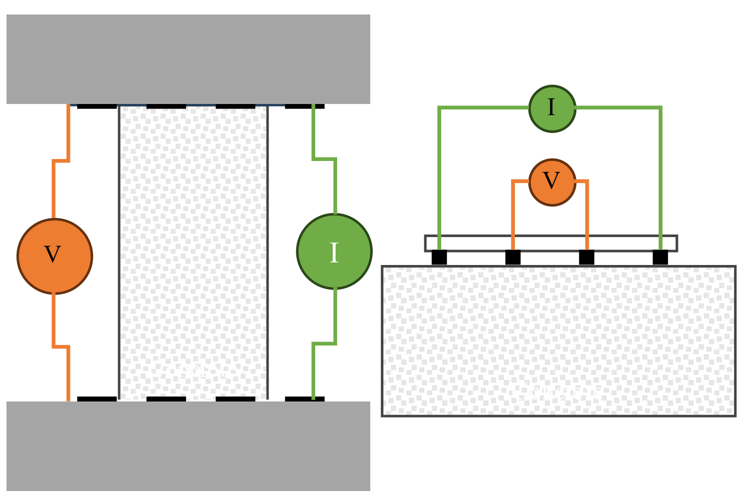
Electrical resistivity testing is a non-destructive testing (NDT) method used to evaluate the durability of reinforced concrete. It has been proposed as a key parameter for estimating the service life of concrete structures by considering both the initiation and propagation periods of corrosion. This method is advantageous due to its ease, speed, and cost-effectiveness. The resistivity of concrete reflects its porosity and connectivity, which are crucial for modeling transport processes and assessing moisture content.

Andrade et al. (2009) presented a model that incorporates resistivity to predict the time until corrosion onset and the corrosion rate, providing a comprehensive approach to durability assessment and quality control in concrete structures. Further, Layssi et al. (2015) compared this method to the traditional Rapid Chloride Permeability (RCP) test, highlighting that resistivity measurements are more straightforward, faster, and can be directly related to the chloride diffusion coefficient using the Nernst-Einstein equation. Key factors influencing these measurements include the degree of saturation, temperature, and signal frequency.

Several comparative studies have correlated electrical resistivity with chloride permeability, including research by Nokken and Hooton (2003, 2006) and Hooton and Charmchi (2005). Spragg et al. (2013) and Spragg et al. (2016) emphasized the impact of conditioning procedures, concluding that resistivity measurements fell within 20% of the formation factor obtained from ionic diffusion tests when adjusted for various factors.

The uniaxial and Wenner probe methods are standard techniques for measuring electrical resistivity (Figure 10). Numerous comparative studies have examined these techniques and their correlation with chloride permeability tests, including work by Shahroodi (2010), Ardani (2012), Tanesi and Ardani (2012), Hooton et al. (2014), Gudimettla and Crawford (2016), and Konecny et al. (2017). These studies confirmed that surface resistivity is a more accessible technique that correlates well with bulk resistivity and chloride permeability tests. Furthermore, Morris et al. (1996) established a relationship between bulk and surface resistivity measures using finite element simulations, which were verified through experimental investigations. Spragg et al. (2012) confirmed these findings, demonstrating a linear relationship between bulk and surface resistivity and within- and multi-laboratory coefficients of variation (COVs).

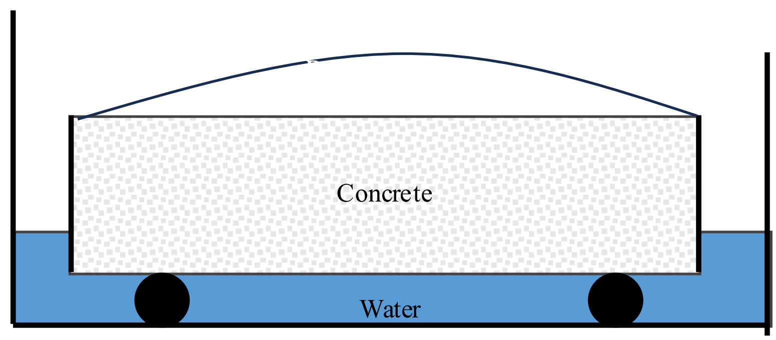
Figure 10. Schematic of Bulk (Left) and Surface (Right) Electrical Resistivity Tests Setup



Water Absorption, Permeability, and Sorptivity Testing

The durability of concrete structures is significantly influenced by their permeability characteristics, which has led to increased interest in sorptivity as a predictive measure for service life (Figure 11). Whiting (1988) demonstrated that permeability is closely linked to the water-to-cementitious materials (w/cm) ratio, indicating that lower ratios substantially reduce permeability. Outcomes emphasized the necessity of a minimum of seven days of moist curing to achieve low permeability values, highlighting the critical role of proper curing practices in enhancing the durability of concrete. Hall (1989) also offered data on the characteristics of sorptivity tests relevant to the flow mechanism in unsaturated media like concrete and mortar. Similarly, Hooton and Karkar (2012) investigated the fluid penetration in concrete to develop proper specifications.

Figure 11. Schematic of Sorptivity Test Setup



Building on this work, DeSouza et al. (1997, 1998) developed a non-destructive field test device to assess concrete absorption rate or sorptivity. Additionally, Bentz et al. (2002) argued that sorptivity, as opposed to traditional permeability assessments, is a more relevant characteristic for evaluating the durability of hydraulic cement concrete.

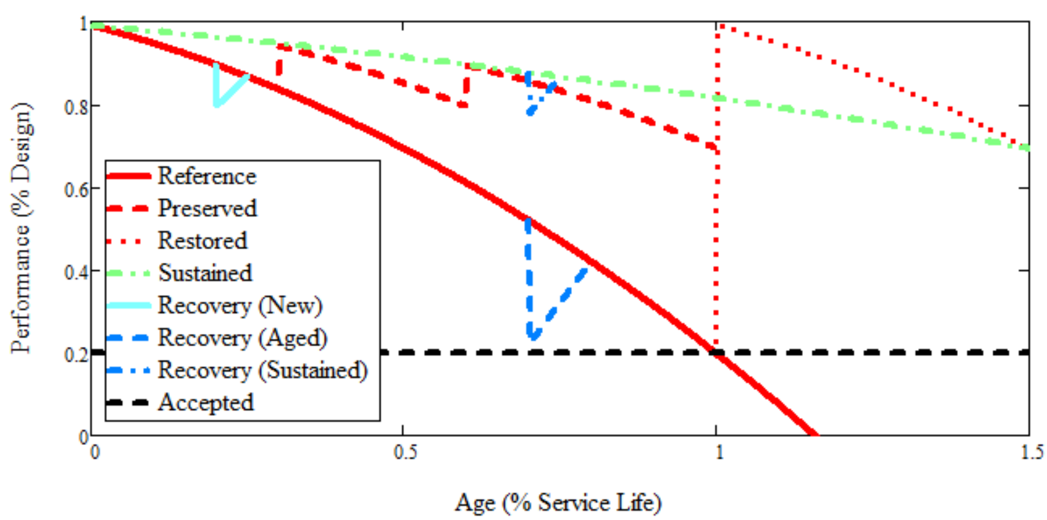
Ramezanianpour et al. (2011) investigated the relationships among concrete resistivity, water penetration, rapid chloride penetration tests (RCPT), and compressive strength. The study found strong correlations between surface resistivity and water penetration and RCPT results, suggesting that surface resistivity can be a reliable, non-destructive indicator of concrete's resistance to chloride penetration. However, no significant correlation was found between compressive strength and resistivity due to various influencing factors.

Furthermore, Zhuang and Wang (2021) examined the relationship between water absorption and chloride ion penetration in concrete containing fly ash, slag, and silica fume at various water-to-binder ratios. Their findings indicated that water absorption can reliably estimate chloride ion penetration, and they observed a good correspondence between the initial water absorption rate and the grade of chloride ion penetration.

2.4. Lifecycle Assessment

Sustainable and resilient infrastructure development requires conducting lifecycle assessments considering societal, environmental, and financial factors. The ongoing life expectancy of transportation infrastructure necessitates lifecycle analysis to identify key parameters in planning, design, construction, maintenance, retrofitting, and restoration (Figure 12). Evaluating lifecycle costs involves addressing economic uncertainties related to common factors such as interest rates, which are crucial for balancing capital and operational expenditures. Additionally, assessing lifecycle environmental impacts encounters challenges in determining the value of energy, emissions, water, waste, and other critical measures affected by climate change. Societal assessments often rely more on qualitative than quantitative measures; however, it is possible to represent these assessments using sustainability credit point systems (Nelson and Tehrani 2018; Tehrani and Nelson 2022).

Figure 12. Infrastructure Lifecycle
(after Tehrani and Nelson 2022)



Cost

The lifecycle cost benefits are derived from available federal and state data, which provides detailed estimates for various construction, maintenance, and removal tasks associated with transportation projects. Similar data is available to provide average financial values, such as interest rates. Vossoughi et al. (2017) utilized these data sets to explore the costs and benefits of using internal curing (IC) for concrete pavements. They compared IC to conventionally cured (CC) pavement through a lifecycle cost analysis (LCCA) based on a design for Dubuque, Iowa.

Vossoughi et al. (2017) conclude that IC concrete enables reduced pavement thickness, increased joint spacing, and decreased maintenance, leading to savings in initial construction costs. Although the initial cost of IC pavement is approximately 3.2% higher than that of CC pavement of the same thickness, it requires less maintenance over its service life. The net present value (NPV) of IC pavement is lower than that of CC pavement, making IC a more cost-effective option.

Vossoughi et al. (2017) highlight several benefits of IC, including reduced shrinkage, improved resistance to freezing and thawing, and decreased fluid transport, all of which contribute to the durability and longevity of concrete pavements. This report suggests further research on other concrete applications using lightweight aggregates, such as sand lightweight, all lightweight, and high-strength lightweight concrete.

Environnemental Impacts

Kalantari et al. (2021) investigate using fine lightweight aggregates for internal curing in concrete. Their findings reveal that internal curing can mitigate early-age cracking and improve overall durability. The research indicates that internal curing can extend the service life of concrete by 6–24%, lower lifecycle costs by 6–18%, and decrease energy consumption and emissions by 7–26%. These results highlight the sustainability advantages of internal curing, particularly in structures such as parking lots and bridge decks.

Tehrani (2021b) expands on internal curing in concrete pavements. This study reports that internal curing can extend service life by 7–10% while reducing lifecycle costs by up to 16.5%. It also emphasizes the effectiveness of internal curing in addressing shrinkage cracking and enhancing hydration, further supporting its sustainability credentials.

Davodijam et al. (2022) examine the application of internal curing in marine environments, such as coastal roads and bridges. They find that it enhances durability in areas exposed to chloride, resulting in a 9–17% service life extension compared to conventional concrete. This research highlights the potential of internal curing to improve the performance of marine infrastructure and reduce environmental footprints.

Finally, Tehrani (2024b) evaluates the benefits of internal curing within the context of lifecycle assessment. The study notes substantial reductions in energy use, emissions, and waste generation. It emphasizes the capacity of internal curing to mitigate early-age cracking and enhance durability, positioning it as a viable option for sustainable infrastructure planning in the face of climate change challenges. Moreover, this study underscores the importance of developing environmental product declarations using the proposed lifecycle assessment.

2.5. Significance of the Research

This research focuses on predicting and extending the service life of concrete pavements and bridges to strategically reduce greenhouse gas emissions. The research addresses the urgent need for improved sustainability and resilience in U.S. transportation infrastructure, which faces challenges from aging structures, funding shortages, and climate-related disasters. By enhancing the durability of concrete materials, mainly through lightweight aggregates and internal curing techniques, the project aims to reduce cracking and permeability, ultimately extending the service life of concrete elements. Longer-lasting concrete reduces frequent repairs and replacements, lowering the embodied energy and greenhouse gas emissions associated with cement production and construction processes. The research also evaluates how different climate zones impact concrete performance, providing crucial data that can inform best practices tailored to specific environmental conditions. This holistic approach fosters the adoption of sustainable materials and methodologies within the transportation sector.

3. Methodology

3.1 Experimental Investigations

Materials and Specimens

Experimental investigations focused on concrete samples that utilized lightweight aggregates sourced from expanded shale, clay, or slate (ESCS). As outlined in Table 1, the mixture designs represented two classes of concrete: normal-strength (Group 1) and high-strength (Group 2). Group 1 included three subgroups: all lightweight (ALW), sand-lightweight (SLW), and internally cured (ICC) concrete. Group 2 comprised only sand-lightweight high-strength concrete (HSSLW). Each group also included a reference sample of normal-weight concrete (NW) and high-strength normal-weight concrete (HSNW).

The concrete mixtures incorporated Portland-limestone cement (Type 1L) along with supplementary cementitious materials such as fly ash (F), class F pozzolan, silica fume (SF), and slag cement (Grade 100), as required. Additionally, the mixtures contained commercially available air-entraining and water-reducing admixtures to meet target design specifications.

Table 1. Concrete Mix Design Specifications

Mix Design	Group 1				Group 2	
	ALW	SLW	ICC	NW	SLW	NW
Compressive Strength, MPa (psi)		28 (4000)			40 (6000)	
Air Content (%)		5-8			5-8	
Equilibrium Density, kg/m^3 (pcy)	None	65-71 (110-120)	None	None	None	None
Normal Weight Coarse Aggregate			+	+		+
Normal Weight Fine Aggregate		+	+	+	+	+
Lightweight Coarse Aggregate	+	+			+	
Lightweight Fine Aggregate	+		+			

Four producers of ESCS aggregates provided samples from six plants across the United States (Table 2 and Figure 13). Not all plants supplied every type of specimen; each plant contributed a representative mix design suitable for the concrete industry in its region. The specimens included cylinders measuring 100 mm (4 in.) in diameter and 200 mm (8 in.) in height, as well as discs 50 mm (2 in.) long cut from the 100-mm (4-in.) diameter cylinders (Figure 14).

Table 2. Sources of Lightweight Aggregate and Concrete

Producers	Plants
Arcosa Lightweight	Brooks (KY), Livingston (AL), Streetman (TX)
Buildex	Dearborn (MO)
Carolina Stalite	Salisbury (NC)
Holcim Utelite	Coalville (UT)

Figure 13. Geographical Distribution of Lightweight Aggregate and Concrete Sources

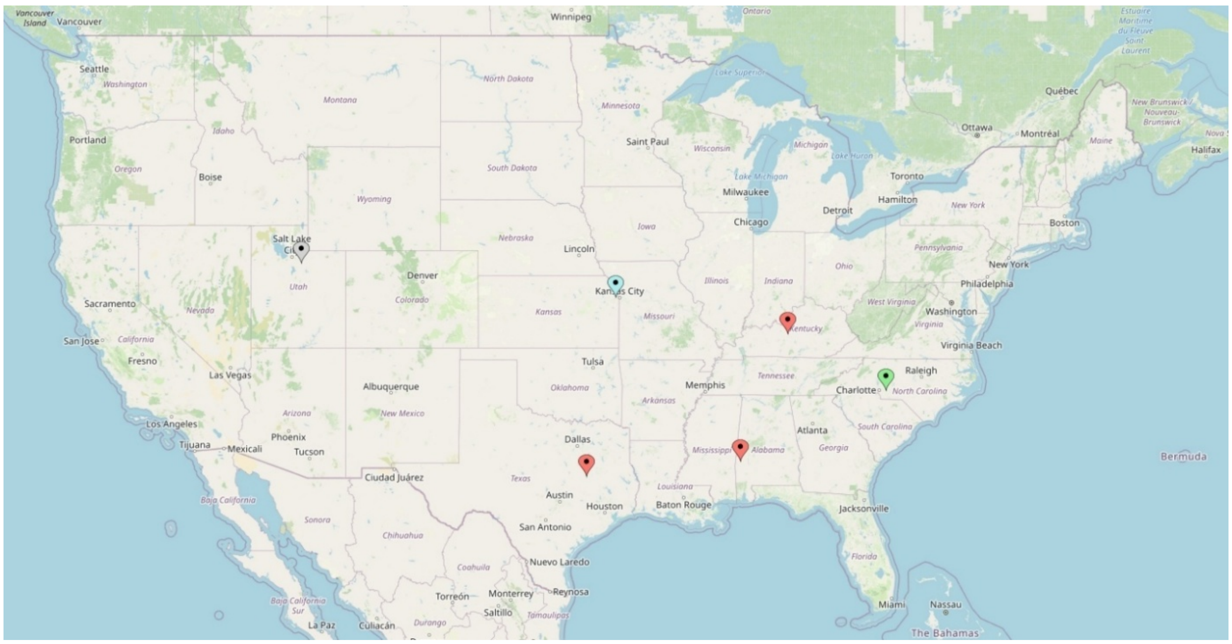


Figure 14. Storage, Protection, and Shipment of Concrete Cylinder and Disc Specimens

3.2 Standard Test Methods and Instruments

Table 3 outlines the standards, specifications, guides, and test methods that govern experimental investigations. ASTM standards and ACI guidelines for preparing and curing concrete test specimens using both lightweight and normal-weight aggregates and concrete. The testing of fresh concrete involved measuring slump for workability and determining air content and plastic density, all of which are in line with ASTM standards.

For hardened concrete, the evaluation of physical and mechanical properties adhered to ASTM standards, including measurements for density (equilibrium density for lightweight concrete), compressive strength at 7 and 28 days, and splitting tensile strength at 28 days. The transport properties assessed included the water absorption rate, electrical resistivity (bulk and surface), and chloride penetration or migration indications. The measurements for these properties were conducted following the appropriate ASTM, AASHTO, and NT Build standards.

