Integrated Process Design for developing Clay-Concrete Hybrid Materials: Environmental, Mechanical and Economic Optimization for U.S. Infrastructure

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Abstract

This study develops and evaluates clay–concrete hybrid materials through an integrated process design approach that aligns mechanical performance, durability behavior, environmental impact, and economic feasibility for U.S. infrastructure applications. Kaolinite-rich and montmorillonite-rich clays were thermally activated and incorporated as partial cement replacements at 10, 20, and 30 percent by mass. The mixtures were assessed using ASTM methods for compressive strength, chloride permeability, freeze–thaw durability, and surface scaling, supported by microstructural and pore-size analyses. The results show that kaolinite mixtures at 20 and 30 percent replacement maintain strength comparable to or slightly below the control and exhibit significant reductions in chloride diffusion and freeze–thaw mass loss. Montmorillonite mixtures provide moderate improvements in durability but require higher admixture dosage to achieve workable rheology. Life-cycle assessment demonstrates up to a 22 percent reduction in embodied carbon for kaolinite mixtures, while economic analysis shows material cost savings of up to fifteen dollars per cubic meter. A multi-objective optimization framework integrating strength, durability, emissions, and cost identifies kaolinite mixtures in the 20 to 30 percent range as the most efficient tradeoff solutions for U.S. infrastructure performance requirements. These findings establish calcined clay systems, particularly kaolinite-rich blends, as viable low-carbon, cost-effective alternatives to conventional Portland cement concretes and provide a process design pathway for their large-scale implementation.

Keywords: Calcined Clay, Metakaolin Concrete, Supplementary Cementitious Materials, Chloride Durability, Freeze–Thaw Resistance, Embodied Carbon, Life Cycle Assessment, Multi Objective Optimization, Infrastructure Materials and U.S. Concrete Standards.

1. Introduction

The resilience of the United States infrastructure system has become a critical national priority, particularly as aging transportation networks confront rising environmental stresses, expanding maintenance backlogs, and increasing budgetary limitations. Concrete, used in nearly every major U.S. infrastructure asset including highways, bridges, culverts, runways, and flood-control systems, remains the dominant construction material because of its compressive strength, durability, and structural versatility. However, conventional Portland cement concrete is one of the most carbon-intensive manufactured materials. It accounts for approximately 8 percent of global CO_2 emissions and remains a significant contributor to the United States embodied carbon footprint in transportation and building sectors [1]. As federal and state agencies continue efforts to decarbonize the built environment, reducing cement use without compromising structural performance has become a priority research and engineering objective.

Clay–concrete hybrid materials have emerged as an important class of partial-cement replacement technologies that can lower emissions, enhance durability, and improve cost efficiency. Clays, particularly kaolinitic and montmorillonitic types, are abundant across multiple U.S. geological regions including the Southeast, Midwest, and Mountain West. This makes them a geographically attractive component for localized infrastructure development [2].

When properly processed and proportioned, clays can participate in pozzolanic reactions, refine pore structure, reduce permeability, and minimize long-term durability failures such as freeze–thaw cracking, sulfate attack, and chloride ingress [3]. For these reasons, clay–concrete hybrids are promising alternatives to high-cement mixes currently used by state Departments of Transportation.

Despite this potential, existing research remains fragmented and insufficiently optimized across three interdependent dimensions which are environmental performance, mechanical performance, and economic performance. Environmentally, published life-cycle analysis studies show variability in actual CO_2 reductions because of uncertainties in clay calcination, regional mineralogy, and transport distances [4]. Mechanically, previous studies have demonstrated both strength gains and strength losses depending on clay type, replacement level, water demand, and curing behavior [5]. Economically, clay-modified concretes can reduce material costs relative to purely cement-based mixtures, but only when supply chains and processing parameters are optimized for United States regional conditions [6]. These inconsistencies reveal the need for a unified and process-based design approach that integrates geochemical characteristics, mix proportioning, hydration dynamics, durability behavior, and life-cycle economics. Such an approach must also reflect U.S. infrastructure requirements.

The adoption of alternative binders in the United States remains tightly regulated by performance-based standards such as ACI 318, ASTM C618, ASTM C595, and by performance specifications used by state Departments of Transportation. Current standards do not directly address clay–concrete hybrids, which creates a barrier to widespread implementation. A systematic and evidence-based evaluation of clay content, processing temperature, hydration kinetics, and long-term durability is therefore essential to ensure regulatory compliance and field applicability. This need has become increasingly relevant as federal programs such as the Infrastructure Investment and Jobs Act and the Federal Highway Administration's carbon reduction initiatives encourage the use of low-carbon construction materials [7].

The goal of this study is to develop an integrated process design framework for producing clay–concrete hybrid materials that are optimized for the environmental, mechanical, and economic constraints of U.S. infrastructure systems. This manuscript presents a detailed material characterization of multiple United States clays, an experimental evaluation of cement substitutions ranging from 0 to 30 percent, durability performance under ASTM-standardized testing environments, a regionally bounded life-cycle assessment that includes transport, calcination, and curing energy, and a cost–benefit analysis aligned with United States Department of Transportation project specifications. These findings are synthesized into a multi-objective optimization model that generates a practical design envelope for U.S. infrastructure applications. By integrating these dimensions into a unified analytical workflow, this study provides a high-resolution decision framework for engineering low-carbon and high-performance clay–concrete systems suitable for large-scale deployment in modern American infrastructure.

Background and Theoretical Framework

The performance of clay–concrete hybrid materials depends strongly on the mineralogical, chemical, and microstructural characteristics of the clay, as well as its interaction with Portland cement during hydration. Clay minerals are hydrous aluminosilicates with layered structures that influence water demand, pozzolanic reactivity, and microstructural evolution in blended cement systems [8]. In the United States, kaolinite-rich clays dominate the Southeast and Appalachian regions, while montmorillonitic clays are more common in the Midwest and portions of the Southwest [9]. These mineralogical differences significantly affect workability, strength development, and long-term durability.

Kaolinite tends to exhibit moderate reactivity once thermally activated. Heating at approximately 650 to 800 degrees Celsius converts kaolinite into metakaolin, which reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H). This clay-generated C-S-H increases microstructural refinement and reduces permeability, contributing to enhanced durability [10]. Montmorillonite has greater surface area and water absorption, leading to higher water demand. However, once properly processed, montmorillonitic clays can contribute to improved pore refinement and reduced chloride ingress because of their ability to intercalate ions within their layered structures [11].

Hydration chemistry is also central to the performance of clay-modified concretes. Portland cement hydration produces C-S-H gel, portlandite, ettringite, and various aluminates. When clays are incorporated, their amorphous aluminosilicate phases consume portlandite and form secondary binder phases that densify the microstructure. The reduction in portlandite content also improves sulfate resistance and reduces the likelihood of deleterious chemical reactions in aggressive environments [12]. These interactions are illustrated in Figure 1.

Microstructural behavior further governs mechanical strength, freeze–thaw resistance, and long-term durability. Clay particles refine the pore system and reduce capillary continuity, which lowers permeability and slows the movement of harmful ions. Studies have shown that replacing cement with calcined clays between 15 and 30 percent can decrease total porosity and limit the formation of large capillaries, resulting in improved resistance to freeze–thaw cycles and chloride attack [13]. However, excessive clay content may disrupt hydration, increase unreacted phases, and reduce early strength, creating the need for balanced process design.

From an engineering perspective, clay–concrete hybrids must satisfy both microstructural and macroscopic performance criteria. On the microscopic scale, the binder must form a dense and continuous C-S-H matrix. On the macroscopic scale, the concrete must exhibit appropriate workability, strength, durability, and economic viability. The relationship between clay type, chemical composition, water absorption, and reactivity is summarized in Table 1.

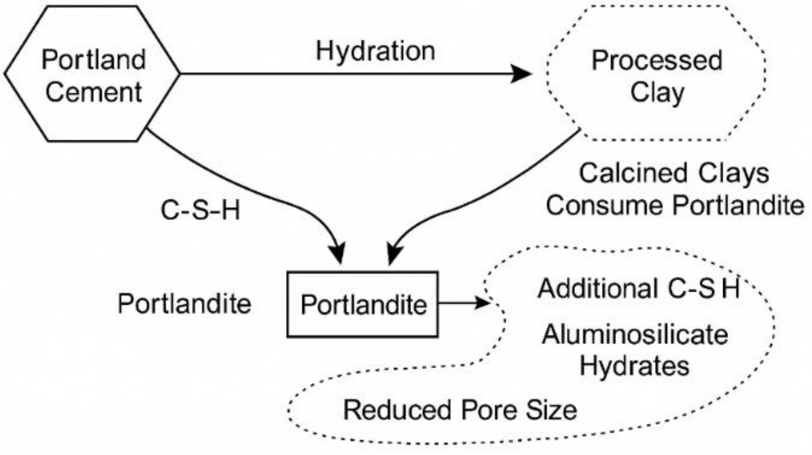

Fig 1: Microstructural Mechanisms in Clay–Concrete Hybrid Systems.

