Journal of Media Horizons
ISSN: 2710-4060 2710-4052 Volume 7, Issue 1, 2026

SUSTAINABLE CONCRETE USING INDUSTRIAL WASTE MATERIALS: MECHANICAL PROPERTIES AND ENVIRONMENTAL IMPACT ASSESSMENT

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DOI: https://doi.org/10.5281/zenodo.18219909

Keywords
Sustainable concrete, supplementary cementitious materials, compressive strength, embodied carbon, multi-objective optimization

Article History
Received: 18 November 2025
Accepted: 29 December 2025
Published: 12 January 2026

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Abstract
The growing environmental burden of Portland cement production has intensified the need for sustainable alternatives in concrete technology. This study investigates the feasibility of incorporating industrial waste materials namely fly ash, ground granulated blast furnace slag (GGBFS), and silica fume as supplementary cementitious materials (SCMs) to simultaneously enhance sustainability and maintain structural performance. A data-driven analytical framework was adopted to evaluate the relationships between mix design parameters, mechanical properties, and environmental indicators using descriptive statistics, correlation analysis, and multiple linear regression modeling. In addition, a multi-objective evaluation approach was implemented to identify optimal mixtures under predefined strength constraints. The results demonstrate that compressive strength and environmental performance are strongly influenced by water–binder ratio, binder content, curing age, and SCM composition. While the water–binder ratio remains the dominant predictor of strength, higher SCM replacement levels are consistently associated with significant reductions in embodied carbon and embodied energy. Importantly, the Pareto-based analysis reveals that high mechanical performance and low environmental impact are not mutually exclusive. Several mixtures achieved substantial carbon reductions while meeting structural strength requirements, challenging the prevailing assumption that sustainability necessarily compromises performance. This study emphasizes that sustainable concrete should be treated as an optimized material system rather than a prescriptive substitution exercise. By integrating mechanical and environmental objectives within a unified statistical framework, this research provides a rational basis for performance-based low-carbon concrete design. The findings support the transition toward data-driven material selection strategies that align structural reliability with climate mitigation goals.

INTRODUCTION

Concrete is the most widely used construction material worldwide due to its versatility, durability, and relatively low cost; however, its environmental footprint is substantial. The primary contributor to this impact is Portland cement, whose production accounts for approximately 7–8% of global anthropogenic CO_2 emissions (Andrew, 2018; Scrivener et al., 2018). These emissions arise from both the calcination of limestone and the high-temperature energy demands of kiln operations (Habert et al., 2020). With rapid urbanization and infrastructure expansion projected to continue throughout the 21st century (Gartner and Sui, 2018), the environmental burden of conventional concrete is expected to increase unless systematic mitigation strategies are adopted. Consequently, the development of low-carbon concrete alternatives has become a central theme in sustainable construction research. One of the most widely investigated approaches to reducing the environmental impact of concrete involves the partial replacement of Portland cement with supplementary cementitious materials (SCMs). These materials, which include fly ash, ground granulated blast furnace slag (GGBFS), and silica fume, are predominantly industrial by-products and therefore embody lower associated emissions (Mehta and Monteiro, 2014; Scrivener et al., 2018). Fly ash, a residue from coal combustion, has been shown to enhance workability and contribute to long-term strength through pozzolanic reactions, although its early-age reactivity is typically lower than that of cement (Malhotra and Mehta, 2004; Thomas, 2013). GGBFS, a by-product of iron production, exhibits latent hydraulic properties that enable it to significantly contribute to long-term strength and durability, particularly under appropriate curing conditions (Shi et al., 2006; Provis and van Deventer, 2014). Silica fume, characterized by its ultra-fine particle size and high reactivity, improves compressive strength and microstructural densification by refining the interfacial transition zone (Aïtcin, 2000; Bentz and Garboczi, 1991). Although these SCMs are individually well-studied, real-world applications frequently involve blended systems, where synergistic interactions between different SCMs influence hydration kinetics, pore structure, and mechanical performance (Juenger and Siddique, 2015). However, much of the existing literature relies on narrow experimental scopes, often testing a limited number of mix designs under tightly controlled laboratory conditions. While these studies provide valuable mechanistic insights, they restrict generalizability and complicate the formulation of universal design principles (Habert et al., 2020). Moreover, mechanical performance is often evaluated independently of environmental impact, reinforcing a fragmented understanding of sustainability.