Table 3. Experimental Investigation Standards

Reference	Standard Specification, Practice, Test Method, Guide or Report
ASTM C33/C33M	Concrete Aggregates
ASTM C330/C330M	Lightweight Aggregates for Structural Concrete
ACI PRC-213	Structural Lightweight-Aggregate Concrete
ASTM C31/C31M	Making and Curing Concrete Test Specimens in the Field
ASTM C192/C192M	Making and Curing Concrete Test Specimens in the Laboratory
ACI PRC-308-213	Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate
ASTM C1761/C1761M	Lightweight Aggregate for Internal Curing of Concrete
ASTM C143/C143M	Slump of Hydraulic-Cement Concrete
ASTM C138/C138M	Density (Unit Weight), Yield, and Air Content (Gravimetric)
ASTM C231/C231M	Air Content of Freshly Mixed Concrete by the Pressure
ASTM C567/C567M	Determining Density of Structural Lightweight Concrete
ASTM C39/C39M	Compressive Strength of Cylindrical Concrete Specimens
ASTM C496/C496M	Splitting Tensile Strength of Cylindrical Concrete Specimens
ASTM C1585	Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes
ASTM C1876	Bulk Electrical Resistivity or Bulk Conductivity of Concrete
AASHTO T358	Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration
ASTM C1202	Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
NT Build 201	Concrete: Making and Curing of Moulded Test Specimens for Strength Test
NT Build 208	Concrete, Hardened: Chloride Content
NT Build 492	Chloride Migration Coefficient from Non-Steady-State Migration Experiments

The PROOVE'it system (Figure 15) evaluates concrete's resistance to chloride ion ingress through three primary tests: the Rapid Chloride Permeability Test (RCPT), the Chloride Migration Test, and the Bulk Electrical Conductivity Test. The RCPT measures the total electrical charge that passes through a concrete specimen, which helps classify its permeability. The Chloride Migration Test determines the chloride migration coefficient by measuring the chloride penetration depth after an electric potential is applied. The Bulk Electrical Conductivity Test calculates the conductivity of the concrete by measuring the current that flows through the specimen. This system provides quick and accurate results, assesses concrete quality, and predicts the service life of materials.

On the other hand, the Resipod (Figure 16) allows for the evaluation of chloride permeability in concrete by measuring surface electrical resistivity. This method is both fast and applicable to new and existing concrete surfaces.

Figure 15. PROOVE'it System
(image courtesy of Germann Instruments)

Figure 16. Resipod Resistivity Meter
(image courtesy of Proceq)

3.3 Analytical Investigations

Service Life Prediction

A common method for predicting the service life of concrete involves measuring the total time required for chloride ions to accumulate at the surface and then transport from the concrete surface to the reinforcing steel bars, as well as the time needed for corrosion of the steel. This method employs the chloride diffusion model based on Fick's second law (Ehlen et al. 2009; Ehlen and Kojundic 2014; Life-365TM 2020). Although the Life-365TM software is publicly available for these analyses, it has certain limitations, such as a maximum analysis period. Therefore, in this research, a similar program to Life-365TM (2020) was developed in MATLAB (MathWorks 2023) to solve the relevant equations without these restrictions.

The diffusion of chloride according to Fick's second law follows (Ehlen et al. 2009; Ehlen and Kojundic 2014; Life-365™ 2020):

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

where C is the chloride content, D is the diffusion coefficient, x is the depth of the chloride intrusion with the maximum value equal to the depth of reinforcing steel or concrete cover, and t is time. The chloride content follows:

$$C(x,t) = C_0\left(1 - erf\,\frac{x}{2\sqrt{Dt}}\right) \quad (2)$$

where C_0 is the chloride content at depth zero. Hence, the diffusion coefficient varies with time and temperature, benchmarked at the 28-day and $293K$ referenced time and temperature respectively (Davodijam et al. 2022):

$$D(T) = D_{ref} \left(\frac{t_{ref}}{t}\right)^m exp\left[\frac{U}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \qquad (3)$$

where U is the activation energy of the diffusion process (35 *kJ/mol*), R is the gas constant (8.3145 *J/mol/K*), and T is the absolute temperature (K).

The Nernst-Einstein equation (Lu 1997) follows:

$$D = \frac{RT\sigma}{Z^2F^2C} \qquad (4)$$

where D is the diffusion coefficient, R is the gas constant (8.3145 *J/mol/K*), T is the absolute temperature (K), σ is the partial conductivity (S/cm), Z is the charge (Coul), F is the Faraday constant (96,500 Coul/mol), and C is the concentration (mol/cm^3).

The corrosion rate of steel bars is influenced by their surface properties and protective measures, with a standard estimated lifespan of six years for conventional steel materials. However, the initial concentration of chlorides and their accumulation rates depend on the specific application and the surrounding environment, particularly considering the climate zone. Additionally, climate change can affect long-term predictions.

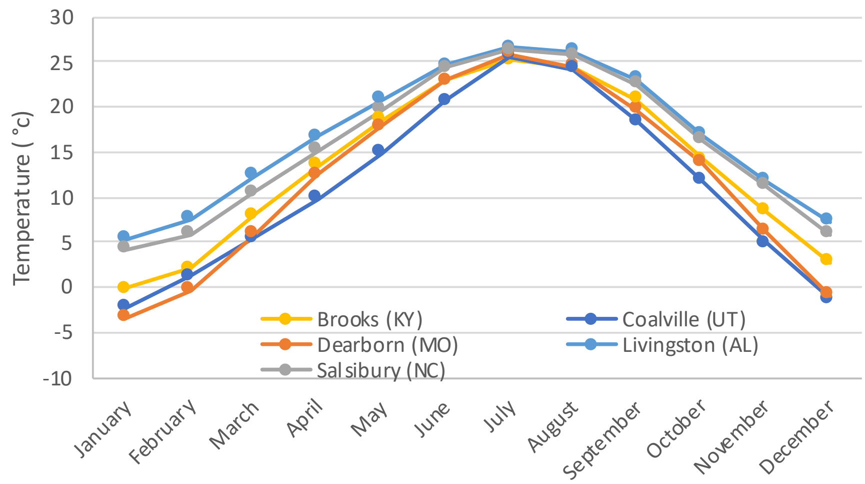
Table 4 lists the chloride accumulation rates for urban bridges, based on recommendations from Life-365TM (2020). The frequency of freeze-and-thaw cycles is the main factor affecting the intensity of chloride accumulation in each zone; therefore, the lowest suggested rate is for arid and hot regions. For urban bridges, the accumulation rate is set at 85% of the rates applicable to parking structures due to their higher exposure to de-icing agents. For marine structures situated 1.5 km from the ocean, the recommended chloride accumulation rate is 0.02% (Kalantari and Tehrani, 2021; Kalantari et al. 2021).

Table 4. Chloride Build-up Rate for Urban Bridges in Various Climate Zones

Climate Zone	Chloride Build-up Rate (% per year)
Very Cold	0.085
Cold	0.068
Moderate	0.0255
Semi-Moderate	0.0170
Semi-Arid to Very Hot	0.0085

The service life prediction for each concrete mix was based on an urban bridge located at or near the plant site (Table 2), with an aim to assess the contribution of lightweight aggregates, regardless of the specific location. A similar analysis can also be used to estimate the service life for other desired locations, including California. The temperature history of the selected plant locations is presented in Life-365™ (2020) using available data sources (Figure 17).

Figure 17. Temperature History of Selected Plant Locations (after Life-365™)



The design of concrete decks or slabs adheres to standard practices as outlined in the relevant guidelines (Table 5). In corrosive environments, concrete typically requires more cover, greater thickness, and additional reinforcement to resist the damaging effects of corrosive agents. Conversely, parking garages with smaller spans necessitate less thickness and reinforcement. Urban bridges, having larger spans and greater exposure to harmful agents, are designed with thicker slabs and increased concrete cover. Additionally, in cold regions, the concrete cover for slabs and decks is slightly thicker than usual due to the more frequent application of de-icing agents. This is also true for cities near water bodies with elevated chloride concentrations (Davodijam et al. 2022).

Table 5. Input Data for the Service Life Prediction

Exposure	Pavement	Urban Highway Bridges
Thickness (mm)	300	200
Concrete Cover (mm)	75	60
Reinforcing Ratio (%)	1.5	1.2
Water-to-Cementitious Materials Ratio (w-cm)	Varies [a]	Varies [a]
Maximum Chloride Concentration (%)	0.60 [b]	0.68 [b]

[a] Mix Design Specific; [b] 85% of the frigid climate

Lifecycle Assessment

The lifecycle assessment evaluates the predicted service life of concrete applications based on their transport properties. It considers both cost and environmental impacts.

Cost analysis encompasses construction and repair activities. The construction cost includes the expenses for concrete and rebar, which have similar unit costs across all applications and locations, adjusted for thickness and reinforcement ratios. Repair costs involve replacing damaged areas per a scheduled plan and grinding surfaces. Calculating total repair costs requires adjustments based on the frequency and intensity of damages (Vosoughi et al., 2017). Typical maintenance involves replacing 1% of the area, grinding the entire surface, and replacing joints every 10 years (SUDAS, 2021).

Cost data was developed using existing literature and updated bid information from transportation projects delivered by CA DOT (Caltrans, 2007) as of January 2025. The cost estimates were created for approximately 2,000 cubic meters of concrete over an area of 10,000 square meters (Table 6). Economic characteristics are provided by NIST (Kneifel and Lavappa 2024).

Table 6. Cost Data (Caltrans 2007; Kneifel and Lavappa 2024)

Item	Unit	Estimated Cost ($)
Ordinary Concrete Materials	m^3	1000
High Strength Concrete	m^3	1050
Reinforcing Steel Bars	tonne	4500
Grinding Existing Concrete	m^2	14
Grinding Existing Bridge Deck	m^2	30
Membrane Waterproof	m^2	140
Deck Seal	m^2	70
Removing Concrete Pavement	m^3	150
Removing Structural Concrete	m^3	380
Inflation Rate	%	1.8
Discount Rate	%	2.0

Using Environmental Product Declarations (EPDs) allows for accurate measurements of the carbon footprints associated with each concrete design. These measures highlight the environmental benefits of the proposed solutions, such as increased lifespan, better utilization of natural resources, and lower energy consumption and emissions (Tehrani 2021b).

The lifecycle assessment adheres to the system boundary outlined in Table 7. The selected modules represent a subset required for a cradle-to-gate Environmental Product Declaration (EPD) (Tehrani 2024b, 2024c), specifically for transportation applications such as pavements and bridges. The production phase is evaluated separately for expanded shale, clay, and slate (ESCS) and concrete manufacturing processes, including ready-mix concrete. Modules related to refurbishment and the consumption of energy and water during the use phase are not included in the scope of this study. Data for each module, as shown in Table 8, are sourced from available Product Category Rules (PCR), EPD, and Lifecycle Assessment (LCA) documents (EPD 2021; ISO 14025) concerning various materials, such as cement (PCA 2016), concrete (NRMCA 2020), steel (CRSI 2017), normal-weight aggregate (Vulcan 2016), and ESCS (ESCSI 2024a; UL 2022). Additionally, referenced engineering manuals and guides provide information on productivity and expected performance measures, including service life (Peurifoy et al. 2018; ACCO 2004; PBO 2018; SUDAS 2021).

Table 7. System Boundary Modules

Phase	Module	Stage
ESCS Production	A1	Mining Shale, Clay, and Slate
	A2	Transport to Rotary Kiln
	A3	Manufacturing ESCS
Concrete Production	A2’	Transport to Concrete Plant
	A3’	Produce Ready Mix Concrete
Pavement Construction	A4	Transport Concrete to the Site
	A5	Concrete Placement
Pavement Service Life	B1	Pavement Use
	B2	Joint Maintenance
	B3	Grinding Repair
	B4	Slab Replacement
Pavement End of Life	C1	Deconstruction
	C2	Transport Waste
	C3	Waste Processing and Crushing
	C4	Disposal
Benefits & Loads Beyond System Boundary	D	Reuse, Recovery, Recycling Potential

Table 8. Global Warming Potential (GWP)

Item	Unit	Global Warming Potential (kg CO_2 eq)	Reference
Cement	Tonne	1040	PCA 2016
Concrete (28-34 MPa) 0-20% SCM	m^3	523.68	NRMCA 2020
Concrete (41-55 MPa) 0-20% SCM	m^3	642.02	NRMCA 2020
Fabricated Steel Reinforcement	Tonne	979	CRSI 2017
Lightweight Aggregates (ESCS)	m^3	111	ESCSI 2023
Gravel	Tonne	6.06	Vulcan 2016
Sand	Tonne	4.89	Vulcan 2016

This Life Cycle Assessment (LCA) considers the productivity rates of construction tasks to determine resource consumption. However, the energy use and emissions associated with construction crews are below an assumed cut-off rate of 1%. Additionally, the system boundary does not include the energy input and emissions from manufacturing construction machinery and plant equipment. The long-lasting nature of this equipment reduces its impact to below the cut-off threshold (Tehrani 2023b).

4. Results

4.1 Experimental Investigations

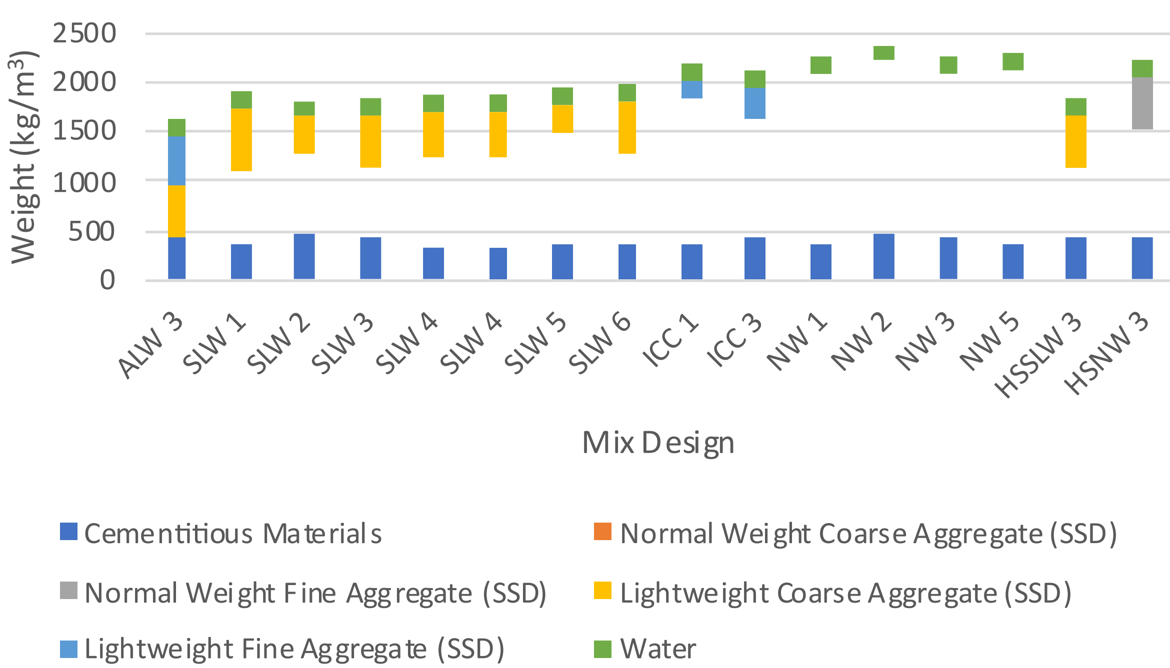
Mix Design and Physical Properties

The plastic density of mixtures depends on the mix specifications and the unit weight of the constituents, including both lightweight and normal-weight aggregates (Table 9). Figure 18 compares the mixture design of the concrete specimens based on the weight of each component. Table 9 defines acronyms in this figure.

Table 9. Fresh Concrete Properties

Concrete Mix	Plastic Density (kg/m^3)	Slump (mm)	Air Content (%)
All Lightweight	1648	152	-
Sand Lightweight	1807–2010	89–229	3.4–7.0
Internally Cured	2223–2243	38–108	5.2
Normal Weight	2255–2289	25–152	2.0-7.0
High Strength Sand Lightweight	1853	114	-
High Strength Normal Weight	2302	95	-

Figure 18. Mixture Design of Concrete Specimens



The unit weight and water absorption of various aggregates are shown in Figures 19 and 20. The specific gravity of normal-weight aggregates ranges from 2.45 to 2.72, with water absorption varying between 0.5% and 1.5%. In contrast, lightweight aggregates have a specific gravity ranging from 0.87 (for coarse aggregates) to 1.88 (for fine aggregates), and their water absorption varies from 6.2% (for fine aggregates) to 32% (for coarse aggregates).