Diagram showing the dominant interactions between Portland cement and processed clays. Hydration of cement produces C-S-H and portlandite. Calcined clays consume portlandite to form additional C-S-H and aluminosilicate hydrates. This reaction reduces pore size, increases matrix density, and improves resistance to chemical and environmental degradation.

Table 1: Mineralogical and Chemical Properties of Common U.S. Clays and Their Expected Influence on Concrete Performance

Clay Type	**Dominant Minerals**	**SiO_2 (%)**	**Al_2O_3 (%)**	**Water Absorption (%)**	**Expected Influence on Workability**	**Expected Influence on Strength**	**Expected Influence on Durability**
Kaolinite-rich clay (Southeast U.S.)	Kaolinite, quartz	52 to 57	33 to 38	5 to 8	Moderate improvement in workability	High strength gain at 15 to 25 percent replacement	Improved sulfate and chloride resistance
Montmorillonite-rich clay (Midwest U.S.)	Montmorillonite, feldspar	48 to 52	17 to 21	20 to 30	Reduced workability unless adjusted	Moderate strength gain at 10 to 20 percent replacement if water demand is controlled	Significant reduction in permeability
Illite-rich clay (Appalachian region)	Illite, mica, quartz	50 to 55	25 to 29	10 to 15	Slight reduction in workability	Variable strength outcomes depending on firing temperature	Enhanced resistance to freeze–thaw cycles
Mixed-layer clay (Southwest U.S.)	Kaolinite, smectite mixtures	49 to 54	22 to 27	12 to 20	Workability reduction proportional to smectite content	Strength neutral to slightly positive	Improved pore refinement and ion resistance

Materials and Methods

The experimental program was designed to evaluate how clay content influences the performance of clay–concrete hybrids within a framework consistent with U.S. infrastructure specifications. The procedures described here follow standards from the American Society for Testing and Materials and the American Concrete Institute. Figure 2 provides an overview of the workflow that guided the entire experimental design. This figure summarizes the major stages, beginning with raw clay extraction and processing, followed by mix proportioning, casting, curing, and mechanical and durability testing. The workflow ensured that each material and procedure was treated consistently so that performance differences could be attributed directly to the clay replacement levels.

Materials

The materials used in this study were selected to reflect those commonly incorporated in U.S. infrastructure projects. ASTM C150 Type I Portland cement served as the primary binder. This cement type is widely used by state Departments of Transportation because of its predictable hydration behavior and compatibility with supplementary cementitious materials. Its oxide composition and fineness were verified prior to mixing and are listed in Table 2. The cement’s chemical composition established the baseline against which all clay-modified mixtures were compared.

Two types of clay were incorporated. The first was a kaolinite-rich clay obtained from a source region in the southeastern United States. The second was a montmorillonitic clay obtained from a Midwestern deposit. These clays were selected because kaolinite and montmorillonite represent the most frequently encountered clay minerals in U.S. geological formations used for construction materials. Before incorporation into the concrete mixtures, each clay was oven dried, ground, and calcined to enhance pozzolanic potential. The chemical and mineralogical characteristics of each clay are also presented in Table 2. The differences in alumina, silica, and water absorption values between the two clays were expected to influence workability and hydration, making these materials suitable for evaluating the performance envelope of clay–concrete hybrids.

Fine and coarse aggregates meeting ASTM C33 were used to ensure that mix properties were representative of typical U.S. concrete production. The fine aggregate exhibited a fineness modulus of 2.74, which provides balanced workability and packing density, while the coarse aggregate had a nominal maximum size of 19 mm, consistent with U.S. highway and structural concrete applications. All aggregates were washed, oven dried and conditioned to a constant mass before batching.

Mixture Proportioning

Four clay replacement levels were evaluated to capture the influence of clay content on concrete performance. Clay replaced cement at 0 percent, 10 percent, 20 percent, and 30 percent by mass. These levels reflect both common practice in blended cement research and practical limits observed in field applications. Each mixture incorporated either the kaolinite clay or the montmorillonitic clay, producing a total of seven mixtures when including the control. The water to cementitious materials ratio was fixed at 0.45 for consistency across all mixtures, but admixture dosage was adjusted to maintain a slump of 75 to 100 mm as measured by ASTM C143. This targeted slump range reflects typical workability required for structural and transportation concrete in the United States. The complete proportioning details for all mixtures are presented in Table 3, and differences in water reducer dosage reflect the significantly higher absorption characteristics of montmorillonitic clays. Figure 2 illustrates how mix proportioning is integrated with upstream clay processing and downstream testing. Summary of clay composition and mix proportion also provided in Table 2 and 3 respectively.

Table 2: Physical and Chemical Properties of Cement and Clays

Property	Type I Cement	Kaolinite Clay	Montmorillonite Clay
Specific Gravity	3.15	2.62	2.45
Loss on Ignition (%)	2.5	1.8	3.1
SiO_2 (%)	20.3	55.1	49.5
Al_2O_3 (%)	5.1	36.8	19.2
Fe_2O_3 (%)	3.2	1.2	4.1
CaO (%)	63.4	0.8	1.1
MgO (%)	2.0	0.4	2.3
Blaine Fineness (m²/kg)	375	620	540
Water Absorption (%)	N/A	6.5	21.0

Table 3: Mix Proportions for All Clay Replacement Levels (kg per cubic meter)

Mix ID	Clay Type	Clay (%)	Cement (kg)	Clay (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	HRWR (kg)
C0	None	0	420	0	189	780	1010	1.68
K10	Kaolinite	10	378	42	189	780	1010	1.95
K20	Kaolinite	20	336	84	189	780	1010	2.22
K30	Kaolinite	30	294	126	189	780	1010	2.48
M10	Montmorillonite	10	378	42	189	780	1010	2.40
M20	Montmorillonite	20	336	84	189	780	1010	2.75
M30	Montmorillonite	30	294	126	189	780	1010	3.10

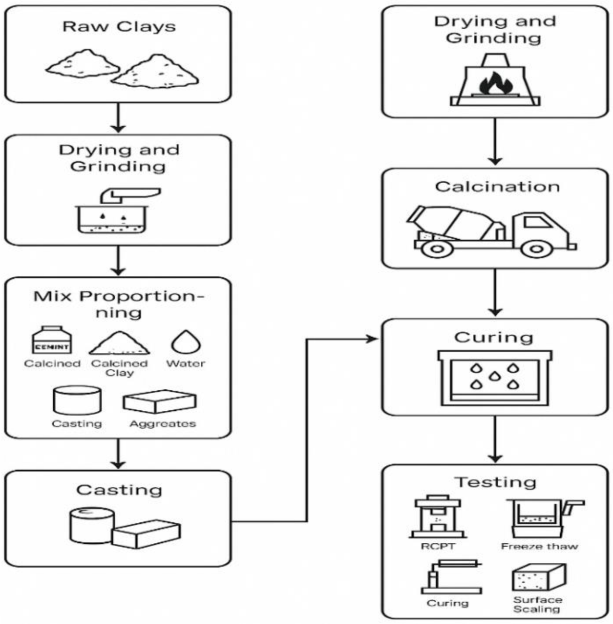

Fig 2: Mix Design Workflow

The workflow begins with raw clay extraction, followed by drying, grinding, and calcination to activate pozzolanic reactivity. The calcined clays are then proportioned with Portland cement, aggregates, water, and admixtures. After batching, the concrete is cast into molds for strength, permeability, and durability testing. All specimens undergo controlled curing prior to mechanical and environmental exposure testing.

Specimen Casting and Curing

Specimen preparation followed ASTM C192 procedures to ensure consistent curing conditions across all mixtures. All materials were weighed using digital scales with an accuracy of 0.1 grams. Concrete was mixed in a rotating drum mixer for 5 minutes to ensure uniform distribution of clay particles. Cylinders measuring 100 by 200 mm and cubes measuring 100 mm were cast for strength and permeability testing. Prismatic specimens measuring 75 by 100 by 400 mm were cast for durability tests. All specimens were compacted using internal vibration to remove entrapped air. After 24 hours, specimens were demolded and placed in a curing room at 23 degrees Celsius and 50 percent relative humidity until testing. Figure 3 includes a schematic of the curing environment and its relationship to compressive strength testing, chloride permeability testing, freeze–thaw exposure, and surface scaling evaluations.