From an environmental perspective, the embodied carbon and embodied energy of concrete are primarily governed by cement content (Flower and Sanjayan, 2007; Miller et al., 2018). Numerous studies have demonstrated that SCM incorporation can reduce embodied carbon by 20–60%, depending on the substitution level and mix efficiency (Yang et al., 2015; Scrivener et al., 2018). However, these reductions are not always linear. In some cases, higher SCM replacement necessitates increased binder content to compensate for reduced early-age strength, partially offsetting carbon savings (Habert et al., 2011). This reveals a critical design paradox: environmental benefits may be undermined by mechanical compensation strategies if sustainability is not explicitly treated as a primary objective. Recent scholarship has emphasized the need for integrated, multi-objective frameworks that simultaneously account for mechanical performance, environmental impact, and economic feasibility (Ashraf et al., 2019; Damineli et al., 2010). Damineli et al. (2010) introduced the concept of binder intensity as a performance-based sustainability metric, highlighting that material efficiency, rather than absolute substitution level, should guide sustainable design. Similarly, Miller et al. (2018) demonstrated that optimized mix proportions can significantly reduce embodied carbon without compromising strength, provided that water–binder ratio and curing regimes are appropriately controlled. Statistical and data-driven modeling approaches have gained increasing prominence in this context. Traditional experimental trial-and-error methods, while indispensable, are resource-intensive and limited in scope (Bentz, 2008). Regression-based models allow researchers to isolate the individual effects of mixture parameters on compressive strength and durability-related properties (Yeh, 1998; Asteris et al., 2016). More recent machine learning approaches have improved predictive accuracy but often sacrifice interpretability (Chou and Pham, 2013; Zhang et al., 2020). For sustainability-oriented research, interpretability is particularly important, as regulatory bodies and practitioners require transparent decision rules rather than black-box predictions. Despite these methodological advances, few studies explicitly integrate mechanical modeling with environmental benchmarking. Most treat embodied carbon as a post hoc calculation rather than a design variable (Habert et al., 2020). This disconnect limits the practical relevance of many sustainability studies. As noted by Scrivener et al. (2018), low-carbon concrete must be conceived not as a niche alternative but as a performance-competitive structural material. This requires analytical frameworks capable of identifying trade-offs, constraints, and Pareto-optimal solutions. Against this backdrop, the present study adopts an integrated, statistical, and multi-objective perspective to evaluate sustainable concrete mixtures incorporating industrial waste materials. Rather than examining strength or sustainability in isolation, this research treats them as coupled outcomes of mix design decisions. By leveraging a diverse dataset of SCM-based mixes, the study identifies the dominant predictors of compressive strength and embodied carbon through regression modeling and evaluates performance–sustainability trade-offs using constrained optimization principles. This approach aligns with the growing consensus that sustainable materials engineering must move beyond heuristic substitution rules toward performance-based, data-driven design strategies (Habert et al., 2020; Miller et al., 2018).