Figure 19. Unit Weight of Aggregates

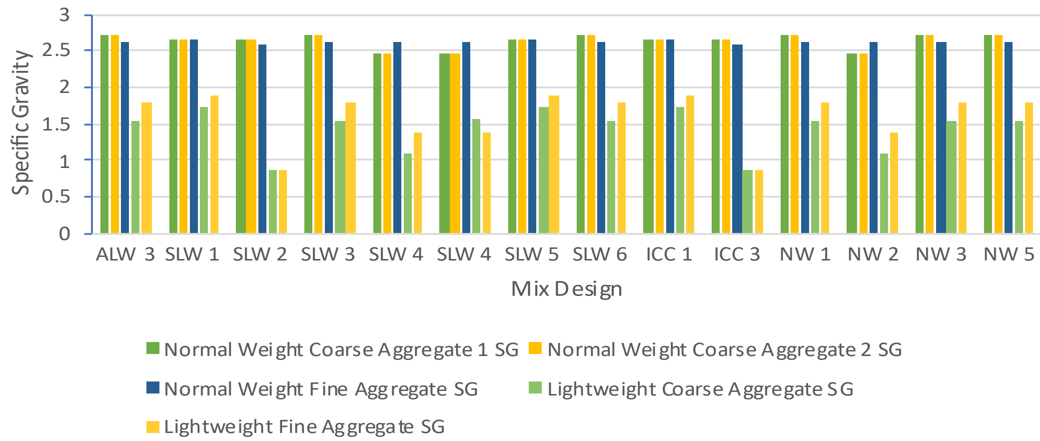
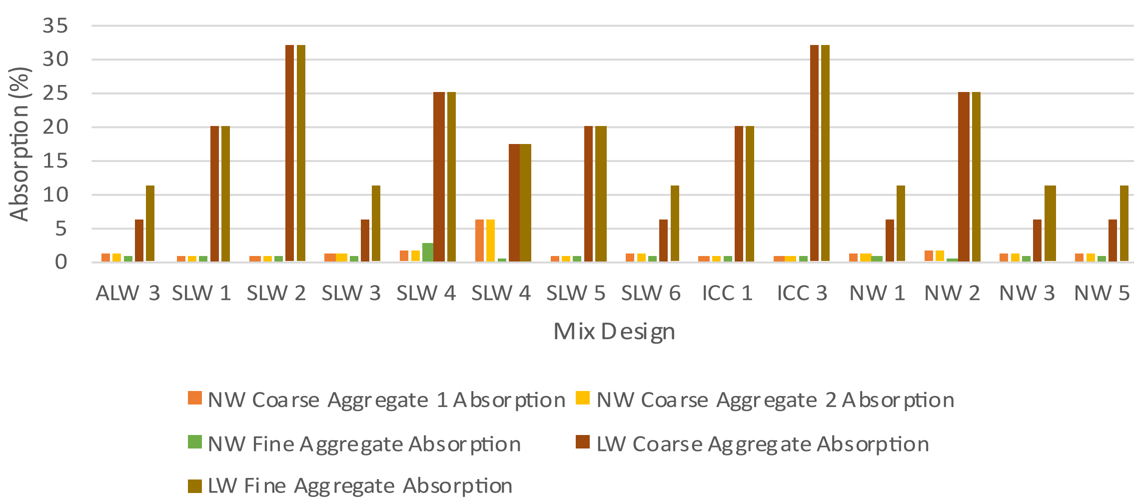


Figure 20. Water Absorption of Aggregates

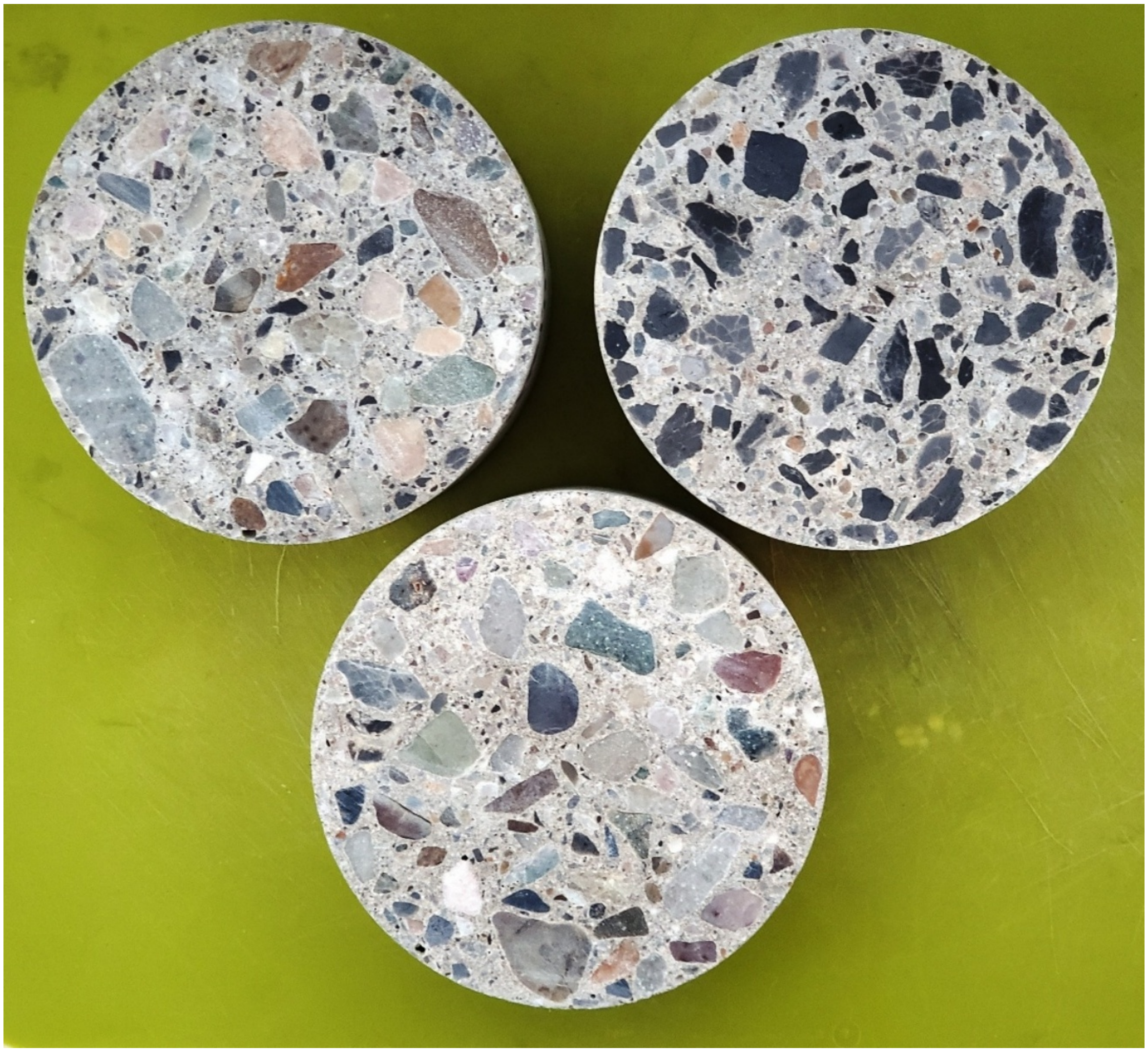


Split samples indicate the higher capacity of concrete containing lightweight aggregates to hold moisture for internal curing than normal-weight aggregates (Figure 21). Split samples also exhibit that the failure plane in sand-lightweight concrete typically passes through the aggregate rather than the interfacial transition zone (ITZ) in normal-weight concrete, promoting a more homogenous behavior. Figure 22 shows a magnified view of the ITZ for selected concrete samples. Figure 23 displays the cut surfaces of concrete containing fine or coarse lightweight aggregates next to normal-weight concrete.

Figure 21. Split Sand Lightweight (Top) and Normal-weight (Bottom) Concrete Samples

Figure 22. Magnified Views of All Lightweight (Left) and Normal-Weight (Right) Concrete Samples

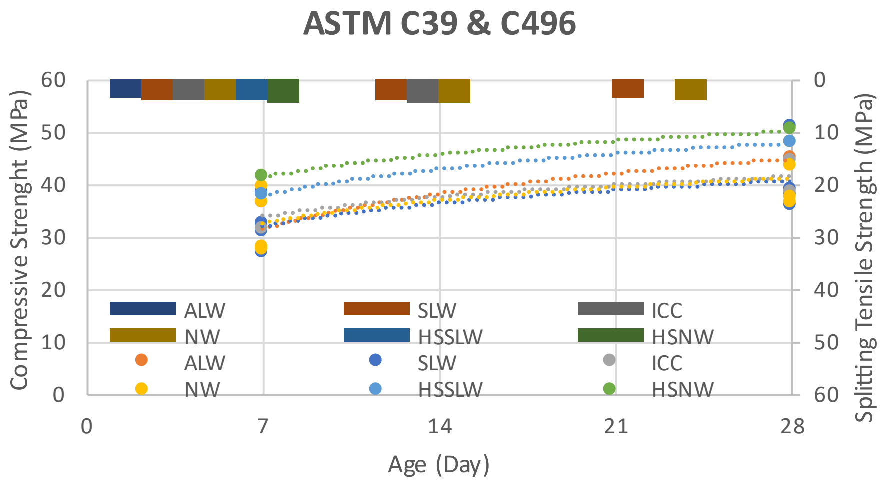
Figure 23. Cut Surfaces of Internally Cured (Top-Left), Sand-Lightweight (Top-Right), and Normal-Weight (Bottom) Concrete Samples



Mechanical Properties

Figure 24 illustrates the compressive and splitting tensile strength of the concrete specimens. Logarithmic trendlines estimate the variation in compressive strength between 7 and 28 days. The results show that all samples exceeded the specified target compressive strength of 28 MPa for normal concrete and 40 MPa for high-strength concrete. The compressive strength of concrete containing lightweight aggregates ranged from 96% to 109% of that of normal-weight concrete. Additionally, the splitting tensile strength of concrete with lightweight aggregates was between 91% and 107% of that of normal-weight concrete, except for all lightweight concrete, which exhibited a strength ratio of 80%.

Figure 24. Mechanical strengths of concrete specimens



Current design codes, such as ACI 318, apply a modification factor using the density of concrete to represent the ratio of splitting tensile strength to compressive strength for concrete that contains lightweight aggregates:

$$\lambda = \begin{cases} 0.75, w_c \leq 1600\, kg/m^3 \\ 0.000463\sqrt{w_c}, 1600 < w_c \leq 2160\, kg/m^3 \\ 1.0, w_c > 2160\, kg/m^3 \end{cases} \qquad (5)$$

where λ is the modification factor, and w_c is the equilibrium density of concrete. The experimental equivalent of the modification factor follows:

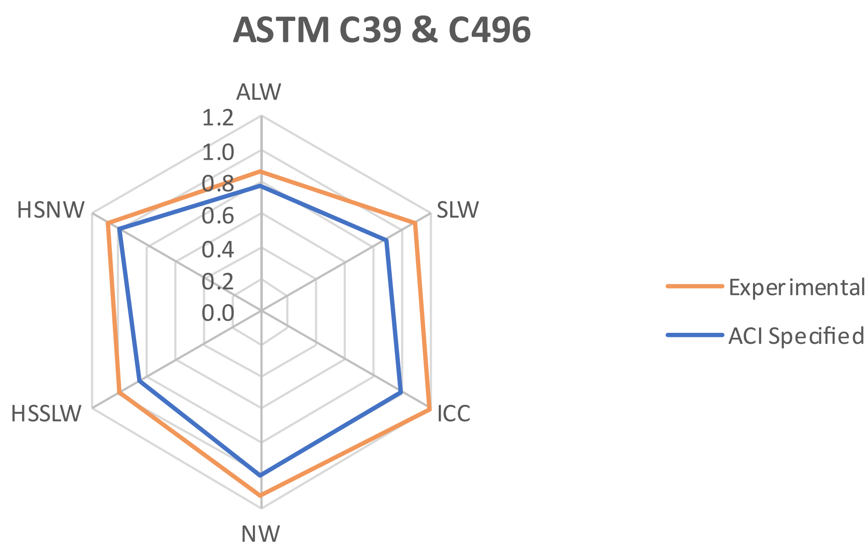
$$\lambda = 1.79 \frac{f_{ct}}{\sqrt{f_c'}} \qquad (6)$$

where f_{ct} and f_c' are the splitting tensile and compressive strengths (MPa) respectively.

Figure 25 compares the modification factors obtained from the design code, represented by Equation 3, with experimental values (Figure 20). The results show that design codes such as ACI 318 underestimate the mechanical performance of lightweight concrete in tension. Specifically, they underestimate it by 12% for Air-Lite Weight (ALW), 24% for Structural Light Weight (SLW), and 16% for High-Strength Structural Light Weight (HSSLW).

For all types except ALW, the modification factor exceeds 1, indicating that no modification factor is necessary. The conservativeness ratios were 13% for Normal Weight Concrete (NWC) and 7% for High-Strength Normal Weight Concrete (HSNWC), both of which were lower than the conservativeness ratios for concrete containing lightweight aggregates. Therefore, concrete with lightweight aggregates demonstrates superior tensile strength to normal-weight concrete, positively influencing other properties such as shear and bonding strength.

Figure 25. Modification Factors of Concrete Specimens



Transport Properties

The measured transport properties of concrete specimens included the water absorption rate, chloride migration, and electrical resistance to chloride ion penetration. Tests were typically conducted at 28 and 90 days, or interpolated values were used when testing at the target age was not feasible. Additionally, raw data from various mix designs and aggregate sources were averaged to represent the results for each group and subgroup of specimens. Specified bias and precision levels for each standard, when available, were considered to identify outliers, allowing us to repeat the test or reject the data.

The water absorption results included the initial and secondary rates of disc specimens at 28 and 90 days, using a minimum correlation coefficient of 0.98 according to ASTM C1585 (Figure 26).

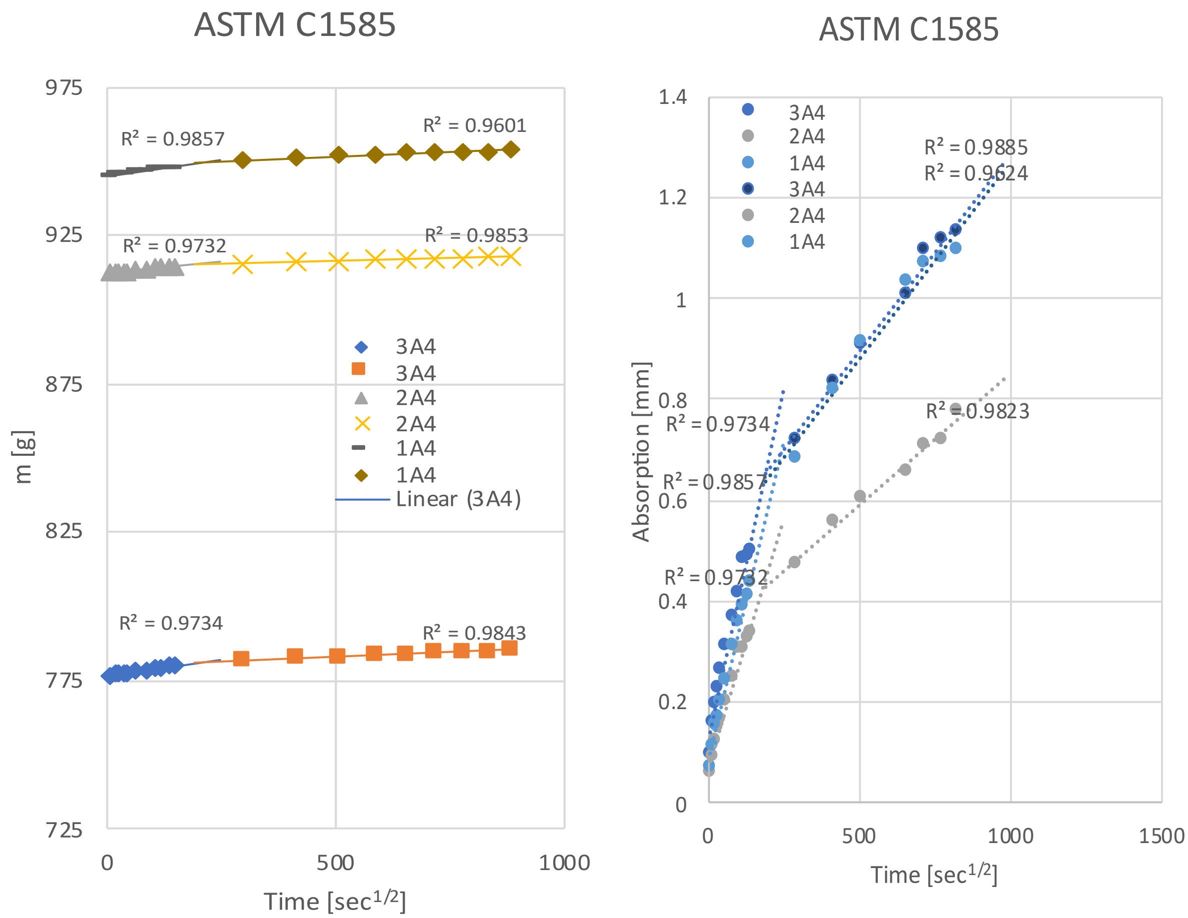
Figure 26. Water Absorption Specimens (Left) Placed in Water (Right)

The absorption follows:

$$I = \frac{m_t}{ad} \quad (7)$$

where I is the absorption, m_t is the change in specimen mass at time t (g), a is the exposed area of the specimen (mm^2), and d is the density of the water (g/mm^3). Then, initial and secondary rates of water absorption ($mm/s^{0.5}$) are the slope of the lines that fit the I versus square root of time t, from 1 minute to 6 hours and from 1 day to 7 days, respectively (Figure 27).

Figure 27. Mass Changes (Left) and Rates of Water Absorption (Right)



The results for the different concrete specimens are compared in Figure 28. The secondary absorption rate is approximately 26 to 43 percent of the initial rate for all concrete specimens, except for the high-strength normal-weight concrete, which significantly reduces at 28 days and reduces further at 90 days. This reduction may be attributed to potential errors during measurement. Additionally, the data indicate a general decrease in the water absorption rate as the concrete ages from 28 to 90 days; however, this trend may not apply universally to all specimens and is not necessarily statistically significant.

Figure 28. Average Rate of Water Absorption

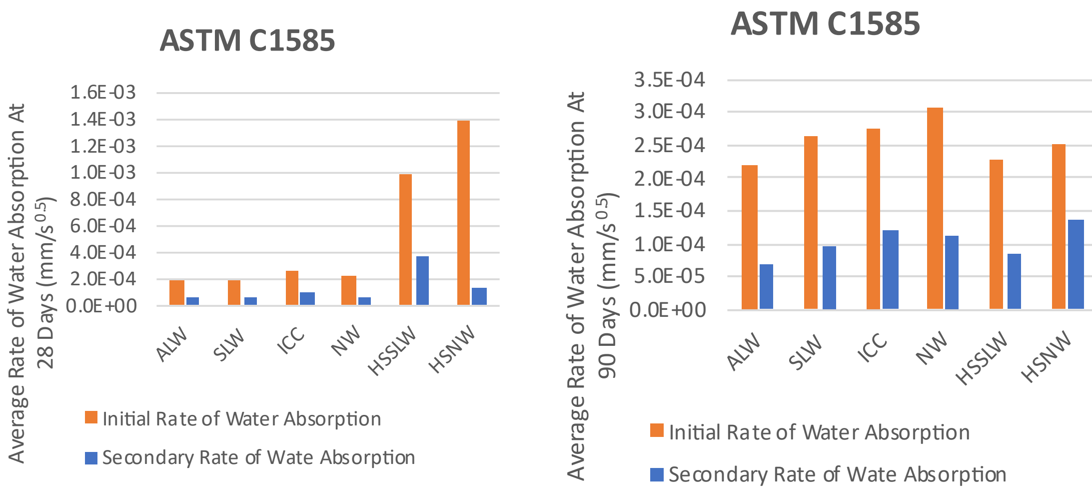
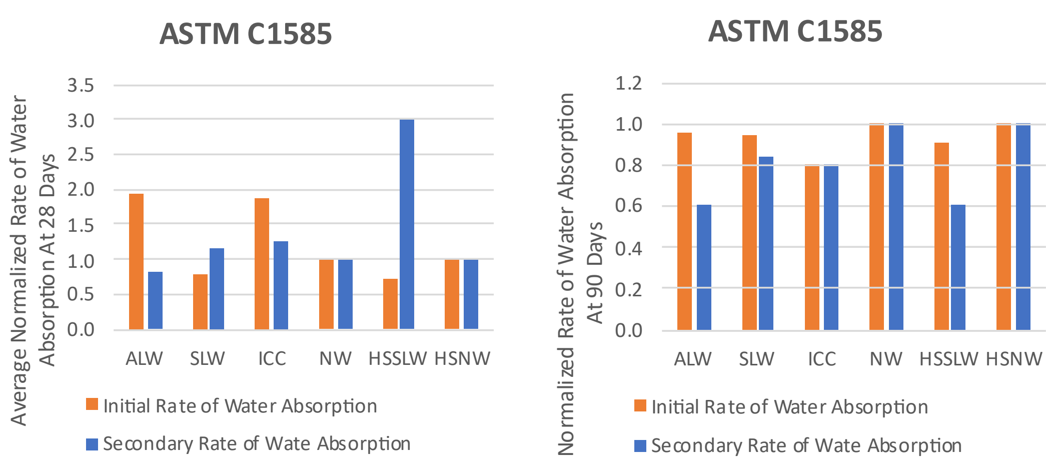


Figure 29 provides the water absorption ratio of concrete containing lightweight aggregates compared to a witness sample, with the ratio being one for both normal-weight (NW) and high-strength normal-weight (HSNW) concrete. The results indicate that concrete with lightweight aggregates may exhibit higher initial or secondary water absorption than normal-weight concrete. However, by the age of 90 days, these absorption rates fall below those of the witness samples. Consequently, lightweight aggregates help reduce the long-term permeability of concrete by lowering initial absorption by 6 to 20 percent and secondary absorption by 7 to 39 percent. Overall, there is no significant difference in the performance of normal and high-strength lightweight concrete.