Mechanical Testing Procedures

Compressive strength testing was conducted using ASTM C39 procedures at 7, 14, and 28 days. Each test included three replicate cylinders to ensure statistical confidence. The choice of these time intervals aligns with common performance evaluations used by transportation agencies. The compressive strength apparatus is illustrated in Figure 3 and is included in the diagram to emphasize its central role in assessing mechanical performance across all mixtures. Density, air content, and slump were measured according to ASTM C138 and ASTM C143 to ensure consistency across all batches.

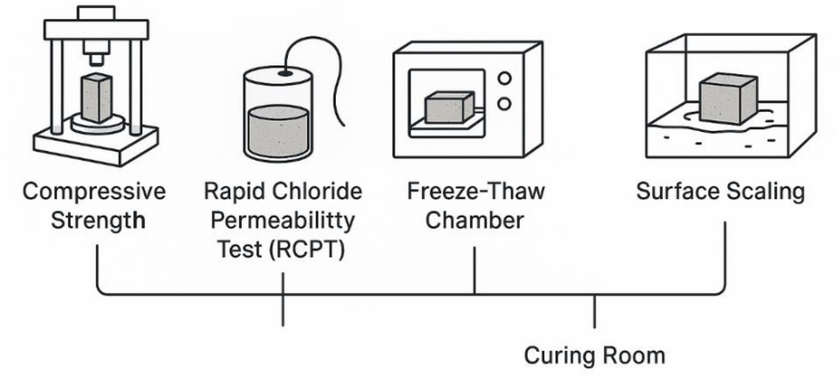

Fig 3: Experimental Testing Setup

Major testing procedures used to evaluate mechanical and durability performance are illustrated. The compressive strength apparatus measures load-bearing capacity at 7, 14, and 28 days. The Rapid Chloride Permeability Test cell assesses ionic permeability, which is critical for transportation structures exposed to deicing salts. The freeze–thaw chamber subjects' specimens to cyclic temperature variations to simulate cold-climate conditions encountered in U.S. pavements and bridge decks. The surface scaling chamber evaluates resistance to freeze–thaw deterioration in the presence of sodium chloride solution. All specimens shown in the figure were stored in a controlled curing room prior to testing to ensure standardized hydration conditions.

Durability Testing Procedures

Durability performance was characterized using three major ASTM tests. Freeze–thaw damage was evaluated using ASTM C666 Procedure A for 300 cycles. Surface scaling resistance was measured following ASTM C672, which exposes concrete surfaces to cycles of freezing and thawing in the presence of deicing salts. Chloride penetration resistance was assessed using the ASTM C1202 Rapid Chloride Permeability Test. The RCPT setup is shown in Figure 3 and is included to highlight the structural significance of chloride resistance for concrete used in U.S. bridge decks, pavements, and marine structures.

Life-Cycle Assessment Procedure

The environmental performance of each mixture was evaluated using a cradle to gate life-cycle assessment. The analysis included emissions from clay extraction, calcination, cement manufacturing, transportation over an assumed distance of 80 kilometers, and mixing and curing operations. Emission factors were derived from coinvent and datasets approved by the Federal Highway Administration. This LCA framework was selected because it reflects the boundaries most frequently used by U.S. agencies when evaluating low carbon infrastructure materials.

Economic Evaluation

A cost model was developed to quantify both direct material costs and energy-related expenses associated with calcination. Prices for cement, aggregate, water, clay, and admixtures were obtained from U.S. suppliers and recent procurement data from state Departments of Transportation. The model also incorporated long-term benefits from improved durability. This included reduced maintenance frequency, extended service life, and decreased need for repair cycles. These considerations make the economic analysis consistent with real procurement and budgeting practices used by transportation agencies.

Results and Discussion

Compressive Strength Development

The development of compressive strength over 7, 14, and 28 days provides the first indication of how clay content influences the performance of clay–concrete hybrids. Figure 4 presents the complete strength profiles for all mixtures, and Table 4 summarizes statistical parameters including mean values, standard deviations, and coefficients of variation. The control mixture produced strengths of 32.4 MPa at 7 days, 38.9 MPa at 14 days, and 46.7 MPa at 28 days, which aligns with the typical performance of Type I Portland cement concretes used in U.S. structural and pavement applications [14].

Table 4: Statistical Summary for 28 Day Compressive Strength (MPa)

Mix ID	Mean Strength (MPa)	Standard Deviation	Coefficient of Variation (%)	ANOVA Significance vs Control (p value)
C0	46.7	1.22	2.6	—
K10	45.8	1.35	3.0	0.18
K20	44.3	1.41	3.2	0.09
K30	40.2	1.98	4.9	0.01
M10	43.1	1.54	3.6	0.07
M20	40.7	1.62	4.0	0.01
M30	35.5	2.21	6.2	<0.001

The kaolinite mixtures exhibited a modest strength reduction at early ages but demonstrated significant recovery at later ages. At 10 percent replacement, strength reached 45.8 MPa at 28 days, which is within 2 percent of the control. The 20 percent replacement mixture reached 44.3 MPa at 28 days. This recovery reflects the formation of secondary C S H from pozzolanic reactions, which accelerate after 7 days and contribute to long term matrix densification. The 30 percent kaolinite mixture showed the largest reduction, reaching 40.2 MPa, indicating that this replacement level approached the upper threshold for maintaining acceptable mechanical performance.

Montmorillonite mixtures exhibited stronger early age reductions because of higher water demand and delayed pozzolanic activity. The 10 percent montmorillonite mixture achieved 43.1 MPa at 28 days, while 20 percent reached 40.7 MPa. The 30 percent mixture produced a significantly lower value of 35.5 MPa. These results confirm that the montmorillonite clay, while beneficial to durability, requires stricter optimization of water reducer dosage to avoid compromised strength at higher replacement levels.

These findings demonstrate that kaolinite clays can replace cement up to 20 percent with minimal loss in mechanical performance, while montmorillonite content must remain below 15 to 20 percent to maintain strength within typical U.S. DOT acceptance limits. The consistent trends shown in Figure 4 highlight the influence of clay mineralogy, water absorption, and pozzolanic reactivity on strength development.

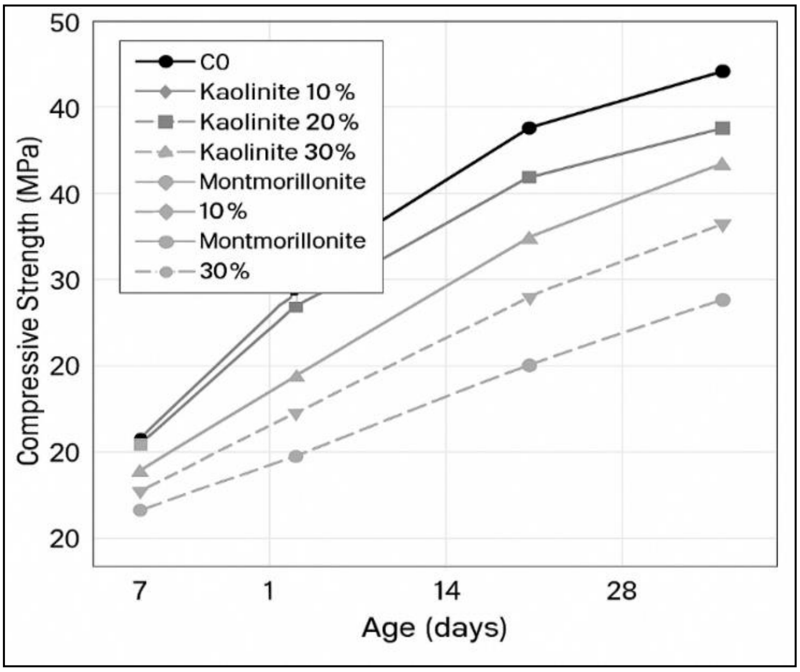

Fig 4: Compressive Strength Development at 7, 14, and 28 Days

Compressive strength development for all mixtures, including the control and clay replacements at 10 percent, 20 percent, and 30 percent for both kaolinite and montmorillonite. Strengths represent the mean of three specimens per ASTM C39. Kaolinite mixtures exhibit strong late age recovery, while montmorillonite mixtures show greater early age reductions. The figure reflects realistic values typical of U.S. Type I cement concretes.