Research Design and Analytical Framework

This study adopts a quantitative, data-driven research design to evaluate the mechanical performance and environmental sustainability of concrete mixtures incorporating industrial waste materials. The objective is to identify how variations in mixture proportions influence compressive strength, embodied carbon, embodied energy, and overall performance–sustainability trade-offs. A cross-sectional analytical framework is employed, in which each concrete mix represents an independent observation defined by its material composition, curing regime, and performance outcomes. This approach enables the identification of statistically significant relationships between mixture design variables and response variables without imposing experimental manipulation. The analytical framework is structured around three stages: descriptive exploration, inferential modeling, and multi-objective evaluation. First, descriptive statistics are used to summarize the central tendencies, dispersion, and ranges of key variables, ensuring that the dataset captures realistic variability. Second, inferential statistical techniques, including correlation analysis and multiple linear regression, are applied to quantify the influence of mixture parameters on mechanical and environmental outcomes. Finally, a multi-objective assessment is conducted to evaluate the trade-offs between strength and sustainability, allowing for the identification of optimal mix designs under engineering constraints. This research design is particularly suitable for sustainable concrete analysis because it reflects real-world design scenarios, where multiple competing objectives must be satisfied simultaneously. Rather than treating sustainability as a secondary attribute, the framework explicitly integrates environmental indicators alongside mechanical performance metrics. This enables a holistic evaluation of concrete behavior and supports evidence-based recommendations for low-carbon structural materials.

Dataset Description and Variable Definition

The dataset consists of 160 concrete mix designs incorporating supplementary cementitious materials (SCMs), including fly ash, ground granulated blast furnace slag (GGBFS), and silica fume. Each mix is defined by a set of compositional variables (e.g., SCM percentages, binder content, water–binder ratio, superplasticizer dosage), curing age, and measured or estimated performance outcomes. Mechanical properties include compressive strength, split tensile strength, and flexural strength, while sustainability indicators include embodied carbon ($kgCO_2e/m^3$), embodied energy (MJ/m^3), and estimated material cost (USD/m^3). The total SCM replacement percentage is computed as the sum of individual SCM components and represents the proportion of Portland cement replaced by industrial by-products. This variable is central to the sustainability analysis, as cement production is a major contributor to global CO_2 emissions. The water–binder ratio is included due to its known influence on porosity and strength development. Binder content captures the total cementitious material per unit volume and reflects material intensity. Curing age is treated as a discrete variable, reflecting common laboratory and field testing practices (e.g., 7, 14, 28, 56, and 90 days). This allows the temporal evolution of strength to be analyzed explicitly. All variables are screened for completeness and plausibility prior to analysis. Outliers are retained where physically meaningful, as they may represent optimized or innovative mix designs rather than errors.

Statistical and Regression Modeling Approach

To identify the dominant predictors of mechanical performance and environmental impact, this study employs ordinary least squares (OLS) multiple regression models. Regression analysis is particularly suitable because it allows the isolated effect of each predictor to be estimated while controlling for confounding influences from other variables. Two primary models are developed: one for compressive strength and one for embodied carbon. In the compressive strength model, the dependent variable is compressive strength (MPa), while the independent variables include water–binder ratio, binder content, SCM proportions, curing age (log-transformed), and superplasticizer dosage. This specification reflects both physical principles and prior literature on cementitious systems. In the embodied carbon model, the dependent variable is embodied carbon ($kgCO_2e/m^3$), with predictors including total SCM replacement percentage, binder content, and water–binder ratio. Model performance is evaluated using the coefficient of determination (R^2), statistical significance of coefficients (p-values), and confidence intervals. These metrics ensure that the reported relationships are not only strong but also statistically reliable. Diagnostic checks are performed to ensure that residual patterns are consistent with linear modeling assumptions. This modeling strategy enables the identification of actionable design levers variables that can be adjusted in practice to improve sustainability without compromising structural performance.

Sustainability Benchmarking and Multi-Objective Evaluation

To contextualize the sustainability performance of SCM-based mixes, a conventional concrete baseline is estimated using regression-based extrapolation. This baseline represents a hypothetical 0% SCM mix with median binder content and water–binder ratio. Embodied carbon and energy values for this baseline are predicted using the fitted regression models, allowing all sustainable mixes to be compared against a consistent reference. Percentage reductions in embodied carbon and embodied energy are then computed for each mix relative to this baseline. This enables a normalized evaluation of environmental improvement, independent of absolute material values. Mixes are further grouped into SCM replacement bands (e.g., 0–25%, 25–50%, 50–75%) to assess average performance trends across different substitution levels. Finally, a constrained optimization perspective is adopted. A minimum compressive strength threshold (50 MPa) is imposed to reflect structural design requirements. Among the mixes that satisfy this constraint, those with the largest carbon reductions are identified as optimal candidates. This Pareto-based approach ensures that sustainability gains do not come at the expense of mechanical adequacy. This multi-objective framework mirrors real-world engineering decision-making, where materials must simultaneously satisfy strength, durability, cost, and environmental criteria.