Figure 29 Normalized Rate of Water Absorption



Bulk electrical resistivity or bulk conductivity follows ASTM C 1876 to indicate the resistance of concrete to chloride ion penetration using cylinder specimens (Table 10).

Table 10. Chloride Ion Penetrability Using Bulk Electrical Resistivity

Bulk Electrical Resistivity (Ω.m)	Chloride Ion Penetrability
Less than 40	High
40 to 80	Moderate
80 to 160	Low
160 to 190	Very Low
More than 190	Negligible

This test replaces ASTM 1760 by substituting the NaCl and NaOH contents with a sponge saturated with simulated fluid. As a result, the ASTM 1760 apparatus (Figure 30) can be used with minor modifications. The following provides the details on bulk electrical resistivity:

$$\rho = \frac{1}{\sigma} = \frac{V}{I}\frac{A}{L} \qquad (8)$$

where ρ is the bulk electrical resistivity (Ω.m), σ is the bulk electrical conductivity (S/m), L is the average specimen length (m), A is the specimen cross-section area (m^2), V is the voltage (V), and I is the current (A).

Figure 30. Bulk Electrical Resistivity Apparatus

The results for all specimens are presented in Figure 31, comparing them with recommended thresholds for chloride ion penetrability. According to these findings, all specimens, except for four data points, exhibited low to moderate chloride ion penetrability, which generally decreased over time.

Figure 31. Bulk Electrical Resistivity

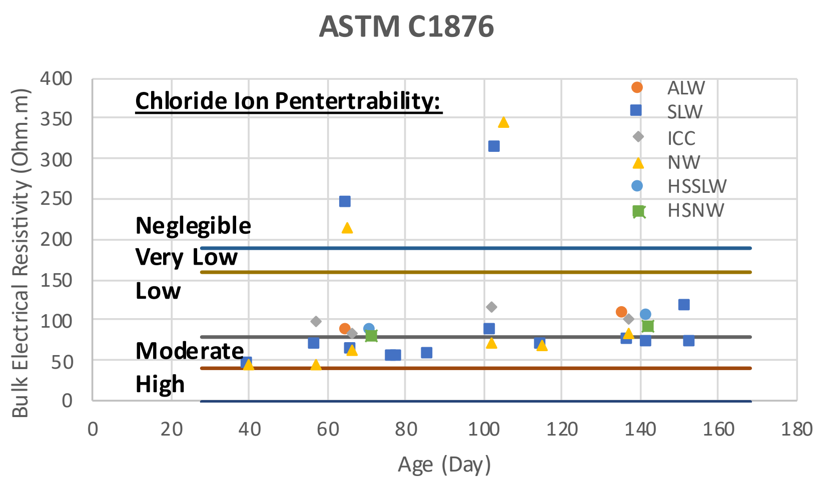


Figure 32 compares the results for 28- and 90-day ages, showing an increase in bulk electrical resistivity with age ranging from 22 to 41 percent, except for four data points that exhibit negligible chloride ion penetrability.

Figure 32. Average Bulk Electrical Resistivity

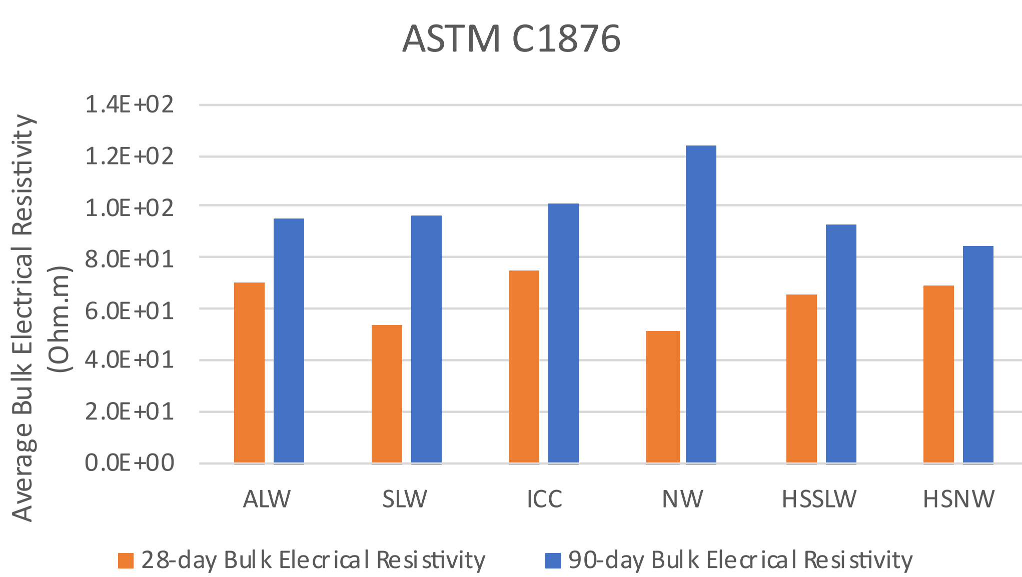


Figure 33 presents the normalized values as ratios of the bulk electrical resistivity of concrete made with lightweight aggregates compared to normal-weight concrete. These results indicate that lightweight aggregates improve the bulk electrical resistivity at 28 and 90 days, except for a minor 4% decrease observed in high-strength concrete at the 28-day mark. Due to the limited number of samples for this specimen, further tests with additional samples are needed. The findings confirm that internal curing significantly reduces chloride ion permeability at 28 and 90 days.

Figure 33. Normalized Bulk Electrical Resistivity

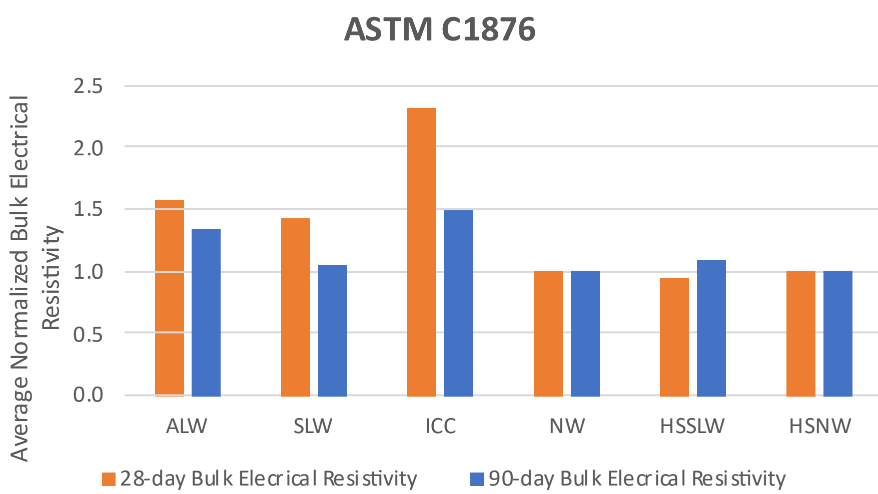
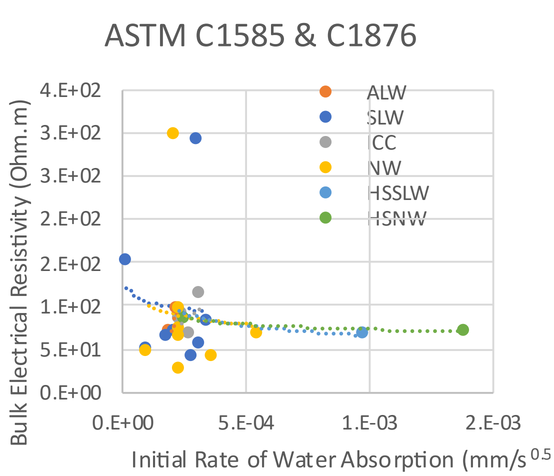
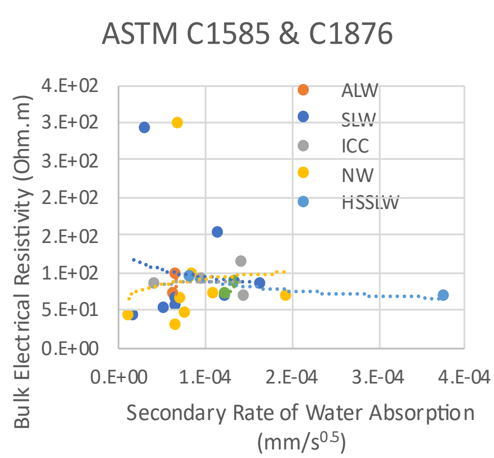


Figure 34 attempts to correlate bulk electrical resistivity with water absorption rates. The trendlines indicate that higher bulk electrical resistivity is associated with lower water absorption rates across all concrete specimens. However, these findings lack statistical significance, especially concerning the secondary water absorption of NW.

Figure 34. Bulk Electrical Resistivity and Rates of Water Absorption





Surface electrical resistivity (AASHTO T 358) is an alternative method to evaluate the concrete's ability to resist chloride ion penetration (see levels in Table 11).

Table 11. Chloride Ion Penetrability Using Surface Resistivity

Surface Resistivity (KΩ.cm)	Chloride Ion Penetrability
Less than 12	High
12 to 21	Moderate
21 to 37	Low
37 to 254	Very Low
More than 254	Negligible

The surface resistivity is as follows:

$$\rho = 2\pi a \frac{V}{I} \qquad (9)$$

where ρ is the resistivity (Ω.m), *a* is the inter-probe distance (m), *V* is the voltage (V), and *I* is the current (A). For accurate conversions, readings obtained from the surface probe should be multiplied by 1.92 compared to the bulk density readings for the 100 by 200 mm (4 in. by 8 in.) cylinder setup. This adjustment accounts for the effects of inter-probe distance and the geometry of the concrete specimen (Morris et al. 1996).

Figure 35 illustrates the surface resistivity of concrete specimens over time compared to the recommended thresholds for chloride ion penetrability. According to these results, the specimens displayed a range of resistivity, categorized from high to low ranks, with two data points falling within the very low rank. Overall, the resistivity increased for all specimens as time progressed.

Figure 35. Surface Resistivity

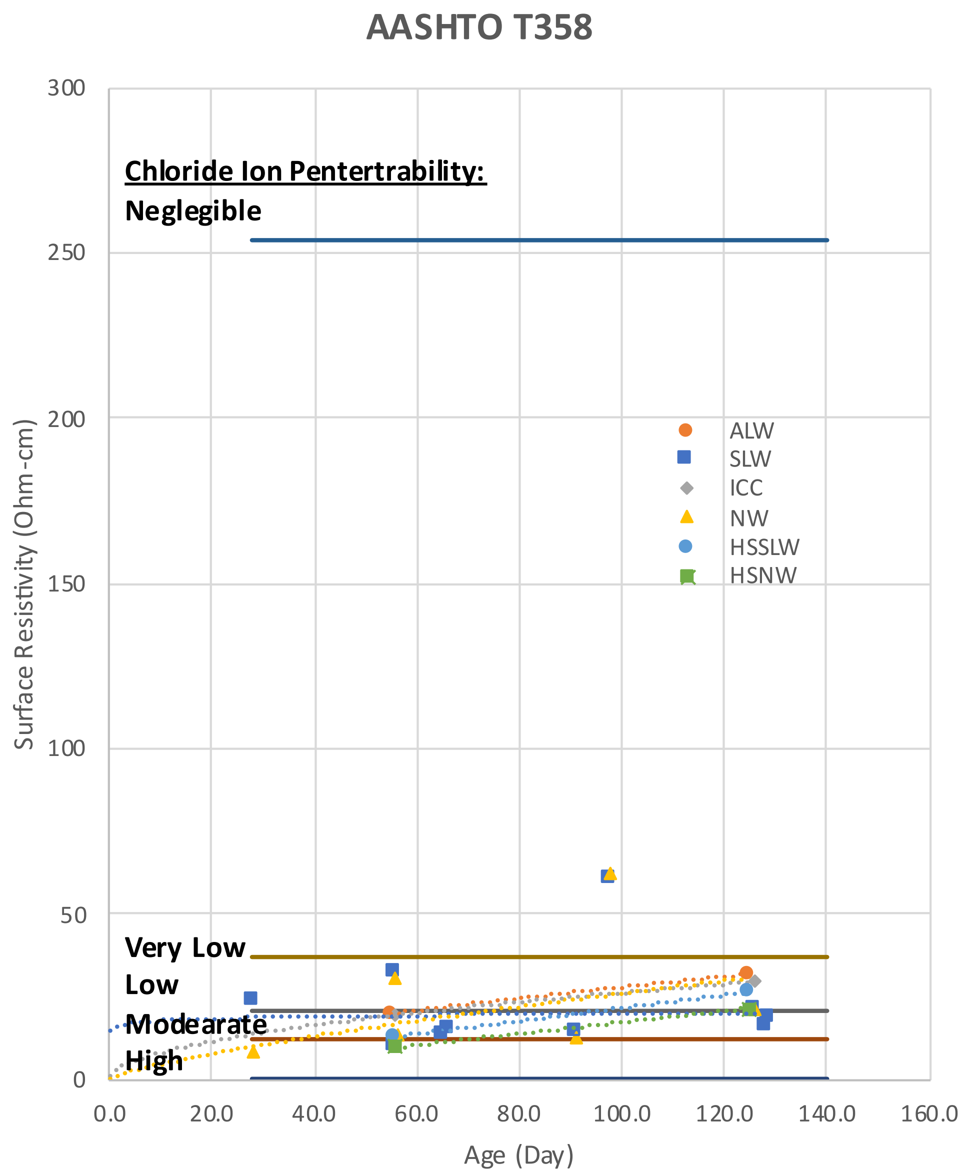


Figure 36 compares the results for ages 28 and 90 days, indicating a considerable increase in surface resistivity of 78 to 220 percent. The increase was significantly higher for high-strength concrete specimens than for normal-strength concrete specimens.

Figure 36. Average Surface Resistivity

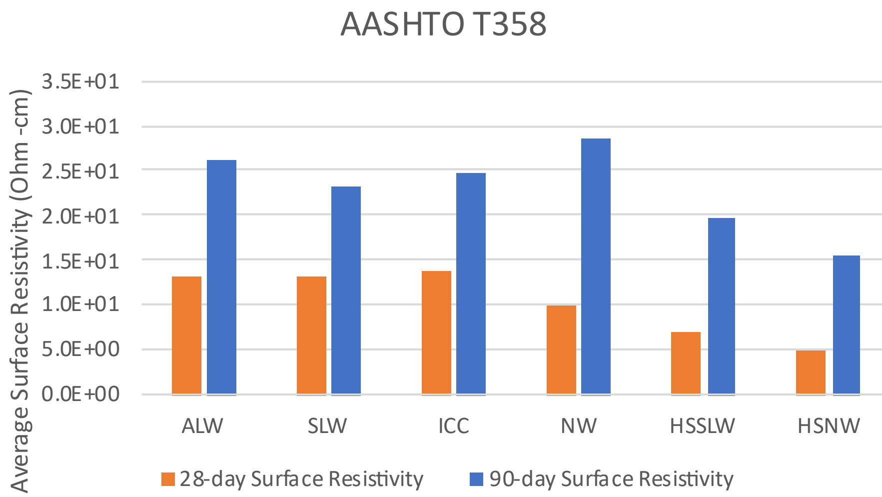


Figure 37 illustrates the impact of lightweight aggregates by comparing the surface resistivity of concrete that contains these aggregates to that of normal-weight concrete through normalized ratios. The results indicate that lightweight aggregates improve surface resistivity at 28 and 90 days, with enhancements ranging from 42 to 55 percent.