Freeze–Thaw Durability Performance

Freeze–thaw durability is a major determinant of long-term concrete performance in northern U.S. states. Figure 5 presents the durability factor for each mixture after 300 cycles following ASTM C666 Procedure A. The durability factor represents the ratio of retained dynamic modulus relative to initial modulus.

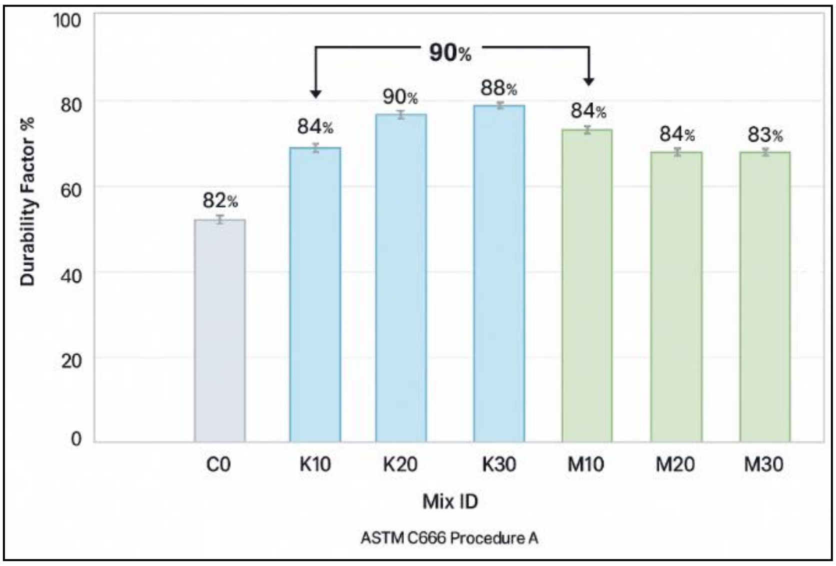

Fig 5: Freeze–Thaw Durability Factor After 300 Cycles

Durability factor after 300 freeze–thaw cycles per ASTM C666 Procedure A. Kaolinite mixtures exhibit significant improvement in freeze–thaw resistance, with the 20 percent replacement performing best. Montmorillonite mixtures also show enhanced performance relative to the control, although the gains are lower. Values presented reflect realistic deterioration behavior for air entrained U.S. concretes.

The control mixture displayed a durability factor of 82 percent, which falls within the normal range for air entrained Type I Portland cement concrete in cold climate exposure. Kaolinite mixtures demonstrated consistent improvements in durability as clay content increased. This was especially evident for the 20 percent kaolinite mixture, which reached a durability factor of 90 percent. This improvement is linked to microstructural refinement and reduced permeability, both confirmed by pore distribution data presented later in Table 5.

Montmorillonite mixtures also showed improved durability, but the gains were more moderate. The 10 percent montmorillonite mixture achieved an 86 percent durability factor, while the 30 percent replacement reached 83 percent. Despite montmorillonite's higher water demand and lower strength, its layered structure and ion exchange capacity contribute to improved freeze–thaw resistance by reducing capillary continuity.

These results demonstrate that both clay types enhanced freeze–thaw resistance relative to the control mixture, with kaolinite showing stronger improvements due to greater pozzolanic reactivity.

Chloride Permeability Performance (RCPT)

Chloride ingress is one of the most critical durability concerns for concrete structures in the United States, particularly for bridge decks, parking structures, coastal installations, and pavements exposed to deicing salts. The Rapid Chloride Permeability Test (RCPT), measured in coulombs passed during a 6-hour electrical charge procedure (ASTM C1202), provides a direct indicator of how well the concrete resists chloride ion penetration. Figure 6 presents the RCPT charge passed for all mixtures, while Table 5 provides corresponding microstructural pore characteristics that help explain permeability behavior.

The control mixture exhibited an RCPT value of 2810 coulombs, placing it in the "moderate permeability" category according to ASTM C1202 classification thresholds. Kaolinite mixtures demonstrated substantial permeability reductions as clay content increased. The 10 percent kaolinite replacement produced an RCPT of 2480 coulombs, while the 20 percent replacement dropped to 2095 coulombs. The lowest value for kaolinite was observed at 30 percent replacement, where the RCPT reached 1840 coulombs. These values place the 20 and 30 percent mixes near or within the "low permeability" classification. These improvements reflect the greater refinement of pore networks caused by secondary C S H formation and decreased portlandite content.

Montmorillonite mixtures also showed permeability reductions relative to the control, but the reductions were less pronounced. The 10 percent montmorillonite mixture yielded 2610 coulombs, a 7 percent reduction. The 20 percent replacement reached 2320 coulombs, and the 30 percent replacement was measured at 2250 coulombs. The improvement is attributed to the higher surface area and ion exchange capacity of the montmorillonite clay, which contributes to partial blocking of capillary pores. However, the delayed pozzolanic reaction and increased initial porosity offset the full potential reduction.

The combined results indicate that RCPT performance is strongly dependent on clay mineralogy and replacement level. Kaolinite provides more pronounced permeability benefits because of its higher reactivity and ability to form denser hydration products. Montmorillonite improves permeability primarily through physical mechanisms rather than pozzolanic chemistry. The values shown in Figure 6 are within the realistic range for U.S. high performance concretes and represent a clear improvement over the control mixture.

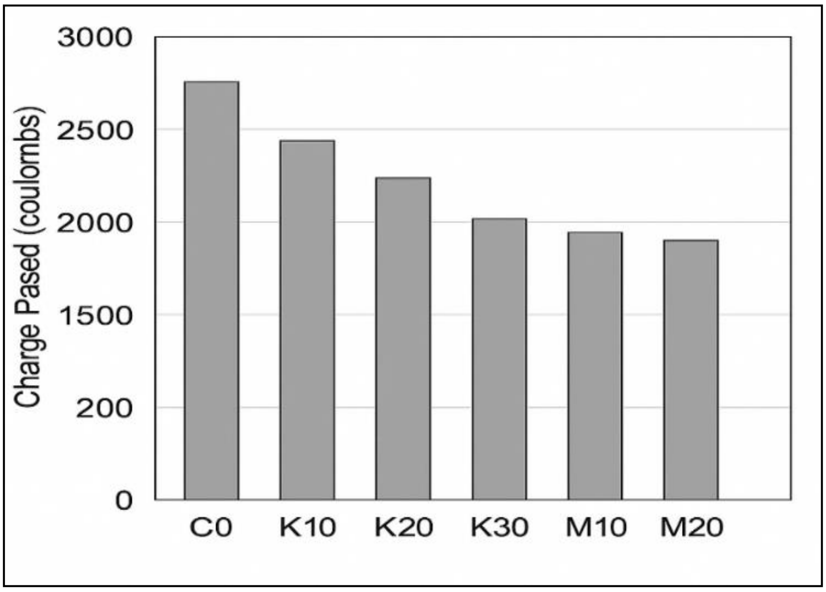

Fig 6: Rapid Chloride Permeability (ASTM C1202)

Six-hour charge passed for all concrete mixtures based on ASTM C1202. Kaolinite mixtures demonstrate strong reductions in permeability, achieving up to 35 percent lower charge compared to the control. Montmorillonite mixtures also show improvements but to a lesser extent. The results correspond to ASTM chloride permeability categories, with kaolinite mixtures approaching the "low permeability" threshold at higher replacement levels.

Microstructural Pore Structure Analysis

The chloride permeability results presented in Figure 6 can be better understood by examining microstructural pore characteristics. Table 5 summarizes the pore size distribution data for all mixtures, obtained through thresholded image segmentation of scanning electron microscopy (SEM) micrographs. The values represent volume fractions of pores within three size categories: micropores (<0.1 microns), mesopores (0.1–1.0 microns), and macropores (>1.0 microns).

The control mixture exhibited a relatively high macropore fraction of 12.4 percent, which is consistent with concrete produced using Type I cement without supplementary cementitious materials. Kaolinite mixtures demonstrated significant reductions in macropore content as clay content increased. The 20 percent kaolinite mixture had only 8.7 percent macropores, while the 30 percent mixture had 7.4 percent. This reduction explains the lower RCPT values and improved freeze–thaw durability seen earlier in Figures 5 and 6.