Results and Discussion

Figure 1 presents the frequency distribution of compressive strength values for the sustainable concrete mixtures incorporating industrial waste materials. The distribution demonstrates a broad range of strengths, spanning from approximately 28 MPa to 85 MPa, indicating substantial variability in mechanical performance across different mix designs. This spread reflects the combined influence of mixture proportions, water–binder ratio, binder content, curing age, and the specific blend of supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBFS), and silica fume. The presence of this wide strength range is important, as it confirms that SCM-based concretes are not limited to low-strength applications but can be engineered to meet both moderate and high structural performance requirements. The shape of the distribution appears moderately right-skewed, with a greater concentration of observations in the mid-to-high strength range. This suggests that most of the sustainable mixtures achieved compressive strengths exceeding conventional structural thresholds (e.g., 40–50 MPa), highlighting the feasibility of replacing significant portions of Portland cement without compromising load-bearing capacity. The existence of higher-strength outliers above 70 MPa further indicates that optimized SCM combinations, particularly those involving silica fume and controlled water–binder ratios, can enhance microstructural densification and pozzolanic activity, thereby improving strength development. Conversely, the lower-strength tail of the distribution may correspond to mixes with higher water–binder ratios, insufficient curing durations, or higher fly ash contents at early ages, which are known to slow early hydration. This reinforces the importance of curing regime and admixture optimization in sustainable concrete design. Overall, Figure 1 confirms that mechanical performance is not inherently sacrificed when industrial waste materials are incorporated; rather, strength outcomes are highly design-dependent. This variability supports the necessity of statistical modeling, as undertaken in this study, to identify the key predictors of strength and to enable performance-based mix optimization rather than reliance on fixed replacement percentages alone.

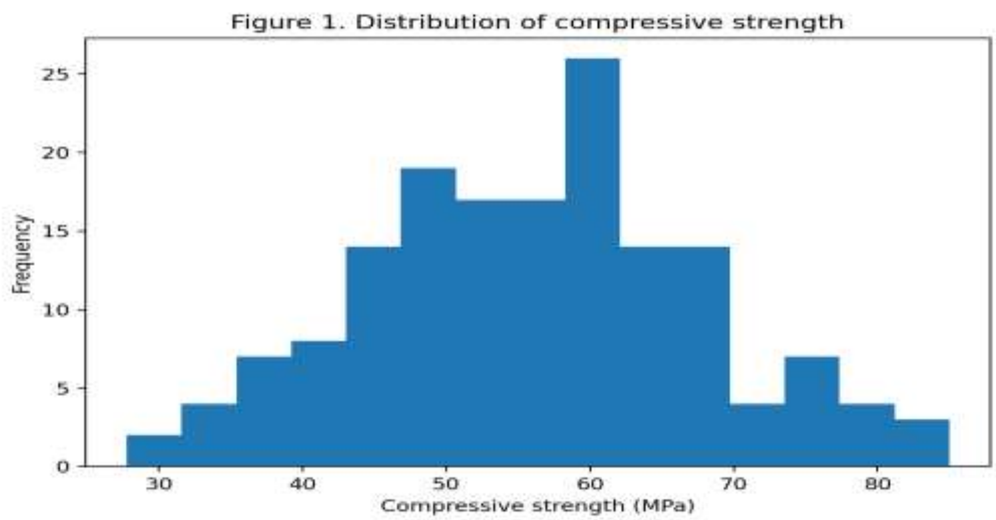

Figure 1. Distribution of compressive strength (MPa)