Figure 37. Normalized Surface Resistivity

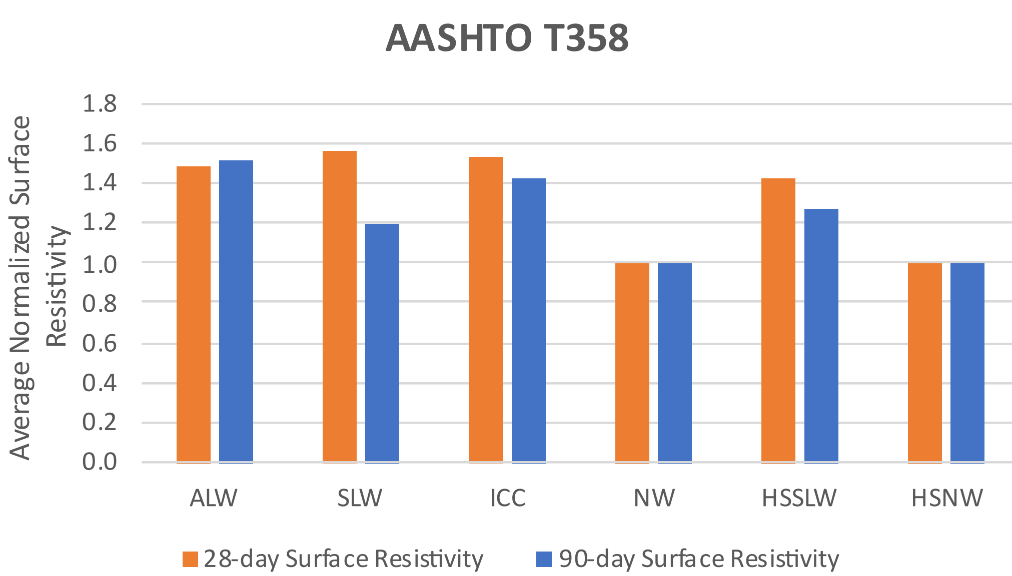
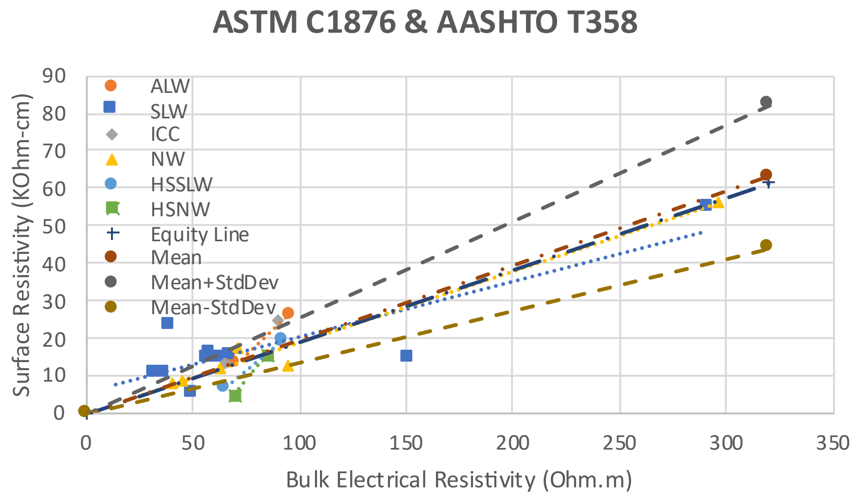


Figure 38 examines the relationship between surface and bulk electrical resistivity results. The slope of the mean value is approximately 1.974, which is 2.83% higher than the theoretical value represented by the equity line. Most data points fall within one standard deviation above or below the mean.

Figure 38. Surface and Bulk Electrical Resistivity



The ASTM 1202 standard evaluates concrete's resistance to chloride ion penetration by measuring its electrical conductivity. It determines the diffusion coefficient based on the charges passing through disc specimens over six hours (Table 12).

Table 12. Chloride ion penetrability using charges passed

Charges Passed (Coulombs)	Chloride Ion Penetrability
More than 4000	High
2000 to 4000	Moderate
1000 to 2000	Low
100 to 1000	Very Low
Less than 100	Negligible

The apparatus used in this study was the PROOVE'it system by Germann (Figure 39), which applied 60 volts to concrete disc specimens. Before testing, the specimens were saturated in a vacuum within a desiccator (Figure 40), which was sealed to prevent moisture or ion transfer from the sides.

Figure 39. Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

Figure 40. Soaking Specimens in Vacuum Desiccator

Figure 41 shows a typical profile of the current passing through specimens during the test. The charges passed are as follows:

$$Q = 900\left(I_0 + 2\sum_{t=30}^{330} I_t + I_{360}\right)\left(\frac{95}{x}\right)^2 \frac{y}{50} \qquad (10)$$

where Q is the adjusted charge passed (coulombs), I_t is the current (A) at time t (min) after the voltage is applied, and x and y are the diameter and length of the test specimen (mm) respectively.

Figure 41. Typical Profile of Current Passing Through Specimens

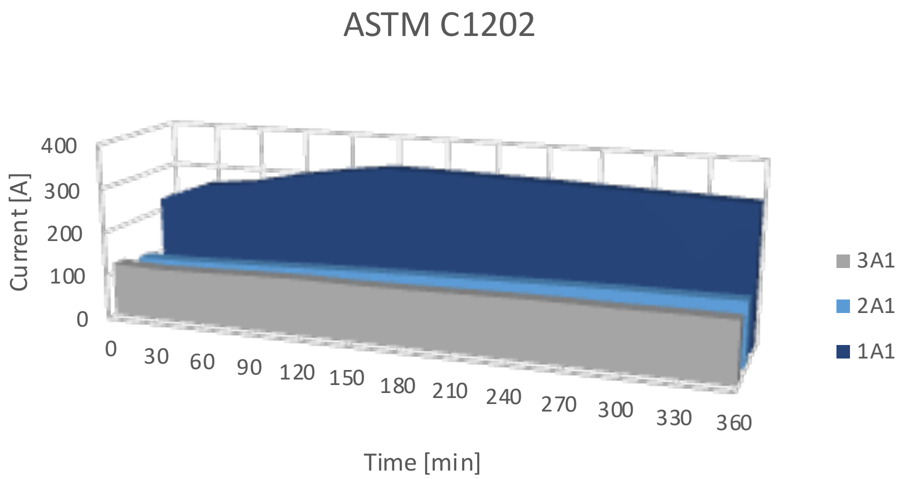


Figure 42 displays data points for all concrete specimens. This indicates that some samples have high chloride ion penetrability, which suggests a broader range of results than bulk electrical resistivity. Additionally, the figure shows that as concrete ages, the number of passed charges decreases, leading to a decline in chloride ion penetrability from high and moderate levels to moderate and low levels, respectively. Although the NW specimens exhibit a higher rate of decline, they still demonstrate greater penetrability on average than the other specimens.

Figure 42. Adjusted Charges Passed

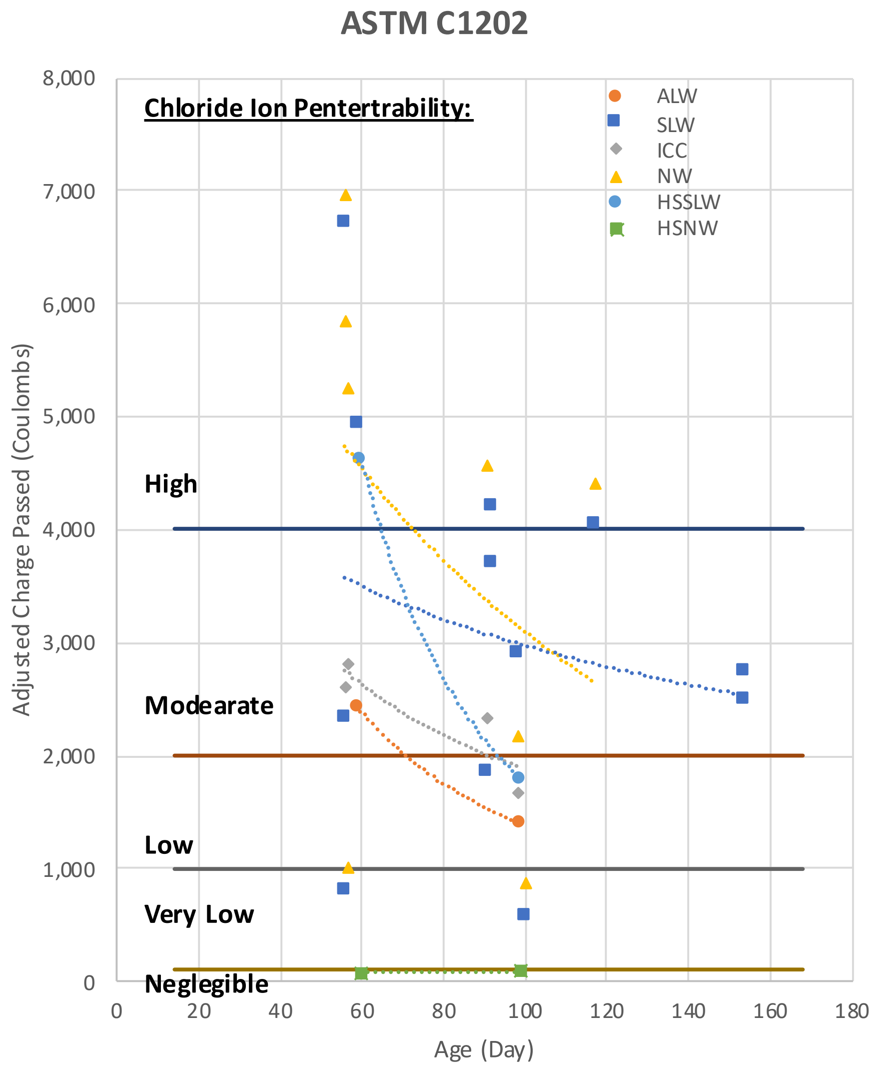


Figure 43 compares the average charges for all specimens, highlighting a decrease in observed values over time. The figure shows that the values for HSSLW are significantly higher at earlier ages but drop sharply as the ages increase. This suggests that there may be an issue with the samples tested earlier.

Figure 43. Average Adjusted Charges Passed

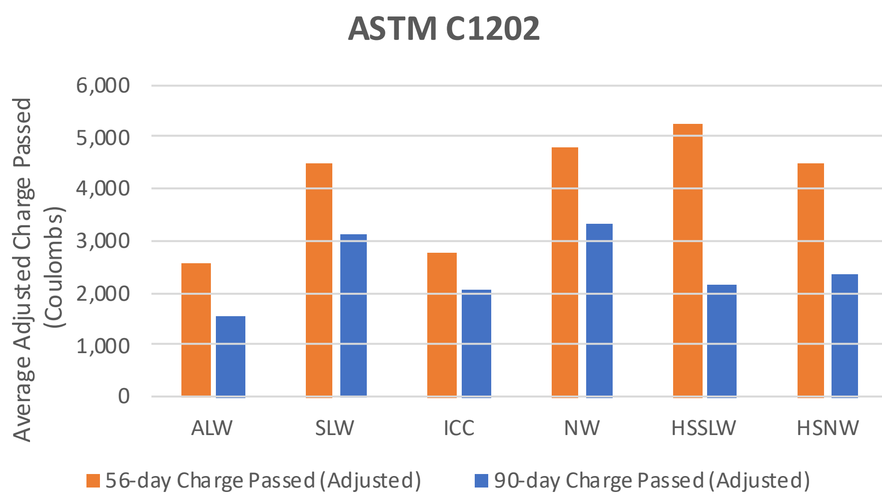


Figure 44 clarifies observations using normalized average values related to the normal weight concrete witness specimens. The results indicate that lightweight aggregates reduce the adjusted passed charges by 22 to 52 percent for normal-strength concrete at 56 days and 7 to 38 percent at 90 days. Additionally, the High-Strength Self-Consolidating Lightweight Concrete (HSSLW) shows an 18 percent increase at 56 days, decreasing to an 8 percent reduction at 90 days.

Figure 44. Normalized Adjusted Charges Passed

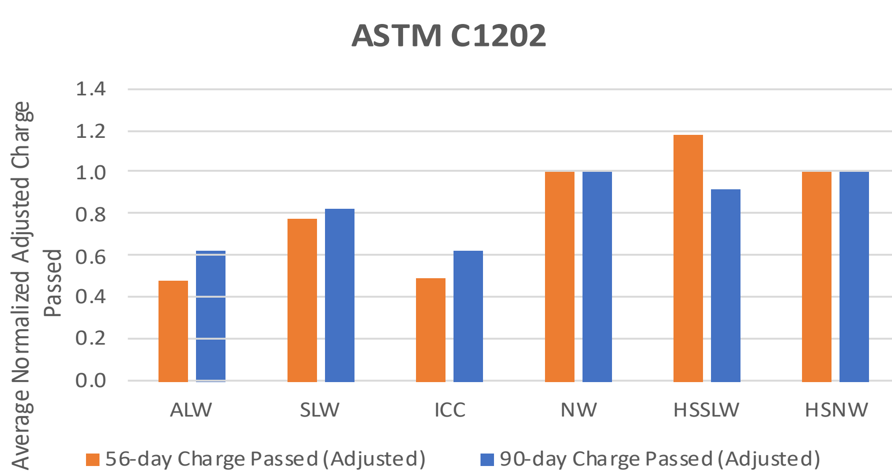
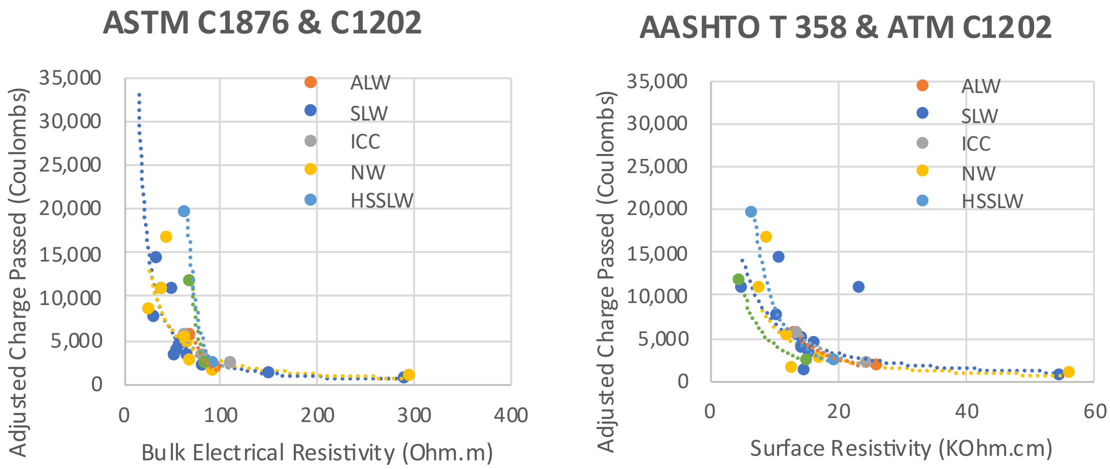


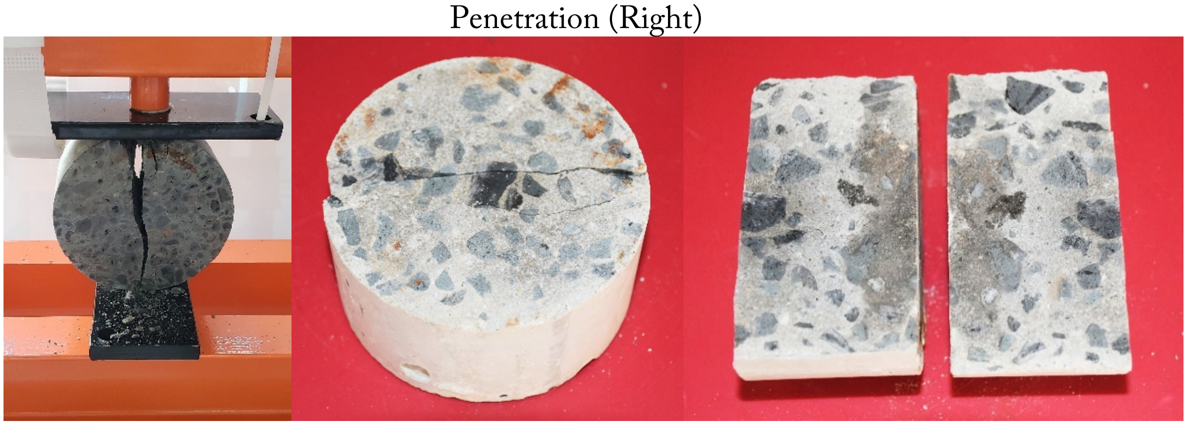
Figure 45 compares the relationship between charges passed to the surface and bulk electrical resistivity results. There is a general trend showing that adjusted charges decrease as resistivity increases. This pattern is consistent for both concrete containing lightweight and normal-weight aggregates. However, the reduction rate is more pronounced in high-strength concrete than normal-strength concrete. This latter observation requires more statistically significant evidence to support it.

Figure 45. Adjusted Charges Passed Versus Resistivity



The NT Build 492 standard specifies the method for determining the chloride migration coefficient in concrete. The first step outlined in this standard involves measuring the charges passed through concrete discs over an extended period, precisely 24 hours for the concrete specimens used in this study, based on the initial currents observed. Adjusting the voltage and duration of the test makes it possible to ensure adequate migration of chloride ions into the concrete, which can be detected through chemical activation. Following this, the non-steady-state migration coefficient is measured based on the depth of chloride penetration in a split sample (Figure 46). Additionally, the total charges passed through the specimen serve as another measure of the penetrability of chloride ions.

Figure 46. Splitting (Left) Specimen (Center) Showing the Depth of Chloride Ion Penetration (Right)



The non-steady-state migration coefficient follows:

$$D_{nssm} = \frac{RT}{zFE}\frac{x_d - \alpha\sqrt{x_d}}{t} \quad (11)$$

where:

$$E = \frac{U-2}{L} \qquad (12)$$

$$\alpha = 2\sqrt{\frac{RT}{zFE}}\, erf^{-1}\left(1 - \frac{2c_d}{c_0}\right) \qquad (13)$$

In these equations:

- D_{nssm} is the non-steady-state migration coefficient (m^2/s).
- z is the absolute value of ion valence, which is one for chloride.
- F is the Faraday constant, $9.648 \times 10^4\, J/(V \cdot mol)$.
- U is the absolute value of the applied voltage (V).
- R is the gas constant, $8.314\, J/(K \cdot mol)$.
- T is the average value of the initial and final temperature in the anolyte solution (K).
- L is the thickness of the specimen (m).
- x_d is the average value of the penetration depths (m).
- t is the test duration (sec).
- c_d is the chloride concentration at which the color changes, 0.07 N for ordinary Portland concrete.
- c_0 is the chloride concentration n the catholyte solution, nearly 2 N, and
- erf^{-1} is the inverse of the error function, $erf^{-1}\left(1 - \frac{2 \times 0.07}{2}\right) = 1.28$.

Substituting known values provides a simplified equation:

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{(U-2)}}\right) \qquad (14)$$

where:

- D_{nssm} is the non-steady-state migration coefficient ($\times 10^{-12} m^2/s$).