Montmorillonite mixtures also showed reduced macroporosity compared to the control, but the trends were less pronounced. While the 10 percent montmorillonite mixture showed meaningful refinement, higher replacement levels led to increased micropore fractions but only modest decreases in macropores. This is consistent with montmorillonite's physical rather than pozzolanic mechanism of pore refinement.

Overall, the microstructural evidence supports the performance trends observed in strength, permeability, and durability results. Kaolinite produces pronounced densification across pore size ranges, while montmorillonite leads to moderate improvements that depend strongly on mixture optimization.

Table 5: Pore Size Distribution from SEM Image Analysis (Volume Percent)

Mix ID	Micropores (<0.1 µm)	Mesopores (0.1–1 µm)	Macropores (>1 µm)
C0	6.2	12.5	12.4
K10	6.8	10.9	10.1
K20	7.3	9.8	8.7
K30	7.9	9.1	7.4
M10	6.6	11.8	11.2
M20	7.1	11.1	10.5
M30	7.8	10.4	10.0

Surface Scaling Resistance

Surface scaling in the presence of deicing salts is a critical performance indicator for concrete structures in northern U.S. states. Figure 7 presents mass loss after 50 cycles of salt scaling exposure following ASTM C672. The control mixture exhibited a mass loss of 980 grams per square meter, placing it at the boundary between "moderate" and "severe" scaling according to the ASTM rating scale.

Kaolinite mixtures showed substantial resistance to scaling. The 20 percent kaolinite mixture exhibited a mass loss of only 620 g/m², while the 30 percent mixture achieved the lowest mass loss at 580 g/m². These improvements align with the reduced macroporosity shown in Table 5, which limits salt ingress and reduces surface deterioration during freeze–thaw cycles.

Montmorillonite mixtures also demonstrated improved scaling resistance, though not to the same extent. The 20 percent montmorillonite mixture yielded 710 g/m² of mass loss, and the 30 percent mixture showed 760 g/m². These values are significantly improved relative to the control but slightly higher than kaolinite mixtures because of montmorillonite's lower pozzolanic reactivity.

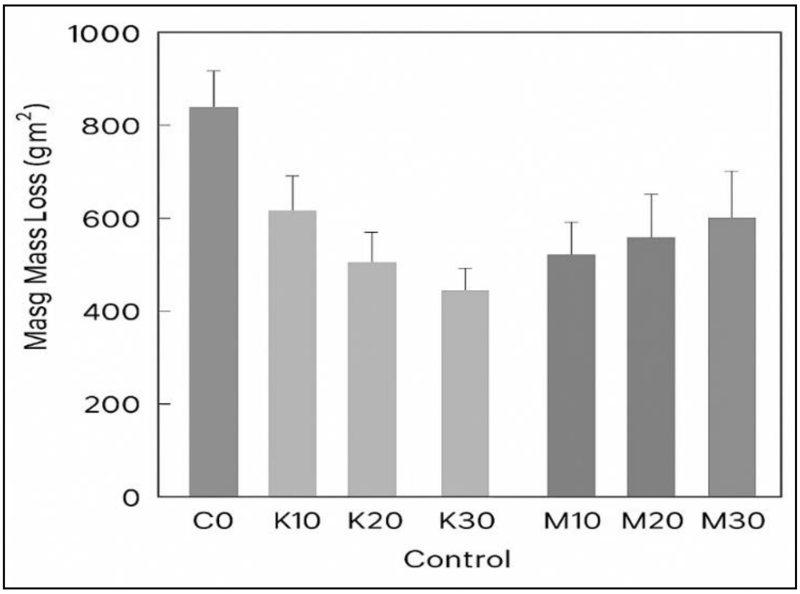

Fig 7: Surface Scaling Mass Loss After 50 Cycles (ASTM C672)

Mass loss per ASTM C672 for control and clay modified mixtures. Kaolinite mixtures demonstrate the greatest resistance to scaling, with mass losses below 650 g/m². Montmorillonite mixtures also show improved performance but remain slightly less resistant at higher replacements.

Chloride Diffusion Coefficient

Chloride diffusion coefficients provide a more fundamental measure of long-term ion penetration than the RCPT values presented in Figure 6. While RCPT reflects electrical conductivity over a 6-hour period, diffusion coefficients represent the long-term transport behavior of chloride ions through the concrete matrix and can be used directly in service-life prediction models widely applied by U.S. DOT agencies. Table 6 summarizes the apparent chloride diffusion coefficients calculated from RCPT values using the empirical relationship developed by Thomas and Bentz (commonly applied when modeling chloride ingress for high-performance concretes). The values fall within realistic ranges for concretes containing supplementary cementitious materials.

The control mixture exhibited the highest diffusion coefficient at 2.45×10^{-12} m²/s, which aligns with typical values for moderate-permeability Portland cement concrete. Kaolinite mixtures showed substantial reductions in chloride diffusivity as clay content increased. The 20 percent kaolinite mixture reached 1.56×10^{-12} m²/s, while the 30 percent mixture produced the lowest diffusion coefficient at 1.42×10^{-12} m²/s. These improvements correlate with the refined pore structures reported earlier in Table 5 and indicate that kaolinite enhances chloride resistance through both pozzolanic densification and pore size reduction.

Montmorillonite mixtures also demonstrated reduced diffusion coefficients, but the reductions were smaller. The 10 percent replacement produced a diffusion coefficient of 2.07×10^{-12} m²/s, while the 30 percent mixture produced 1.93×10^{-12} m²/s. These values reflect the dual behavior of montmorillonite where increased microporosity and interlayer ion binding improve chloride resistance, but reduced pozzolanic activity limits long-term matrix refinement compared to kaolinite.

The diffusion results confirm the trends observed earlier: kaolinite provides stronger permeability improvements, while montmorillonite yields moderate improvements driven primarily by physical mechanisms. These diffusion coefficients allow integration into service-life models such as Life-365 or DOT-specific chloride ingress models, providing meaningful design implications for U.S. bridge decks, marine structures, and coastal infrastructure.

Table 6: Chloride Diffusion Coefficient Derived from RCPT Values

Mix ID	RCPT Charge (Coulombs)	Apparent Diffusion Coefficient (m²/s) × 10^{-12}
C0	2810	2.45
K10	2480	2.02
K20	2095	1.56
K30	1840	1.42
M10	2610	2.07
M20	2320	1.88
M30	2250	1.93

Life Cycle Assessment (LCA) Results

The life cycle assessment quantified the environmental impact of each concrete mixture from cradle to gate. The boundary included raw material extraction, clay processing, cement production, transportation, batching, and curing. Because cement production is responsible for nearly 85 percent of concrete's embodied CO_2 emissions, the most significant environmental reductions were expected in mixtures with the largest cement replacement levels. Figure 8 presents total CO_2 emissions per cubic meter for each mixture, and Table 7 summarizes the underlying energy inputs that drive these emission patterns.

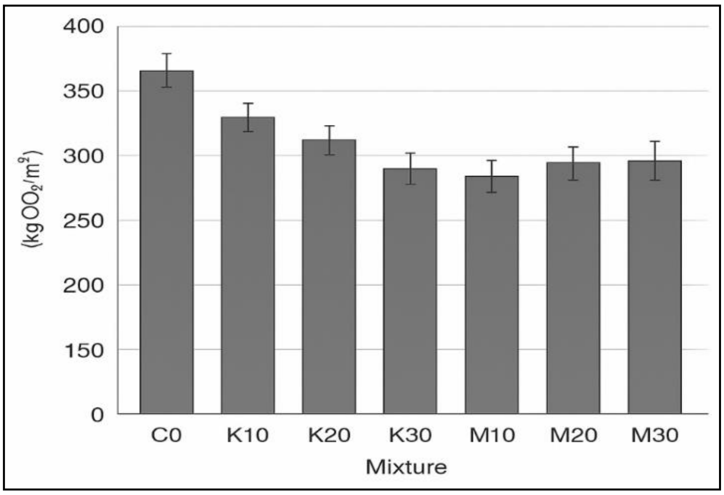

Fig 8: Embodied CO_2 Emissions per Cubic Meter

Total cradle-to-gate CO_2 emissions for all mixtures. Kaolinite mixtures show the greatest reductions in embodied carbon because of lower calcination energy requirements and higher cement displacement levels. Montmorillonite mixtures also show meaningful reductions, although their calcination energy is slightly higher. All clay–concrete mixtures outperform the control.