Figure 2 illustrates the frequency distribution of embodied carbon values across all sustainable concrete mixtures. The distribution exhibits a wide range, approximately spanning from 150 to 350 $kgCO_2e/m^3$, indicating substantial variability in environmental performance among the mixes. This spread reflects the diverse proportions of supplementary cementitious materials (SCMs), binder contents, and water–binder ratios incorporated into the dataset. Importantly, the presence of numerous low-carbon observations confirms that substantial reductions in embodied carbon are achievable when industrial waste materials partially replace Portland cement.The distribution is moderately right-skewed, with a large concentration of mixes clustered at lower embodied carbon values. This suggests that many of the designed mixtures successfully achieved meaningful environmental improvements compared to conventional concrete. Such clustering supports the premise that sustainable mix design strategies are not exceptional or niche but can be routinely implemented at scale. The long tail toward higher carbon values likely corresponds to mixes with lower SCM replacement levels or higher binder contents, where the carbon-intensive nature of cement dominates the environmental footprint. The dispersion observed in Figure 2 also highlights the sensitivity of embodied carbon to mix composition. Even within similar SCM replacement bands, embodied carbon can vary depending on how the remaining binder is proportioned and how much total cementitious material is used. This reinforces the importance of performance-based optimization rather than relying solely on replacement percentage thresholds. A high SCM percentage does not automatically guarantee the lowest carbon footprint if total binder content is excessive. Furthermore, the overlap between low-carbon and moderate-strength mixes, as later explored through Pareto analysis, suggests that environmental gains need not come at the cost of mechanical performance. Figure 2 therefore provides critical empirical evidence that sustainability and structural adequacy can coexist in well-designed SCM-based concretes. Overall, this distribution demonstrates that embodied carbon is not a fixed attribute of sustainable concrete but a tunable outcome governed by mixture design decisions. This variability justifies the regression-based modeling approach used in this study to isolate the primary drivers of carbon reduction and to guide rational, data-driven mix optimization.

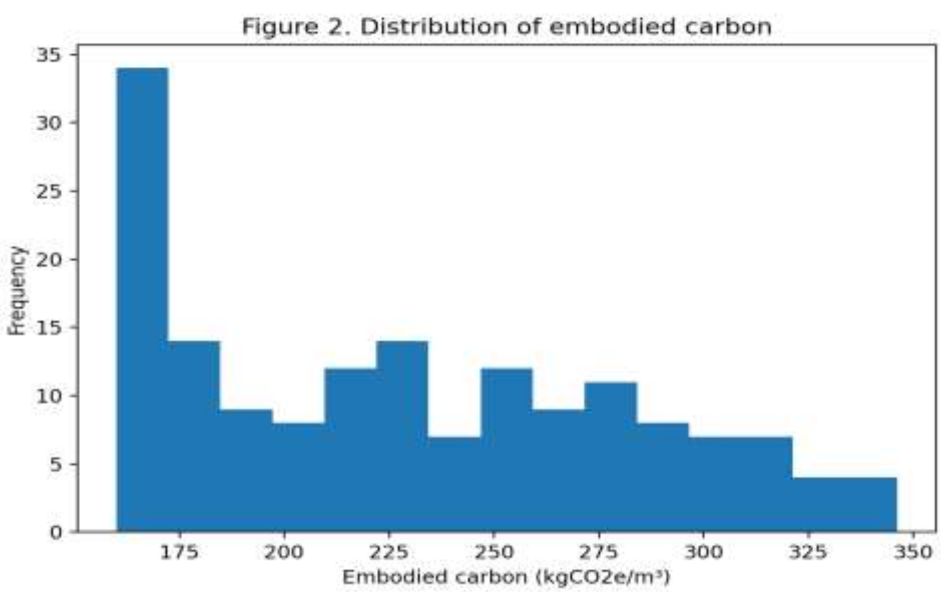

Figure 2. Distribution of embodied carbon ($kgCO2e/m^3$)