- U is the absolute value of the applied voltage (V).
- T is the average value of the initial and final temperature in the anolyte solution (°C).
- L is the thickness of the specimen (mm).
- x_d is the average value of the penetration depths (mm), and
- t is the test duration (hour).

The average value of the penetration depth is based on seven measurements taken at 10-mm intervals within the middle portion of the sample, excluding the 20-mm cover on each side. A primary concern regarding penetration depth is that low-porosity aggregates, such as normal-weight gravel, may obstruct migration, while high-porosity aggregates, such as lightweight aggregates, may facilitate it. An alternative method that measures the electrical charges passed can be employed to validate these results. According to the Nernst-Einstein equation (Equation 6), the diffusion coefficient can be determined using electrical resistivity (or conductivity) (Szweda et al. 2023):

$$D_{NE} = \frac{RT}{z^2F^2}\frac{t_i}{C_i\gamma_i\rho_{BR}} \qquad (15)$$

$$\rho_{BR} = \frac{100}{\sigma} \qquad (16)$$

$$\sigma = \frac{QL}{VtA} \qquad (17)$$

where D_{NE} is the diffusion coefficient (m²/s), R is the universal gas constant ($8.314\,J/(K \cdot mol)$), T is the absolute temperature (K), z is the valence of ions (1), γ_i is the activity coefficient of chloride ions (1), C_i is the concentration of chloride ions (mol/m³), ρ_{BR} is the volumetric resistivity, σ is the conductivity (Ω/m), Q is the charge (coulomb), L is sample thickness (m), V is electrical potential (V), A is the cross-sectional area of the sample (m²), and t is time (sec).

Figure 47 compares non-steady-state migration and diffusion coefficients obtained from the NT Build 492 test. It clearly shows a reliable relationship between these values for normal weight (NW) concrete; however, such a trend cannot be observed for concrete that contains lightweight aggregates. These results suggest that it would be more appropriate to investigate diffusion coefficients instead of migration coefficients to assess the contribution of lightweight aggregates.

Figure 47. Non-Steady-State Migration Versus Diffusion Coefficients

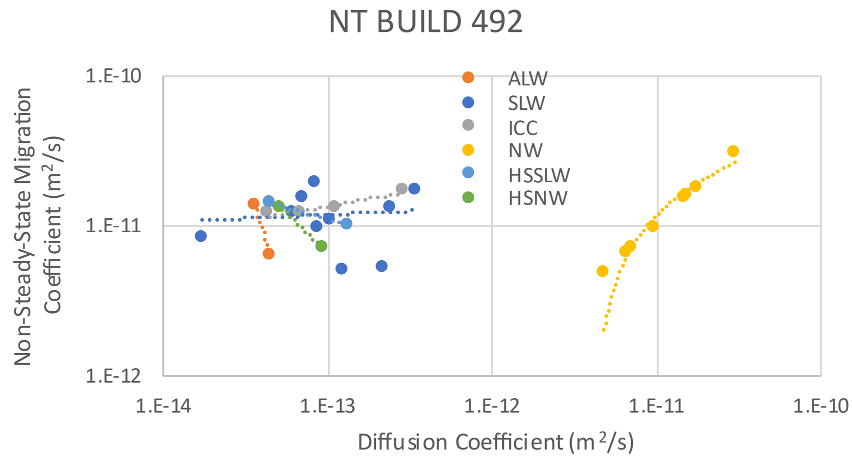


Figure 48 compares the chloride migration and diffusion coefficients. The graphs indicate that the diffusion coefficients derived from the charges passed suggest a trend of decreasing diffusion over time for all concrete specimens. However, this trend is not evident for the migration coefficient, except in the NW specimen.

Figure 48. Non-Steady-State Migration (Left) and Diffusion (Right) Coefficients

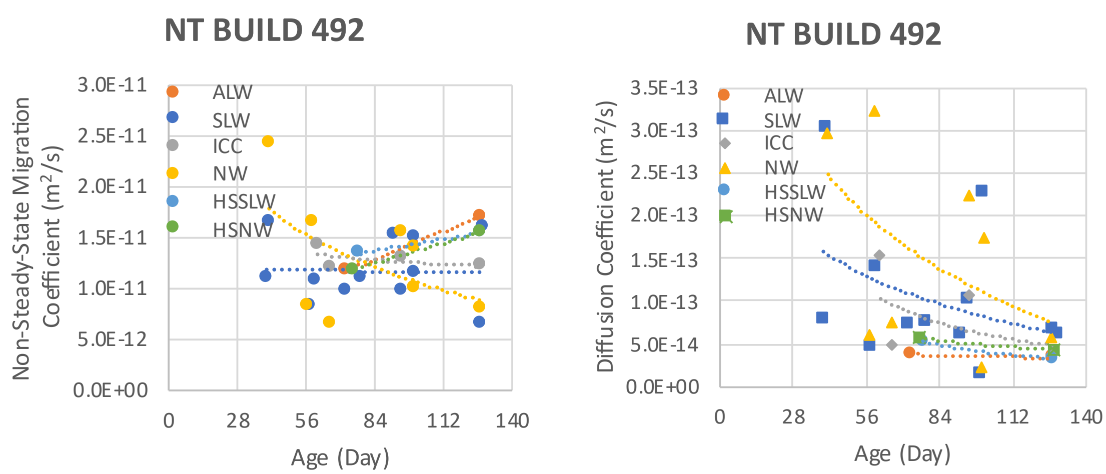
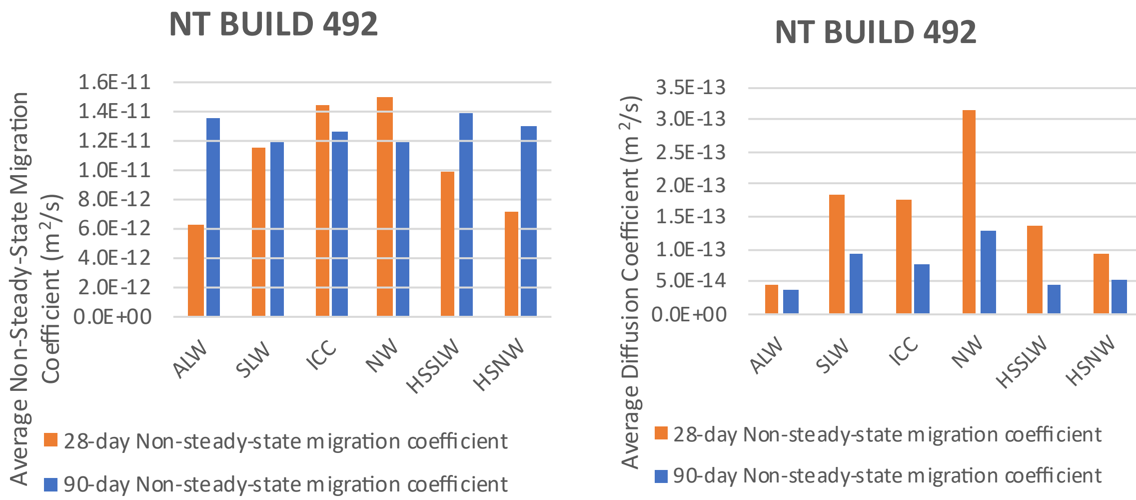


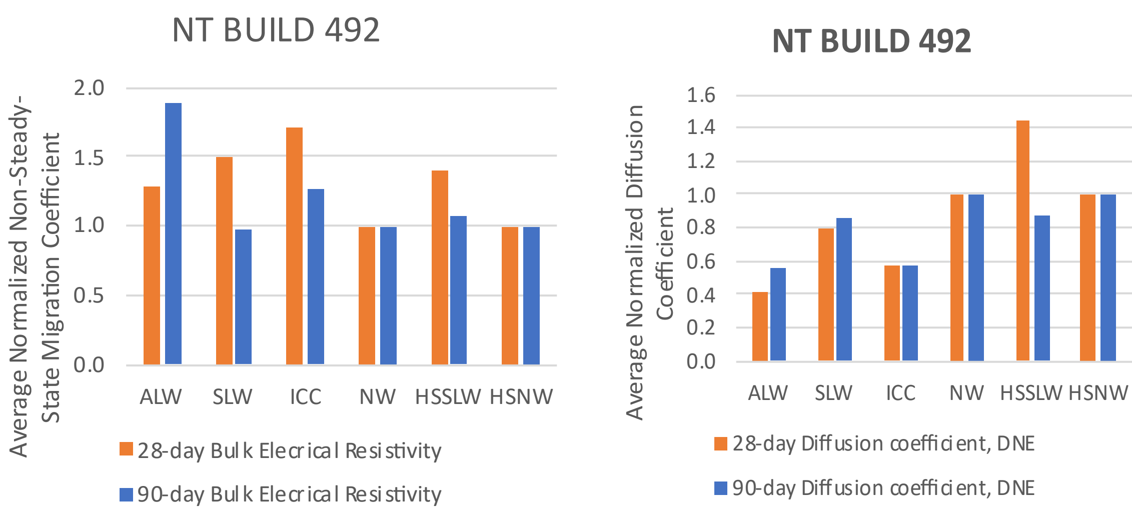
Figure 49 also supports earlier observations, indicating that the migration coefficient experiences slight changes, usually reductions, between the ages of 56 and 90 days. However, this pattern does not apply to observations on the ALW and HS samples, which exhibit noticeable increases. In contrast, diffusion coefficients consistently show the expected decline over time across all specimens. The results also confirm that lightweight aggregates decrease diffusion coefficients, except for a single instance of HSSLW at the 28-day mark.

Figure 49. Average Non-Steady-State Migration (Left) and Diffusion (Right) Coefficients



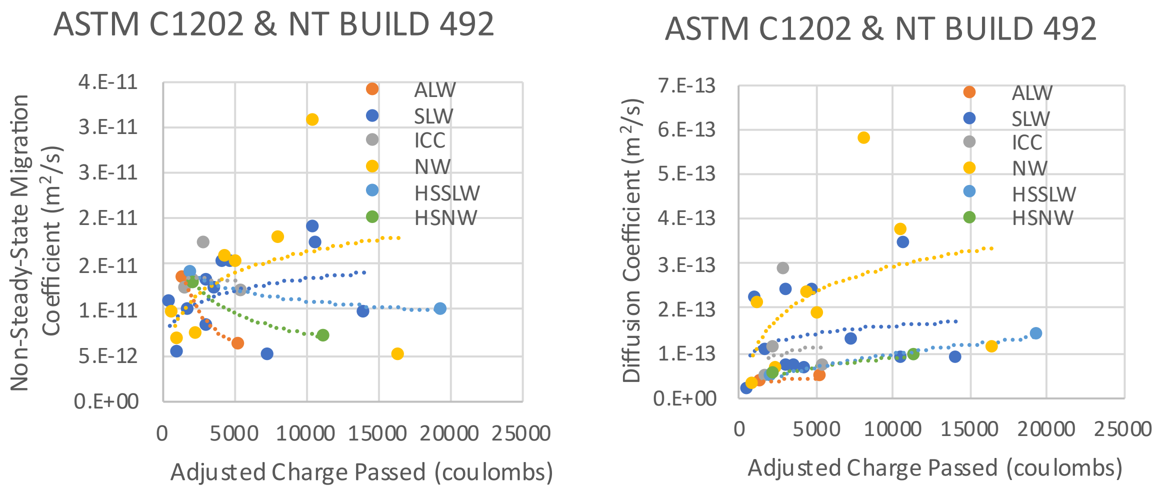
The normalized ratios in Figure 50 indicate that concrete containing lightweight aggregate has a slightly higher migration coefficient compared to the normal-weight control specimens. However, the impact of the lightweight aggregate is reflected in the reduction of the diffusion coefficient, which varies from 13 to 58 percent, except in a single case involving HSSLW at 28 days.

Figure 50. Normalized Non-Steady-State Migration (Left) and Diffusion (Right) Coefficients



The diffusion coefficients from NT Build 492 are comparable to ASTM C1202, but this is not true for the migration coefficient, except for NW concrete (Figure 51).

Figure 51. Comparing Results from NT Build 492 and ASTM C1202



4.2 Analytical Investigations

Service life Prediction

Simulations of diffusion coefficients over time reveal the depth of chloride ion penetration and the period required for these ions to reach the surface of the steel reinforcing bar, marking the initiation of corrosion. The service life of this system encompasses both the initiation and propagation periods, totaling six years for conventional black steel. The experimental diffusion coefficients and their rates of change for each concrete specimen align with the average values obtained from ASTM C1202 and NT Build 492. Hence,

$$m = \left(\ln \frac{D_{t2}}{D_{t1}}\right) / \left(\ln \frac{t_1}{t_2}\right) \quad (18)$$

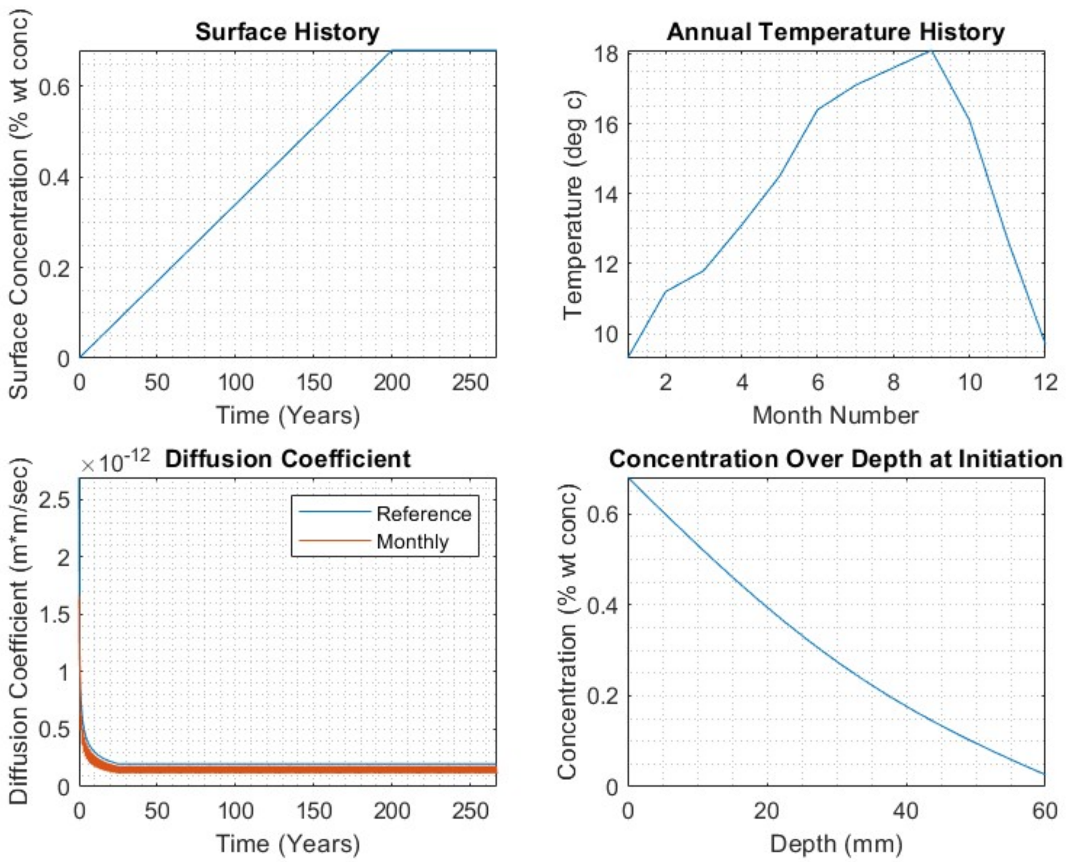
where m is the logarithmic rate diffusion coefficient change, t_i is the time of measurement at instance i, D_{ti} is the measured diffusion coefficient at time t_i. The reference diffusion coefficient, say at 28-day, follows:

$$D_{ref} = D_t \left(\frac{t}{t_{ref}}\right)^m \qquad (19)$$

where D_{ref} and D_t represent diffusion coefficient at desired reference time t_{ref} and available measurement at time t, respectively.

Figure 52 displays a typical series of graphs illustrating numerical simulation procedures for predicting service life based on Fick's second law. The arrangement and design of these graphs adhere to the patterns established by Life-365™.

Figure 52. Solving Service Life Prediction Using Fick's Second Law



Various material properties and climate conditions influence the predicted service life of concrete. Therefore, when comparing the service life of different concrete specimens, it is important to relate them to the service life of a witness sample tested in the same climate. Consequently, the varying trends in predicted service life, based on diffusion coefficients, shown in Figure 53, are affected by the specific locations where these measurements are taken.