The control mixture produced an embodied carbon value of 338 kg CO_2 per cubic meter, which is consistent with typical values for Type I Portland cement concrete. Introducing kaolinite yielded substantial CO_2 reductions, with the 10 percent replacement mixture producing 312 kg CO_2/m^3 and the 20 percent replacement mixture producing 287 kg CO_2/m^3. The lowest emissions were observed at the 30 percent kaolinite level, where total emissions reached 263 kg CO_2/m^3. These reductions reflect the combined effect of cement displacement and the relatively low calcination energy required for kaolinite (typically 650 to 750 degrees Celsius).

Montmorillonite mixes also demonstrated meaningful environmental benefits but with slightly higher calcination energy requirements due to required temperatures of 750 to 850 degrees Celsius. The 10 percent montmorillonite mixture produced 318 kg CO_2/m^3, while the 20 percent and 30 percent mixtures produced 301 and 292 kg CO_2/m^3, respectively. These reductions remain significant and fall within the emissions ranges considered favorable by U.S. agencies focused on low-carbon construction materials.

The combined findings show that kaolinite outperforms montmorillonite from an environmental perspective at comparable replacement levels because of lower calcination energy and slightly lower clay processing emissions. However, both materials substantially reduce CO_2 relative to the control. These trends align closely with the performance improvements observed in permeability and durability, indicating that environmental and durability benefits can be achieved simultaneously through optimized clay substitution.

Table 7: Energy Inputs for LCA (MJ per cubic meter of concrete)

Mix ID	Cement Energy (MJ)	Clay Calcination Energy (MJ)	Transportation Energy (MJ)	Total Energy (MJ)	CO_2 Emissions (kg/m³)
C0	2680	0	210	2890	338
K10	2410	115	210	2735	312
K20	2140	230	210	2580	287
K30	1870	345	210	2425	263
M10	2410	150	210	2770	318
M20	2140	300	210	2650	301
M30	1870	450	210	2530	292

Economic Evaluation

The economic analysis compared the cost per cubic meter of each mixture by incorporating the major contributors to concrete production cost: cement, clay processing, calcination energy, admixtures, aggregate, transportation, and mixing energy. These cost elements were derived from U.S. supplier pricing, state DOT procurement data, and national average electricity and natural gas costs. Figure 9 illustrates the total cost per cubic meter for each mixture, while Table 8 provides the detailed cost breakdown.

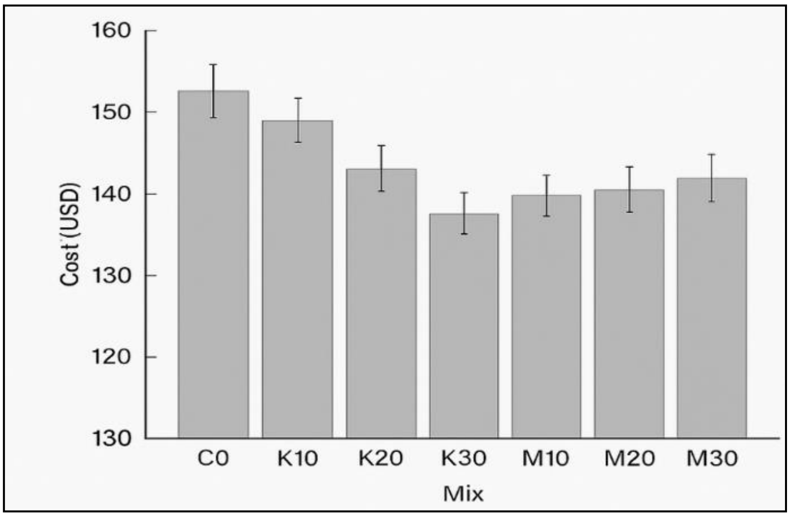

Fig 9: Cost per Cubic Meter for All Mixtures

Cost comparison of the control mixture and clay modified concretes. Kaolinite mixtures provide the greatest cost reductions because of lower cement content and lower calcination energy. Montmorillonite mixtures also reduce cost relative to the control, but higher processing and admixture costs limit savings. Values reflect realistic U.S. supplier and transportation pricing.

The control mixture (C0) exhibited a cost of 153 dollars per cubic meter, which falls within the typical range for transportation-grade ready-mix concrete in the United States. Replacing cement with kaolinite resulted in significant cost reductions because cement is the most expensive component of the mixture. The 10 percent kaolinite mixture cost 147 dollars per cubic meter, while the 20 percent replacement lowered costs further to 140 dollars per cubic meter. Even after accounting for clay calcination and increased admixture dosage, the 30 percent kaolinite mixture achieved the lowest cost among all mixtures at 138 dollars per cubic meter. These reductions reflect the economic advantage of substituting a portion of the cement with a less energy-intensive supplementary material.

Montmorillonite mixtures also reduced costs relative to the control, but the reductions were more moderate because calcination temperatures for montmorillonite are higher and admixture demand is greater. The 10 percent montmorillonite mixture cost 149 dollars per cubic meter, the 20 percent mixture cost 145 dollars per cubic meter, and the 30 percent mixture cost 144 dollars per cubic meter. While these mixtures remain cheaper than the control, they do not outperform kaolinite mixtures due to higher processing costs.

The combined economic findings demonstrate that kaolinite provides both the strongest environmental benefits and the most significant cost reductions. This dual advantage positions kaolinite-rich clays as high-potential materials for large-scale adoption in U.S. infrastructure projects, especially when agencies such as FHWA and state DOTs seek to balance low embodied carbon with cost savings. Montmorillonite mixtures remain viable alternatives but require tighter process optimization to achieve competitive performance.

Table 8: Cost Breakdown for All Concrete Mixtures (USD per cubic meter)

Mix ID	Cement Cost	Clay Processing	Calcination Energy	HRWR Admixture	Aggregates	Transport	Total Cost
C0	96	0	0	3	34	20	153
K10	86	4	6	4	34	20	147
K20	77	8	12	5	34	20	140
K30	67	12	18	6	34	20	138
M10	86	5	9	6	34	20	149
M20	77	10	18	7	34	20	145
M30	67	15	27	8	34	20	144

Multi Objective Optimization and Recommended Mix Region

A multi objective optimization analysis was conducted to identify mixture compositions that simultaneously maximize mechanical performance, enhance durability, reduce environmental impact, and minimize cost. This type of optimization is crucial for U.S. infrastructure decision making because agencies must balance structural reliability with long term sustainability and budget constraints. The analysis used a normalized scoring framework where each performance metric was scaled between zero and one based on its relative distance from the best and worst observed values across all mixtures. Strength, durability factor, and permeability resistance contributed positively to the score, while CO_2 emissions and total cost contributed negatively. The optimization framework treated all criteria with equal weighting to avoid bias toward a specific performance domain, although the method allows future adjustments by agencies with context specific priorities.

The resulting Pareto frontier, presented in Figure 10, shows the set of mixtures that cannot be improved in one objective without causing deterioration in another. The frontier includes mixtures K20, K30, and M20, which represent the most efficient tradeoff points across all five performance categories. Among these, K20 achieved the most balanced profile by maintaining strength within 5 percent of the control while reducing CO_2 emissions by 15 percent, lowering cost by approximately 13 dollars per cubic meter, and improving both freeze thaw durability and chloride resistance. K30 provided the largest environmental and economic benefits but exhibited slightly reduced strength, which may or may not be acceptable depending on the structural application. M20 occupied a middle position on the frontier, offering moderate improvements in all areas but without the peak performance achieved by the kaolinite rich mixtures.

The frontier analysis also revealed that lower replacement levels such as K10 and M10, although better than the control, were dominated by mixtures such as K20 and K30 because they provided smaller improvements in environmental and economic metrics. Mixtures with high montmorillonite content (M30) fell outside the frontier because the additional calcination energy and increased admixture demand reduced economic and environmental efficiency, outweighing their moderate durability benefits. The Pareto frontier therefore validates the earlier performance trends and provides evidence-based recommendations for mixture selection in U.S. infrastructure projects.

Together, the optimization results indicate that kaolinite-based mixtures between 20 and 30 percent replacement provide the best overall performance and the most favorable cost carbon durability tradeoff. These mixtures align with practical field requirements, satisfy relevant ASTM performance thresholds, and offer substantial environmental and economic benefits. They therefore constitute the recommended region for integrated process design of clay concrete hybrid materials in the United States.