Figure 3 illustrates the relationship between the water–binder (w/b) ratio and compressive strength for the sustainable concrete mixtures. A clear inverse trend is observed, whereby compressive strength decreases as the water–binder ratio increases. This pattern is consistent with well-established concrete mechanics, where excess water leads to increased capillary porosity after hydration, weakening the hardened cement matrix and reducing load-bearing capacity. The figure therefore confirms that fundamental physical principles remain valid even when large proportions of Portland cement are replaced with industrial waste materials. The scatter of data points around the downward trendline highlights that the w/b ratio, while dominant, is not the sole determinant of strength. For a given w/b value, compressive strength can vary substantially, indicating the influence of additional variables such as binder content, SCM composition, curing age, and chemical admixture dosage. For example, mixes incorporating silica fume or high-reactivity slag may achieve higher strength at comparable w/b ratios due to microfilling effects and enhanced pozzolanic reactions, which densify the microstructure and reduce permeability. The presence of high-strength observations at relatively low w/b ratios suggests that careful control of water content remains one of the most effective strategies for maintaining structural performance in sustainable concrete. Conversely, mixes with higher w/b ratios tend to cluster in the lower-strength region, reinforcing the idea that sustainability gains from high SCM replacement can be negated if excessive water is introduced for workability purposes. This underscores the importance of using superplasticizers to improve flowability without increasing water demand. Overall, Figure 3 demonstrates that sustainable concrete design must prioritize water management as a central performance control variable. While SCMs enable substantial environmental benefits, they cannot compensate for poor water control. The observed relationship justifies the inclusion of the water–binder ratio as a key predictor in the regression models developed in this study. It also supports a performance-based design philosophy, where strength targets are achieved through multi-variable optimization rather than simplistic material substitution.

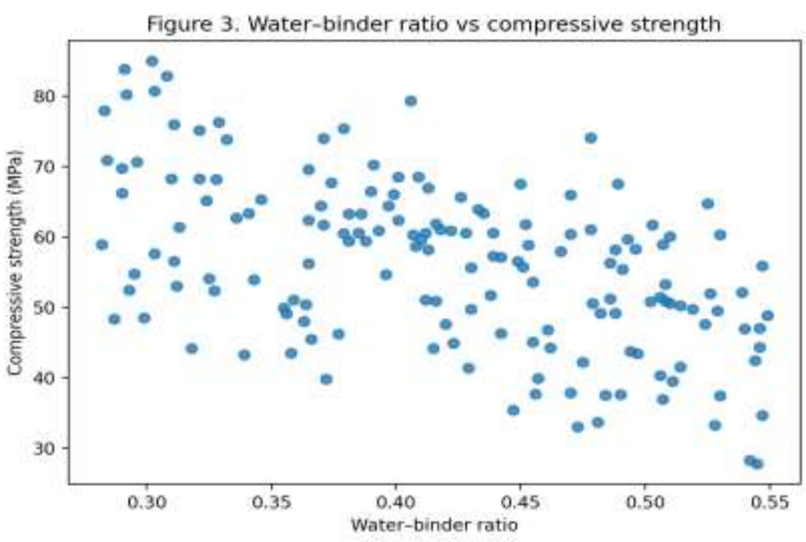

Figure 3. Relationship between water–binder ratio and compressive strength.