Figure 53. Service Life Prediction Using Diffusion Coefficient

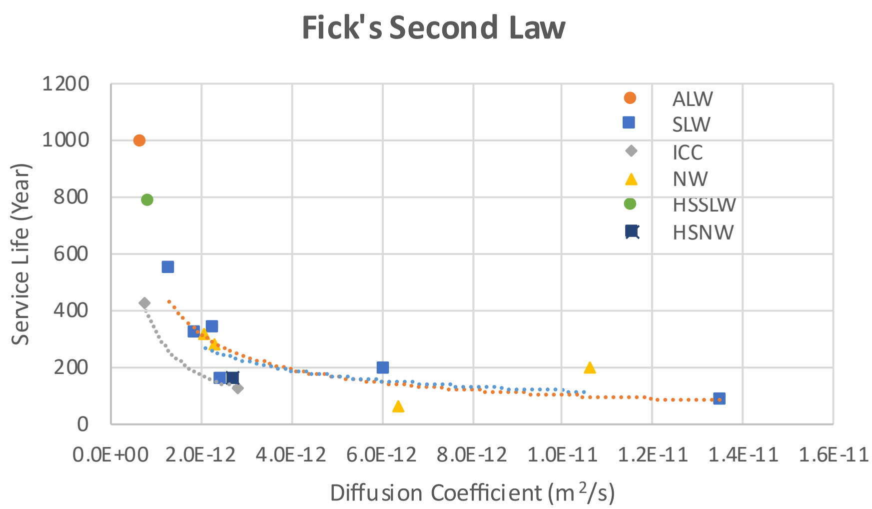
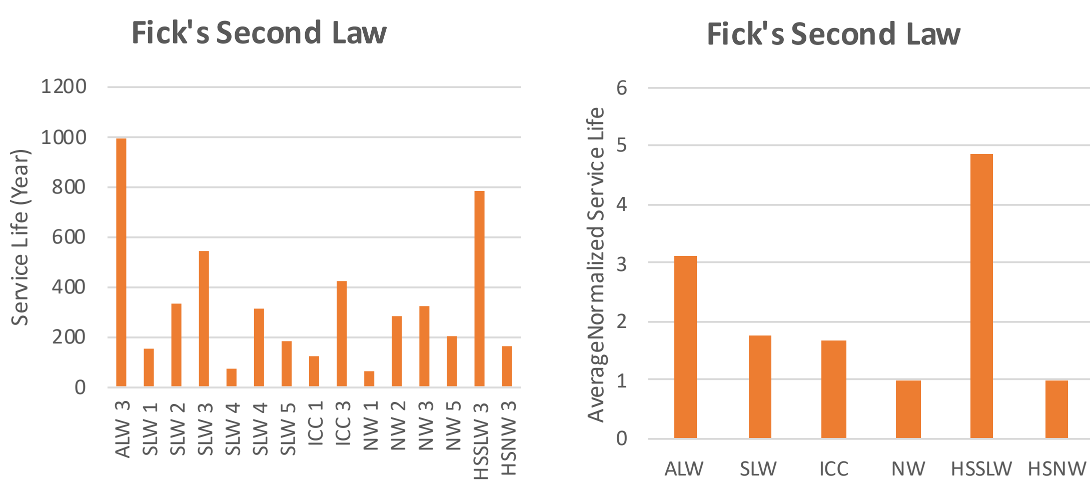


Figure 54 shows the predicted service life of each sample at specific locations, when available, along with the normalized average ratio comparing the predicted service life of concrete containing lightweight aggregates to that of normal-weight concrete. The comparison indicates that lightweight aggregates can extend the service life of normal-weight concrete by 66 to 211 percent for normal-strength concrete and by up to 388 percent for high-strength concrete. The specimens labeled ALW and HSSLW represent individual sampling locations.

Figure 54. Raw Data (Left) and Normalized (Right) Predicted Service Life



Lifecycle Assessment

Lifecycle assessment considers key objective parameters related to economic and environmental impacts, specifically cost and greenhouse gas emissions. Since the predicted service life varies across different scenarios in this study, we use equivalent annual cost (EAC) estimates for comparison. The EAC includes annualized present costs, such as construction expenses, periodic operating costs like maintenance and repairs, and decommissioning costs related to removal and recycling.

$$EAC(i, L) = \frac{[i(1+i)^L]}{[(1+i)^L - 1]}\left\{C + \sum \frac{1}{(1+i)^t} O_t + D\frac{1}{(1+i)^L}\right\} \quad (20)$$

where, C is the cost of construction, O_t is the cost of operation at time t, say maintenance, repair, or retrofit, L is the service life, i is the applicable interest rate, and D is the cost of decommissioning, say removing and discarding. This equation can be simplified to a zero-interest economic environment, which suffices for this comparative study:

$$EAC = (C + \sum O_t + D)\frac{N}{L} \quad (21)$$

where N is the analysis period, say 500 years, or any number more significant than the maximum service life of concrete specimens to allow a meaningful comparison.

When comparing the lifecycle costs of different concrete specimens, it is important to reference the lifecycle cost of a witness sample from the same source. The variations in lifecycle costs as a function of service life are shown in Figure 55 and are attributed to minor differences among sources. For example, the cost relationship between high-strength concrete mixtures differs from that of normal-strength concrete mixtures.

Figure 55. Lifecycle Cost as a Function of Service Life

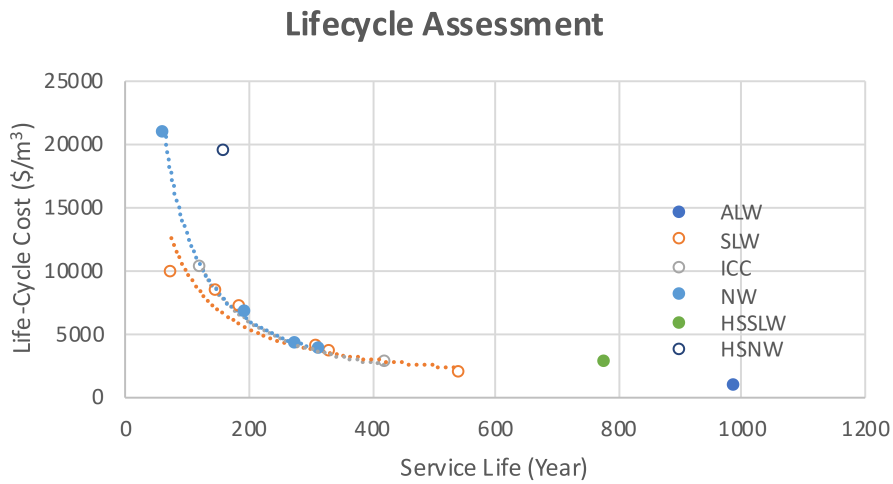
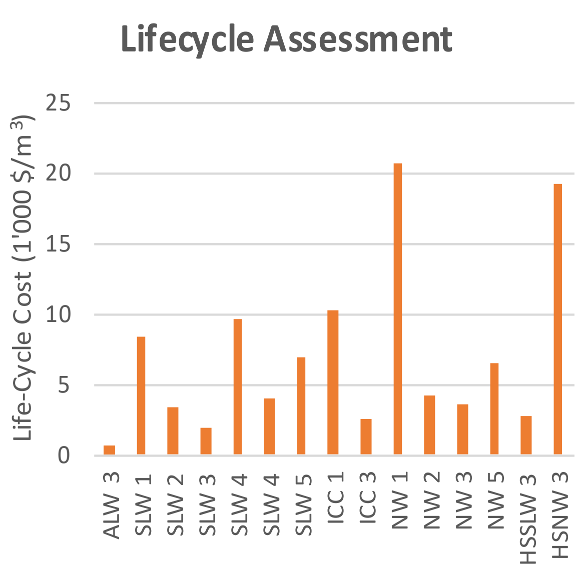
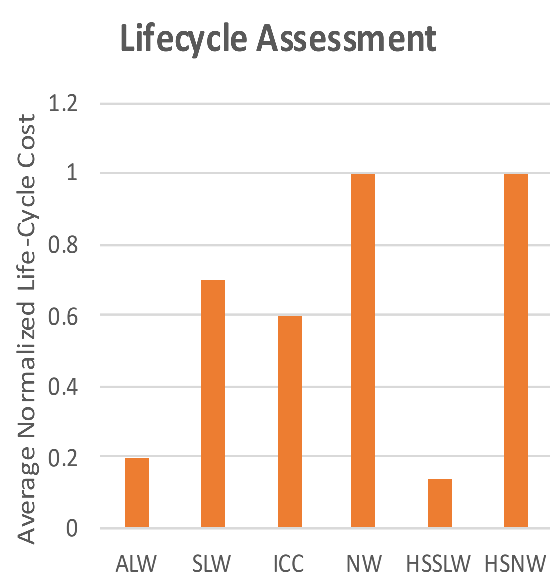


Figure 56 presents the raw data collected on the lifecycle costs of each sample, when available, along with the normalized average ratio of lifecycle costs for concrete containing lightweight aggregates compared to standard normal-weight concrete. This comparison indicates that lightweight aggregates can reduce the lifecycle cost of normal-weight concrete by 30 to 40 percent for SLW and ICC, respectively, and up to 80 and 86 percent for ALW and HSSLW concrete, respectively. It is important to note that the specimens for ALW and HSSLW are sourced from single locations.

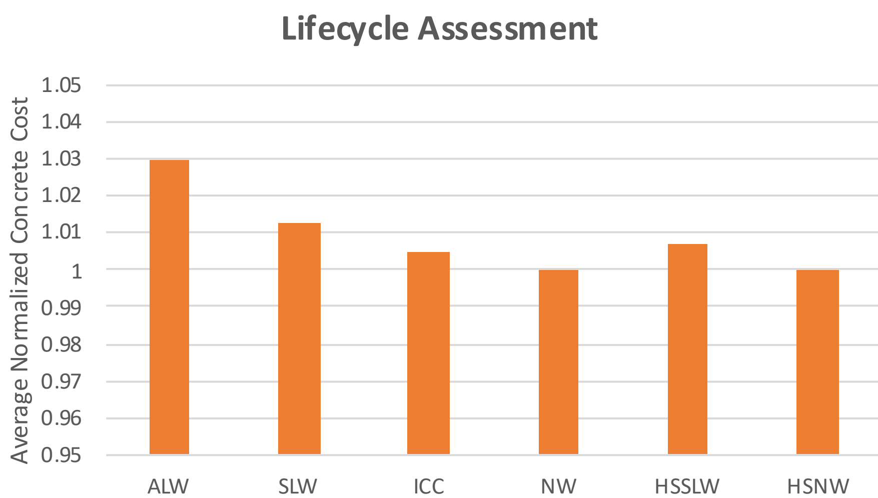
Figure 56. Raw Data (Left) and Normalized (Right) Lifecycle Cost





It is beneficial to examine the initial construction costs for each type of concrete. A comparison of the normalized construction costs in Figure 57 shows that concrete containing lightweight aggregates is generally more expensive than normal-weight concrete. The additional expense of using lightweight aggregates increases the initial material costs by approximately 1 to 3 percent. However, the lower density of lightweight aggregates allows for more concrete volume to be transported at the same cost, which helps offset the increased material costs. Additionally, these estimates should consider the savings in construction time and costs associated with curing, thanks to the internal curing properties of lightweight aggregates.

Figure 57. Concrete Cost



The advantages of lightweight aggregates can also be seen in the environmental impact of concrete materials. Greenhouse gas emissions (GHGs) play a significant role when comparing concrete mixtures. Since concrete materials are major contributors to GHG emissions compared to construction operations, using Environmental Product Declarations (EPDs) for concrete constituents is an acceptable method to assess the lifecycle of GHGs. Manufactured materials, such as cement and lightweight aggregates, generate more GHG during production than raw materials directly sourced from mines, such as sand and gravel. Therefore, it is crucial to normalize GHG emissions to predict service life for any analysis period and to compare GHG emissions accurately. Additionally, it is essential to include a bottom-up estimate based on the actual mixture design of each sample to calculate the overall GHGs as a measure of global warming potential (GWP).

Figure 58 reflects the variation of GWP during the production phase (A1–A3) for each sample and shows the average values for each subgroup. The results demonstrate that GHG emissions depend on the mix design, whether light or normal-weight concrete. Furthermore, high-strength concrete does not necessarily lead to higher GHG emissions if the mixture effectively incorporates supplementary cementitious materials (SCMs) and admixtures instead of merely increasing the cement content.

Figure 58. Greenhouse Gas Emissions Impact of Global Warming Potential

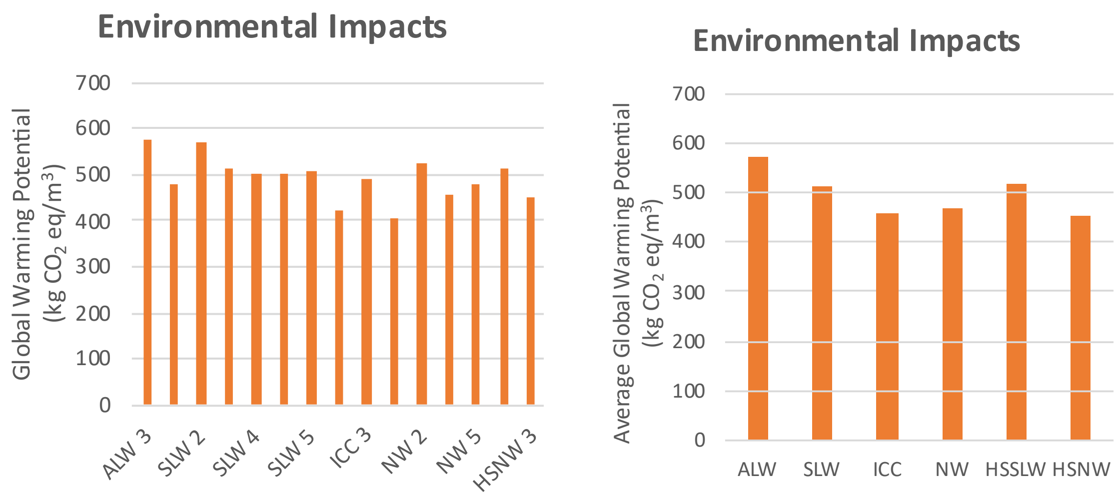


Figure 59 compares normalized greenhouse gas (GHG) emissions from concrete containing lightweight aggregates to those from normal-weight concrete, focusing on both production and lifecycle domains. The production-only analysis indicates that lightweight aggregates increase GHG emissions by 7% to 26%. However, when considering the predicted service life to calculate annual GHG emissions, lightweight aggregates decrease the global warming potential (GWP) of normal-weight concrete by 59%, 20%, and 33% for ALW, SLW, and ICC, respectively. Furthermore, the HSSLW shows a 77% reduction in GHG emissions compared to HSNW concrete.

Figure 59. Normalized Production (Left) and Annualized Lifecycle (Right) Greenhouse Gas Emissions Impact of Global Warming Potential

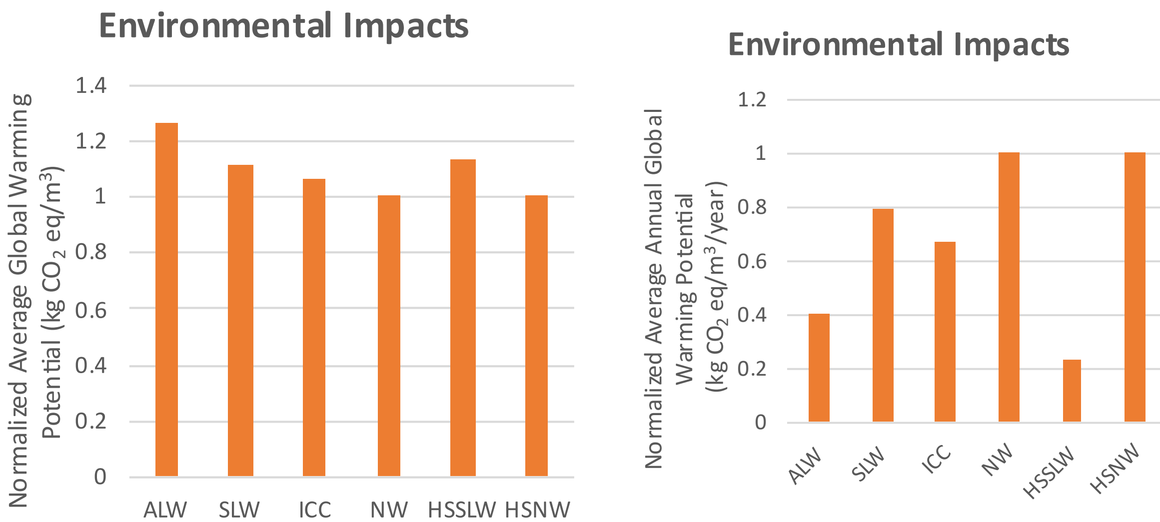
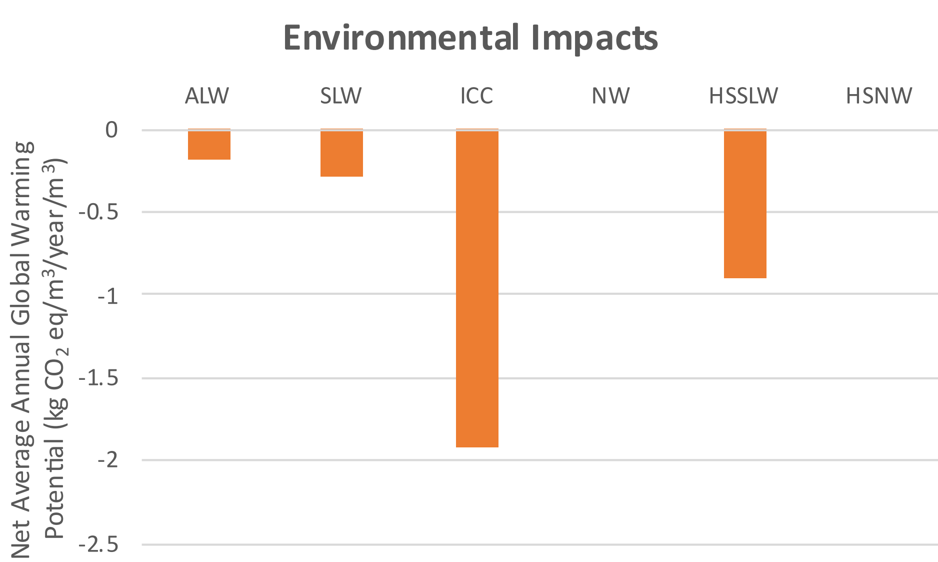


Figure 60 displays the net greenhouse gas (GHG) emissions associated with each unit volume of lightweight aggregates used in concrete mixtures. This comparative measure shows that, despite the relatively small quantities of lightweight aggregate used in internally cured concrete applications, internally cured concrete (ICC) offers the highest return regarding reduced net GHG emissions. Additionally, the lower density of all lightweight or sand-lightweight concrete contributes to decreased self-weight, reducing the overall consumption of structural materials and further lowering GHG emissions.

Figure 60. Net Annualized Lifecycle Greenhouse Gas Emissions Impact of Global Warming Potential



5. Summary & Conclusions

5.1. Summary

This project examined concrete made with lightweight aggregates sourced from expanded shale, clay, and slate from six different plants. The concrete samples were divided into two main groups: normal-strength and high-strength mix designs. The normal-strength group consisted of four subgroups: all lightweight, sand lightweight, internally cured, and normal-weight concrete. The high-strength group included two subgroups: sand lightweight and normal-weight concrete.

The experimental studies focused on the physical, mechanical, and transport properties of the concrete samples. The transport property tests included measuring the water absorption rate, surface and bulk electrical resistivity, and chloride diffusion and migration. Analytical investigations involved predicting the service life of the concrete using Fick's second law and assessing the lifecycle contributions of lightweight aggregates. This assessment encompassed lifecycle costs and greenhouse gas emissions, representing their potential impact on global warming.

Figure 61 displays the effects of lightweight aggregates on reducing unit weight while maintaining compressive and splitting tensile strength in concrete. The outcomes reveal the conservativeness of the existing code-imposed modification factors for concrete containing ESCS.