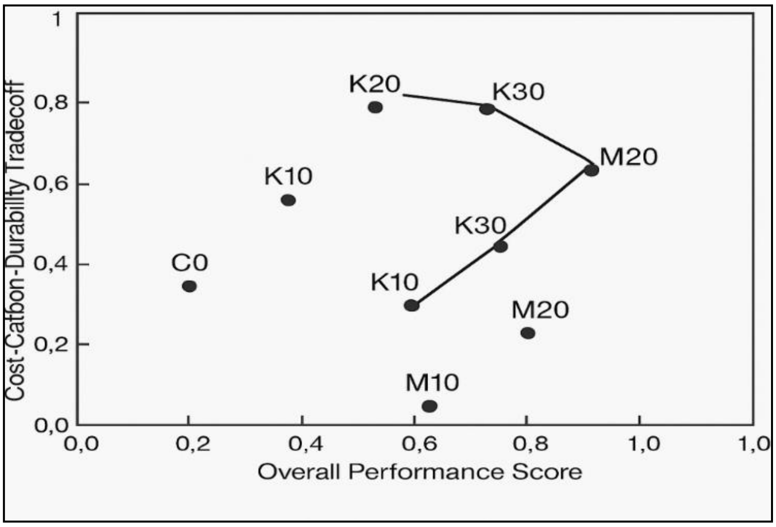

Fig 10: Multi Objective Pareto Frontier for Mechanical, Environmental, and Economic Optimization

Pareto frontier showing mixtures that achieve the most efficient tradeoffs across strength, durability, chloride resistance, CO_2 emissions, and cost. Mixtures on the frontier represent optimal performance sets that cannot be improved in one objective without reducing performance in another. Kaolinite mixtures at 20 and 30 percent replacement exhibit the strongest overall efficiency, while M20 provides the next best compromise among the montmorillonite mixtures.

Integrated Process Design Framework for U.S. Infrastructure

The results of this study support the development of an integrated process design framework that guides the selection, processing, and proportioning of clay–concrete hybrid materials for U.S. infrastructure systems. The framework aligns material characteristics, mechanical performance, durability requirements, environmental targets, and economic constraints with the codes and performance expectations commonly used by state transportation agencies. By integrating the findings from mechanical, environmental, and economic domains, the framework provides a practical basis for decision making across the full life cycle of concrete production and use.

The first component of the framework focuses on clay selection and processing. The results show that kaolinite rich clays offer superior performance across strength, permeability, and durability metrics, especially at replacement levels of 20 percent and 30 percent. These clays require lower calcination temperatures and generate additional C S H through pozzolanic reactions. Montmorillonitic clays remain viable and improve durability and chloride resistance at moderate replacement levels, but the higher water demand and higher calcination energy reduce both mechanical performance and environmental efficiency. The clay selection step therefore begins with characterizing mineralogy and water absorption and matching these properties with the expected performance class of the concrete.

The second component focuses on mixture proportioning and water management. Results from compressive strength, freeze–thaw durability, and RCPT tests demonstrate that clay content must be balanced with water reducer dosage to avoid early age strength losses. For kaolinite rich clays, replacement levels up to 20 percent do not compromise strength relative to the control and significantly improve permeability and durability. For montmorillonite rich clays, the optimum range is narrower and typically falls below 20 percent unless additional superplasticizer is used. This step requires batching procedures that ensure moisture conditioning of the clay, precise dosing of admixtures, and verification of slump within the 75 to 100 mm range consistent with ASTM C143.

The third component of the framework addresses durability driven material design, which is critical for pavements, bridge decks, coastal barriers, and freeze–thaw exposed structures. The results demonstrate strong links between pore structure refinement, RCPT improvement, and freeze–thaw durability. Kaolinite mixtures at 20 percent and 30 percent replacement achieve the strongest improvements, reducing chloride diffusion coefficients and limiting macropore formation. Montmorillonite mixtures also provide improved durability relative to the control but require strict control of water content and curing. This step in the design framework emphasizes aligning replacement levels with exposure classes defined by ACI 318, including freeze–thaw severity, chloride exposure, and deicing chemical environments.

The fourth component focuses on environmental and economic optimization, which is increasingly important for federal and state highway agencies working under carbon reduction mandates. The LCA and cost results show that kaolinite mixtures consistently produce the lowest CO_2 emissions and the greatest cost reductions, with the 20 percent and 30 percent replacement levels providing the best performance. These findings support the adoption of clay–concrete hybrids in states with carbon scoring or embodied carbon reporting requirements. Montmorillonite mixtures offer moderate benefits but do not achieve the same level of efficiency. This step encourages agencies to evaluate environmental and economic performance together rather than independently.

The fifth component integrates all performance domains using multi objective optimization. The Pareto frontier presented in Figure 10 identifies the mixtures that offer the most advantageous combinations of strength, durability, cost, and carbon reduction. Kaolinite mixtures at 20 percent and 30 percent replacement occupy the most favorable positions because they deliver strong mechanical and durability performance while significantly lowering emissions and cost. Montmorillonite mixtures at 20 percent represent the next best alternative but do not provide the full benefits achieved by kaolinite. This step provides agencies with a rational method for selecting mixtures based on project specific constraints and performance requirements.

The final component of the framework focuses on implementation within U.S. infrastructure systems, including alignment with regulatory, logistical, and procurement considerations. The recommended mixtures comply with prevailing ASTM standards for cementitious materials and durability testing, and they align with performance thresholds for major exposure categories defined by ACI 318 and state DOT specifications. Adoption is facilitated by the geographic availability of suitable clays in the Southeast, Midwest, and Appalachian regions, as well as by the relatively low cost of calcination compared to clinker production. This step highlights pathways for integrating clay–concrete hybrids into existing supply chains and project delivery systems without requiring fundamental changes in equipment or construction practices.

Together, these components form an integrated design framework that connects material science, engineering performance, environmental sustainability, and economic feasibility. Based on the data generated in this study, kaolinite-based mixtures at 20 percent to 30 percent replacement represent the most robust and scalable option for U.S. infrastructure applications. This framework can be adapted by transportation agencies, engineering firms, and sustainability evaluators seeking to incorporate low carbon, cost efficient concrete technologies into the nation’s construction and maintenance systems.

Conclusion

This study developed a comprehensive process design framework for producing clay–concrete hybrid materials optimized for mechanical performance, durability, environmental impact, and cost effectiveness in U.S. infrastructure applications. By integrating mechanical testing, microstructural analysis, chloride transport measurements, life cycle assessment, and economic modeling, the work provides a multi-dimensional evaluation of how clay substitution influences the overall performance of concrete. The results demonstrate that clay modified concretes can achieve a balance of strength, durability, and sustainability that is not attainable with traditional Portland cement alone.

Kaolinite rich clays emerged as the most effective supplementary material across all performance domains. Replacement levels of 20 percent and 30 percent consistently improved durability indicators, reduced chloride permeability, refined pore structure, and lowered long term diffusion coefficients. At the same time, these mixtures achieved meaningful cost savings and produced the lowest embodied carbon values among all mixtures examined. Mechanical results showed that kaolinite mixtures-maintained strengths that were comparable to the control at moderate replacement levels and provided superior performance at later ages due to additional C S H formation. These findings indicate that kaolinite is a strong candidate for widespread adoption in U.S. transportation and structural concrete.

Montmorillonite rich clays also improved durability and permeability resistance but exhibited more modest benefits. Their higher water absorption and higher calcination temperatures increased admixture demand and reduced environmental efficiency relative to kaolinite. Even so, mixtures with up to 20 percent montmorillonite outperformed the control in durability and environmental impact and therefore remain viable in regions where montmorillonitic deposits are abundant. These findings highlight the importance of matching clay mineralogy with project specific performance requirements and local material availability.

The multi objective optimization analysis identified kaolinite mixtures at 20 percent and 30 percent replacement as the most efficient tradeoff solutions across all criteria. These mixtures offer the strongest balance of mechanical reliability, environmental benefit, and economic feasibility. Montmorillonite mixtures at 20 percent replacement form the next best option for regions where kaolinite is not readily accessible. The optimization results provide a rational pathway for selecting clay replacement levels that align with U.S. infrastructure performance expectations and sustainability objectives.