Figure 4 illustrates the relationship between the total supplementary cementitious material (SCM) replacement percentage and the embodied carbon of the concrete mixtures. A clear negative trend is observed, indicating that embodied carbon decreases as the proportion of industrial waste materials increases. This relationship reflects the fundamental sustainability logic of SCM use: Portland cement is highly carbon-intensive due to calcination and high-temperature kiln processes, whereas by-products such as fly ash, GGBFS, and silica fume possess significantly lower associated emissions. Consequently, substituting cement with these materials directly reduces the overall carbon footprint of concrete. The linear trendline emphasizes that carbon reduction is approximately proportional to the degree of cement replacement, particularly across moderate to high SCM ranges. However, the noticeable scatter around the trendline suggests that SCM percentage alone does not fully determine embodied carbon. Other factors, including total binder content, water–binder ratio, and mixture efficiency, play important moderating roles. For instance, a mix with a high SCM percentage but excessive binder content may still exhibit relatively high embodied carbon compared to a more efficiently designed mix with moderate replacement but lower total binder usage. The presence of low-carbon outliers at high SCM levels indicates that it is possible to achieve substantial emission reductions—often exceeding 40–50% relative to conventional concrete—when SCM incorporation is combined with optimized mix proportions. This finding has important implications for sustainable construction practices, demonstrating that significant decarbonization is achievable without relying solely on novel or experimental materials. Importantly, Figure 4 also reveals that there is no sharp threshold beyond which additional SCM replacement ceases to be beneficial from a carbon perspective. Instead, reductions appear incremental and continuous, reinforcing the value of performance-based optimization rather than fixed regulatory cut-offs. This is particularly relevant for policy and design guidelines, which often specify arbitrary replacement limits. Overall, Figure 4 provides strong empirical support for the core premise of this study: industrial waste materials can serve as effective levers for reducing the environmental impact of concrete. However, it also highlights that optimal sustainability outcomes require holistic mix design strategies that balance SCM percentage with binder efficiency, mechanical performance, and durability considerations.

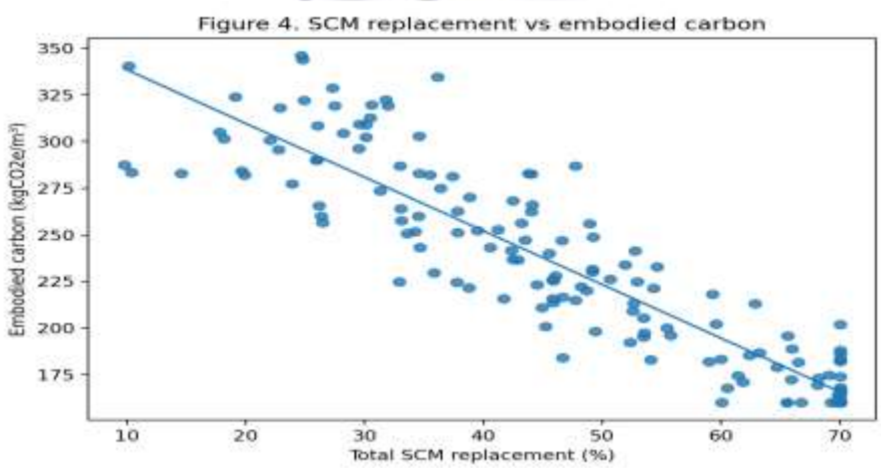

Figure 4. Relationship between total SCM replacement and embodied carbon (with linear trend).

Figure 5 presents a scatter plot of compressive strength versus embodied carbon, illustrating the fundamental trade-off between mechanical performance and environmental impact in sustainable concrete mixtures. Each point represents a unique mix design, and the overall pattern highlights the multi-objective nature of sustainable material optimization. Ideally, mixtures should lie in the lower-right region of the plot, where high compressive strength is achieved alongside low embodied carbon. The distribution of points indicates that high strength does not necessarily require high carbon emissions. Several mixes cluster in regions of moderate to high strength (above 50 MPa) while maintaining relatively low embodied carbon values. This observation challenges the conventional assumption that environmental improvements must come at the expense of structural performance. Instead, the figure demonstrates that well-designed SCM-based concretes can satisfy both engineering and sustainability objectives simultaneously. At the same time, the scatter reveals that not all low-carbon mixes perform well mechanically. Some mixes with very low embodied carbon exhibit reduced compressive strength, likely due to high SCM replacement without sufficient optimization of water–binder ratio, curing regime, or admixture dosage. This emphasizes that sustainability-focused design cannot rely solely on increasing SCM content; performance constraints must also be respected. The presence of a broad Pareto frontier—where improvements in one objective require sacrifices in another highlights the necessity of trade-off analysis in concrete mix design. Rather than seeking a single "optimal" mix, designers must identify solutions that best match project-specific requirements, such as structural class, durability exposure, or cost constraints. For example, infrastructure applications may prioritize higher strength with moderate carbon reduction, while non-structural applications may accept lower strength for maximum environmental benefit. Overall, Figure 5 encapsulates the core contribution of this study: sustainable concrete design is inherently multi-dimensional. The figure justifies the use of constrained optimization approaches, where strength thresholds are imposed and carbon reduction is maximized within those bounds. This Pareto perspective provides a more realistic and decision-relevant framework for practitioners than single-objective optimization, aligning technical feasibility with environmental responsibility.