Figure 61. Contributions of Lightweight Aggregates to the Physical and Mechanical Properties of Concrete

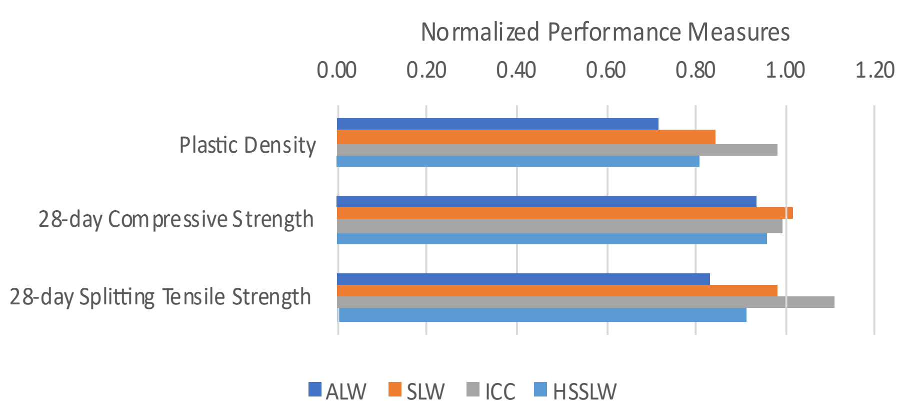
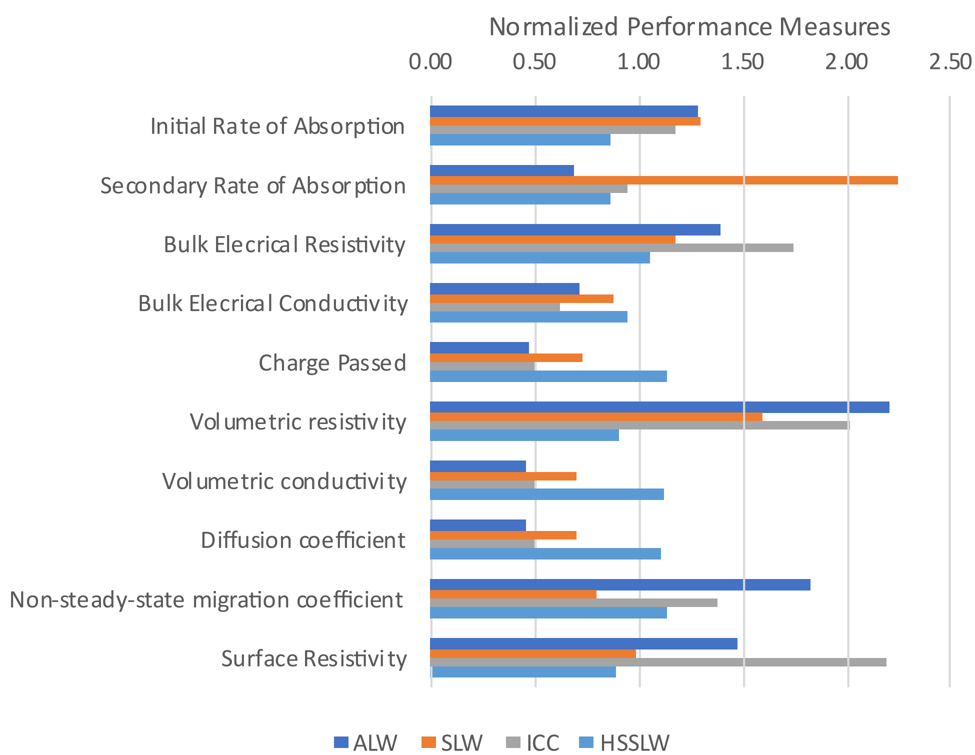


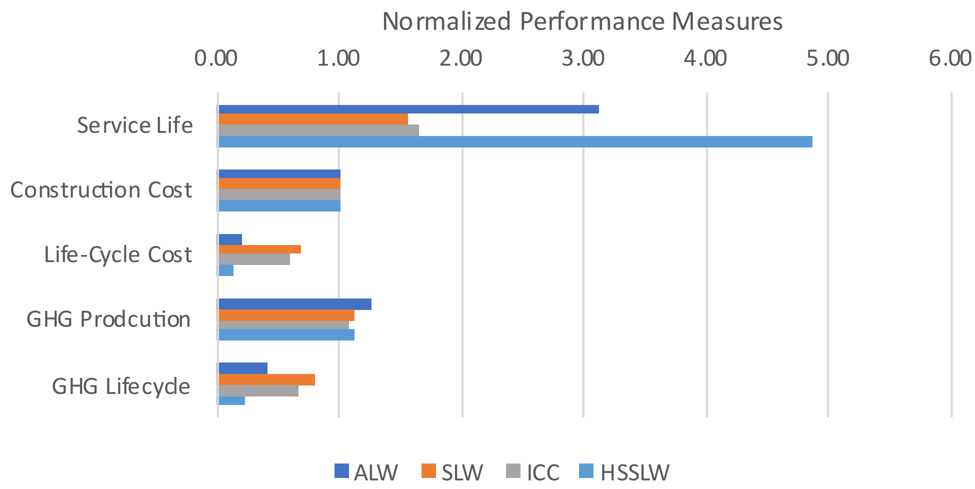
Figure 62 demonstrates how the addition of Expanded Shale Clay Slate (ESCS) improves the electrical resistivity of concrete, even with variations in the water absorption rate, compared to normal-weight concrete. Additionally, lightweight aggregates proved effective in reducing the chloride diffusion coefficient. Comparative analyses indicated that the porosity of the aggregates can affect the non-steady-state chloride migration coefficient. Therefore, it is important to base the diffusion coefficient on the charges passing through the concrete rather than solely measuring the chloride penetration depth within the sample.

Figure 62. Contributions of Lightweight Aggregates to Transport Properties of Concrete



Lightweight aggregates significantly enhance the service life of concrete while also reducing lifecycle costs and greenhouse gas emissions. Figure 63 indicates that the long-term performance of concrete made with lightweight aggregates far outweighs any modest increases in cost or greenhouse gas emissions associated with the production and construction of these materials.

Figure 63. Contributions of Lightweight Aggregates to Lifecycle Measures of Concrete



5.2. Conclusions

The study compares the service life and lifecycle costs of concrete made with lightweight aggregates to that of normal-weight concrete. The raw data indicates that the predicted service life of concrete containing lightweight aggregates can be considerably longer, showing improvements ranging from 66% to 211% for normal-strength concrete and up to 388% for high-strength concrete.

A lifecycle assessment examined economic and environmental impacts, focusing on costs and greenhouse gas emissions (GHGs). To simplify the analysis, the study used equivalent annual cost (EAC) estimates within a zero-interest economic framework to compare concrete scenarios. The findings suggest that lightweight aggregates can significantly lower lifecycle costs—30% to 40% for normal-strength applications and up to 86% for high-strength concrete.

The initial construction costs slightly increased from 1% to 3% due to using lightweight aggregates. However, this increase is balanced by savings from reduced transportation costs and shorter construction times. Moreover, emphasizing greenhouse gas (GHG) emissions revealed that concrete significantly contributes to environmental impacts. The production of lightweight aggregates, such as expanded shale, clay, and slate, can lead to higher GHG emissions than raw materials. Nevertheless, the improved service life of these materials leads to a significant reduction in global warming potentials (GWPs) over the lifecycle of concrete elements.

The findings highlight the benefits of using lightweight aggregates in concrete mixtures. These materials offer an increased service life and lower lifecycle costs, making a strong case for their application in construction. Although there may be a slight rise in initial material costs, the overall savings from improved durability, reduced maintenance expenses, and a decreased environmental impact more than compensate for this increase. Furthermore, careful mixture design is essential for managing greenhouse gas (GHG) emissions, indicating that the environmental advantages of lightweight aggregates can be enhanced through strategic planning.

In summary, using lightweight aggregates improves the durability and cost-effectiveness of concrete while also supporting sustainability goals by reducing lifecycle costs and greenhouse gas (GHG) emissions. This comparative analysis highlights the opportunity to implement lightweight aggregates in transportation projects like pavements and bridges.

Appendix A. Lifecycle Analyses for California

This appendix follows the methodology used in the main body of the report to provide insights into the predicted service life and lifecycle performance measures of concrete that contains lightweight aggregates, as compared to conventional normal-weight concrete.

Figure 64 illustrates the temperature history of San Francisco, a representative city in California with significant transportation infrastructure and a high population, as a challenging climate context.

Figure 64. Temperature History of San Francisco, CA

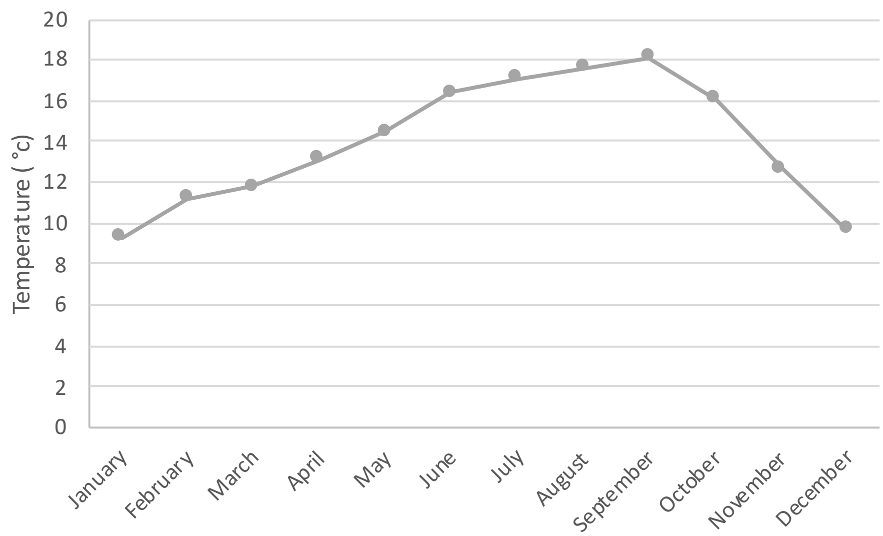
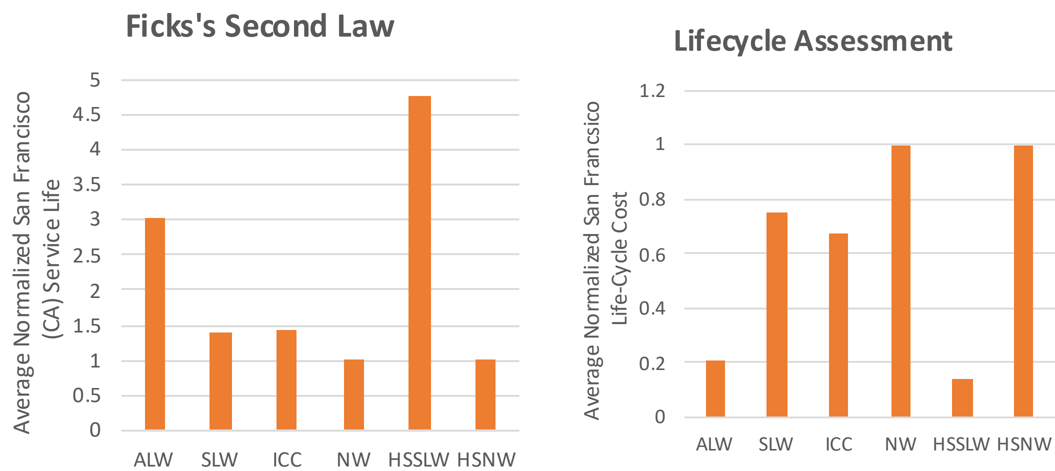


Figure 65 summarizes the results of the normalized average predicted service life for different concrete types. These results closely follow the trends observed in Figures 54 and 56.

Figure 65. Predicted Service Life of Bridge Decks in San Francisco, CA



Similarly, Figure 66 parallels prior results in Figure 59 regarding global warming potentials to show that lightweight aggregates help reduce greenhouse gas emissions in California.

Figure 66. Annualized Lifecycle Greenhouse Gas Emissions Impact of Global Warming Potential in San Francisco, CA

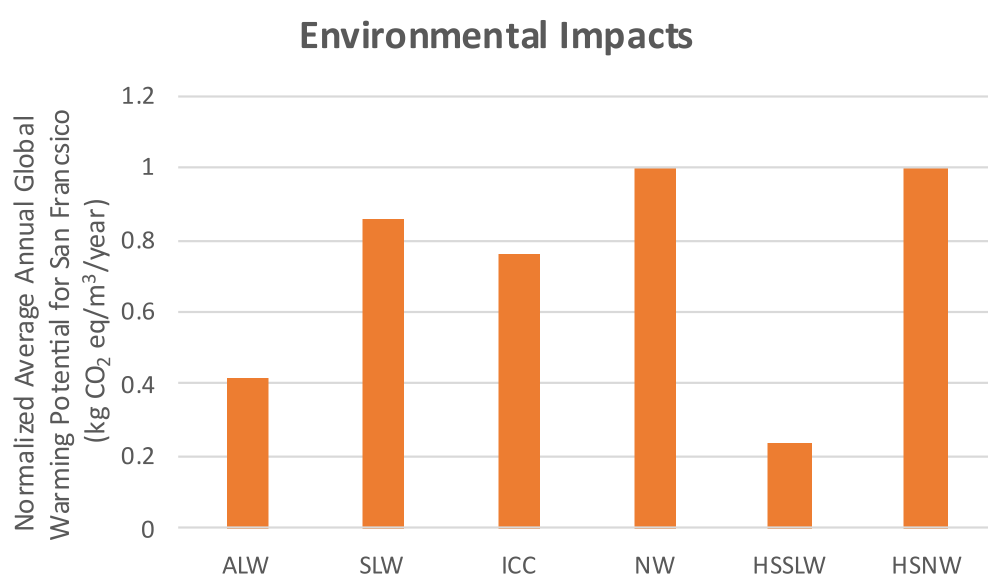
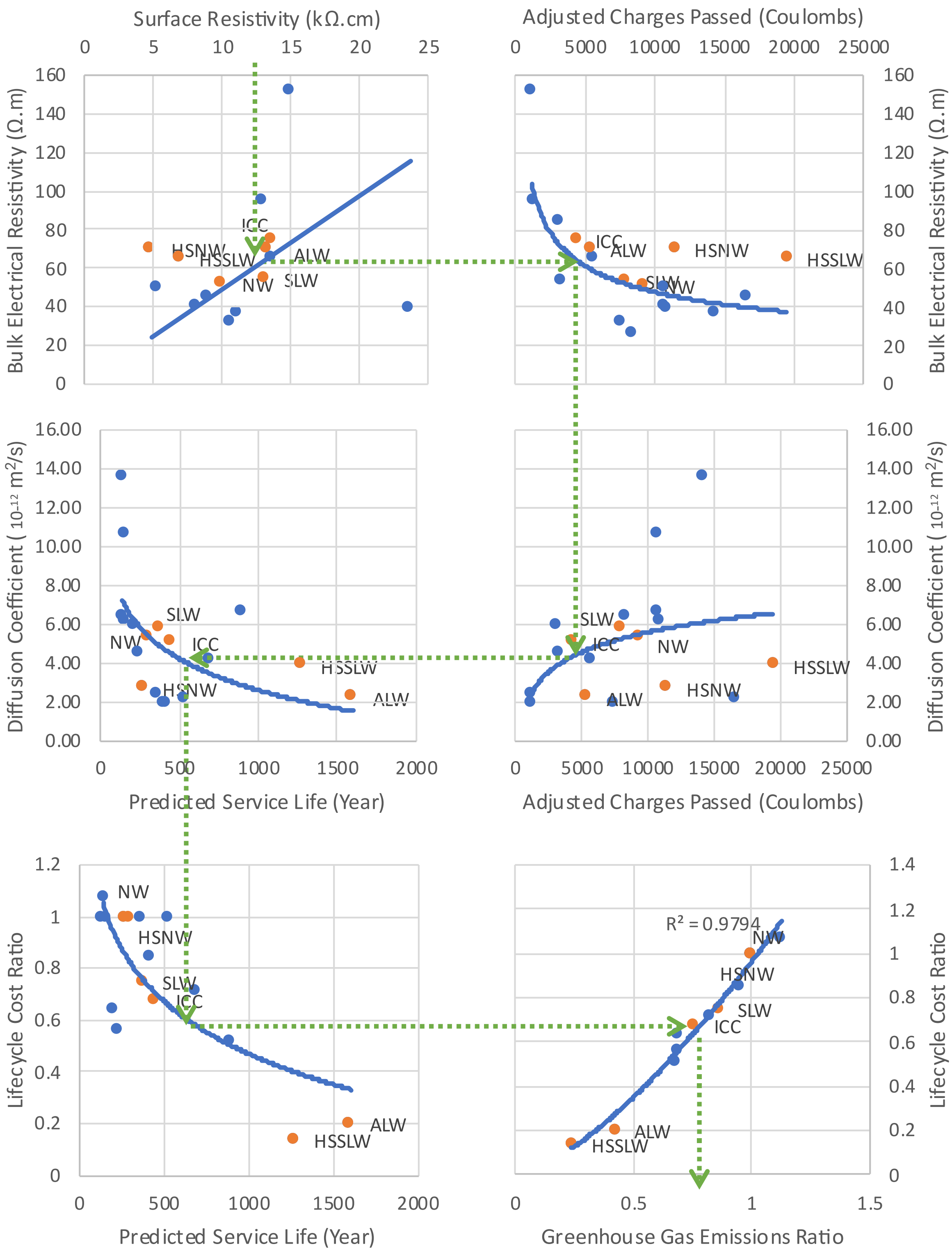


Figure 67 traces transport properties using a typical line through various standards to extend the predicted service life of the concrete and reduce lifecycle cost and greenhouse gas emissions in San Francisco, CA.

Figure 67. The Green Path of Measuring Transport Properties of Concrete Containing ESCS to Reduce Lifecycle Cost and Global Warming Potential in San Francisco, CA



In summary, although there are different climate zones worldwide, especially microclimates in California, using concrete with lightweight aggregates can decrease the greenhouse gas emissions impact related to global warming potential by 14 to 76 percent.

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