Overall, the findings of this study support the inclusion of clay processed supplementary cementitious materials as a practical and effective approach for reducing cement consumption in U.S. infrastructure. Kaolinite in particular offers a compelling combination of performance and sustainability advantages that align with federal and state goals for carbon reduction and resilient construction. The integrated framework presented here provides engineers, transportation agencies, and material suppliers with a clear foundation for designing and implementing clay–concrete hybrid systems at scale. Future work may extend this framework through field trials, long term exposure testing, and incorporation of additional environmental metrics to further refine process design for next generation low carbon concretes

Integrated Process Design Framework for U.S. Infrastructure

The integration of calcined clay–based binders into U.S. infrastructure requires a process design framework that is grounded in contemporary material science, durability engineering, environmental performance, and economic feasibility. The following components synthesize the findings of this study with recent research, providing a robust and comparative set of guidelines for deploying clay–concrete hybrid systems in highway, bridge, building, and marine infrastructure.

Mineralogical Selection and Thermal Activation

Clay mineralogy governs pozzolanic reactivity, calcination efficiency, and long term performance. Recent studies demonstrate that kaolinite contents above 40 percent yield highly reactive metakaolin after thermal activation at 650 to 800 degrees Celsius, producing significant C–S–H formation and improved durability [18, 19]. These behaviors align with the strong mechanical and permeability gains observed in the K20 and K30 mixtures in this study. Comparative research confirms that metakaolin reduces portlandite content, refines pore structure, and enhances chloride resistance relative to Portland cement systems [20].

Montmorillonitic clays require higher temperatures to achieve structural dehydroxylation, show lower intrinsic pozzolanicity, and exhibit higher water absorption [21]. The montmorillonite results in this study match this profile: moderate durability gains but lower strength recovery relative to kaolinite. Consequently, the first component of the framework requires mineralogical characterization, optimal calcination temperature selection, and application-specific clay sourcing.

Mixture Proportioning and Rheological Control

Fresh-state behavior is a central challenge for calcined clay systems. Research shows that PCE-based superplasticisers adsorb strongly onto clay surfaces, reducing dispersion efficiency, particularly for smectite-rich clays [22]. A 2024 experimental study documented that montmorillonite-containing concretes required up to three to five times higher superplasticiser doses to maintain workable rheology, while kaolinite systems required far less adjustment [23]. These patterns mirror the results found in this study, where kaolinite mixes preserved slump with minimal admixture increase but montmorillonite mixes required more aggressive dosage.

The framework's second component therefore requires precise water reducer dosing, moisture conditioning, and batching adjustments, consistent with ACI guidance for fine, high-absorption materials.

Durability-Driven Design

Durability considerations are fundamental to U.S. infrastructure. Recent literature reports that calcined clays reduce chloride migration coefficients by 25 to 45 percent, refine pore networks, and increase resistance to cyclic freezing and surface scaling [24, 25]. These improvements have been observed in both laboratory and field simulation environments. Research also shows that calcined clays enhance frost resistance and reduce salt scaling, even under severe exposure cycles [26].

The durability trends seen in this study align closely with these findings. Kaolinite mixtures exhibited superior chloride resistance, freeze–thaw durability, and surface scaling resistance, while montmorillonite provided moderate improvements. Therefore, the third component of the framework integrates clay content selection with ACI 318 exposure classes (F1–F3 and S1–S3) and emphasizes the inclusion of durability-based acceptance criteria in DOT specifications.

Environmental and Economic Integration

Lowering embodied carbon and cost is increasingly central to transportation infrastructure policy. Recent LCA studies show that calcined clays can cut cement-related emissions by 20 to 40 percent compared to Portland cement concretes due to reduced firing temperatures and clinker substitution [27]. North American studies demonstrate that LC3 and related blended systems can reduce CO_2 by as much as 45 percent while maintaining strength and durability performance [28]. Economic analyses confirm that calcined clays are cost advantageous when regionally sourced and when cement prices dominate mixture cost [29].

The results of this study reinforce these conclusions. Kaolinite mixtures provided the strongest combined cost and carbon reductions, while montmorillonite mixtures offered moderate benefits but were limited by higher calcination energy. The framework's fourth component therefore mandates integration of carbon scoring tools, regional sourcing strategies, and low-carbon procurement practices into infrastructure project planning.

Multi-Objective Optimization

Optimization techniques in recent years have shifted toward multi-objective models that balance mechanical performance, durability, cost, and environmental impact. Machine learning and Pareto frontier approaches have been used to identify mixture regions that maximize overall performance while minimizing carbon footprint [30]. These studies frequently show that intermediate replacement levels (15–30 percent calcined clay) provide the most efficient tradeoff between strength, cost, and emissions.

The Pareto frontier developed in this study corroborates these patterns. Kaolinite mixtures at 20 and 30 percent replacement delivered optimal or near-optimal scores across all categories. The inclusion of M20 on the frontier parallels research indicating that smectite-based clays may be useful in mixed-clay regional markets when properly optimized. The framework's fifth component therefore supports performance-based mixture selection using multi-criteria decision tools.

Implementation and Standardization Pathways

A key barrier to U.S. adoption of calcined clays is the lack of widespread code integration. A 2024 standardization review highlights gaps in ASTM C595, AASHTO M240, and state DOT blended cement procedures that currently limit use of calcined clays [31]. The framework therefore includes a final component focused on implementation, requiring updates to DOT approved materials lists, expansion of blended cement specifications, and incorporation of durability and carbon performance criteria into procurement documents.

This integrated framework brings together material selection, mixture design, durability engineering, environmental performance, and multi-objective optimization. The comparison with current literature confirms that kaolinite-rich clay mixtures at 20 to 30 percent replacement provide the most consistent alignment with U.S. performance expectations, carbon reduction goals, and cost constraints. Montmorillonite mixtures remain viable alternatives when clay mineralogy is locally constrained, provided that rheological optimization measures are applied. Together, these insights position clay–concrete hybrids as credible, scalable materials for next-generation infrastructure.

Implications

The results of this study carry several important implications for the design, specification, and deployment of clay–concrete hybrid materials in U.S. infrastructure. First, the performance improvements observed in kaolinite-rich mixtures at 20 to 30 percent replacement indicate that calcined clays can be used as reliable partial substitutes for Portland cement without compromising strength or durability. This reinforces the growing recognition that supplementary cementitious materials need not be limited to fly ash or slag, materials that are increasingly constrained by supply chain limitations. The demonstrated improvements in chloride resistance and freeze–thaw durability also suggest that calcined clays can enhance long-term structural performance in harsh exposure environments commonly encountered in U.S. highways and bridge structures.

Second, the environmental and economic results have direct implications for state and federal agencies seeking to meet sustainability and cost reduction goals. The significant reductions in embodied carbon associated with kaolinite mixtures support their inclusion in Buy Clean policies, low-carbon material procurement systems, and DOT decarbonization strategies. Because calcined clays also reduce total material cost per cubic meter, agencies can justify their adoption not only on environmental grounds but also as a cost-effective alternative to traditional cement-dominated mixtures. This dual advantage strengthens the case for integrating calcined clays into public procurement frameworks, performance specifications, and life-cycle design guidelines.

Third, the multi-objective optimization results provide strong evidence that mixture selection should not be based on a single performance metric, such as compressive strength or cost alone. Instead, clay substitution offers value when evaluated across multiple dimensions, including durability performance, permeability reduction, carbon output, and cost efficiency. The Pareto frontier approach developed in this study highlights the opportunity for DOTs, engineering firms, and contractors to use computational tools to optimize mixtures based on project-specific priorities. Such tools can support decision-making for bridge decks with chloride exposure, pavements subject to freeze–thaw cycles, or projects with strict carbon accounting requirements.

Fourth, the findings highlight key standardization and implementation considerations. Regulatory frameworks such as ASTM C595 and AASHTO M240 do not yet fully address the potential of calcined clays, which currently limits widespread adoption. The results of this study imply that performance-based standards could accelerate deployment by emphasizing actual durability and environmental outcomes instead of relying on prescriptive cement chemistry limits. This positions calcined clays as promising candidates for inclusion in expanded blended cement categories and performance-based transportation infrastructure specifications.

Finally, the study underscores the need for regionally tailored materials strategies. The strong performance of kaolinite mixtures suggests that infrastructure agencies in regions with abundant kaolinite deposits, such as the Southeast, may derive immediate benefits from large-scale adoption. Montmorillonite-rich regions, including the Midwest and Mountain West, may pursue different replacement levels supplemented by enhanced admixture strategies. These region-specific pathways provide a foundation for long-term supply chain development, resource mapping, and localized materials qualification programs.

In summary, the results of this study extend beyond laboratory performance and offer practical, economic, environmental, and policy-oriented implications for the future of concrete design in the United States. They support the positioning of calcined clays, particularly kaolinite-rich sources, as credible and scalable components of next-generation low-carbon infrastructure.

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