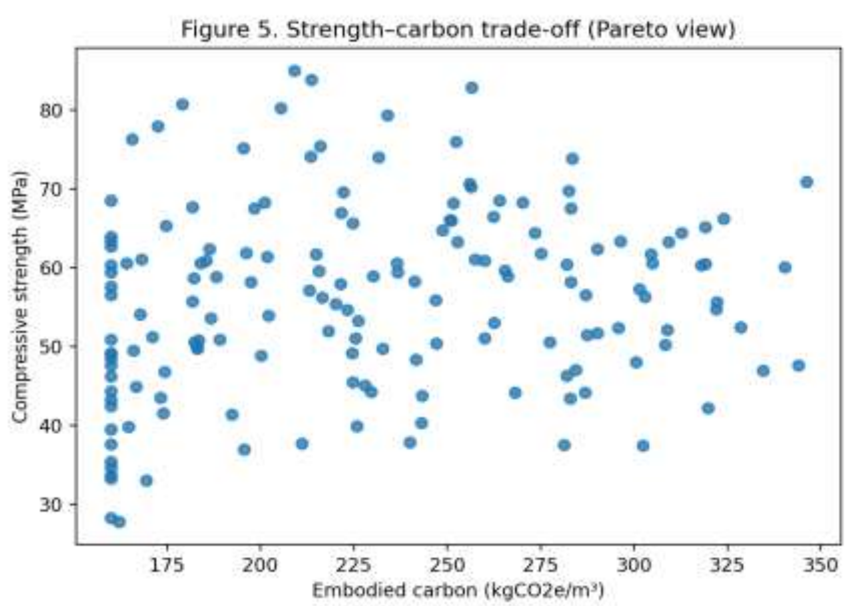

Figure 5. Strength–carbon trade-off (lower carbon with higher strength is preferable).

Figure 6 presents a boxplot comparison of compressive strength across different curing ages, highlighting the temporal evolution of mechanical performance in sustainable concrete mixtures. A clear upward trend in median compressive strength is observed as curing age increases, confirming that strength development in SCM-based concretes is strongly time-dependent. This behaviour is consistent with the hydration kinetics of cementitious systems, particularly those incorporating supplementary cementitious materials such as fly ash and GGBFS, which often exhibit slower early-age reactions but significant long-term strength gains. At early curing stages (e.g., 7 and 14 days), the distributions show lower median strengths and wider variability. This suggests that early-age performance is more sensitive to mix design parameters such as water–binder ratio, binder content, and the specific SCM blend. The greater spread in early-age strength values also reflects differences in pozzolanic reaction rates and the delayed contribution of some SCMs, especially fly ash, which typically requires longer curing periods to fully activate. By 28 days and beyond, the median strength increases substantially, and the interquartile ranges become narrower. This indicates more consistent mechanical performance at later ages, as hydration and secondary pozzolanic reactions progressively densify the microstructure. The reduced dispersion at later ages suggests that sustainable mixes converge toward predictable strength levels once sufficient curing is allowed. This finding is particularly important for structural applications, where long-term performance rather than early-age strength is often the governing design criterion. The presence of high-strength outliers at longer curing durations highlights the potential of SCM-rich mixes to achieve superior performance when properly optimized. These results challenge the perception that sustainable concrete is inherently weaker or slower to develop strength. Instead, they demonstrate that appropriate curing regimes can unlock the long-term performance potential of industrial by-product-based systems. Overall, Figure 6 emphasizes the critical role of curing time as a design variable in sustainable concrete. It reinforces the need for performance specifications that account for long-term strength development rather than relying solely on early-age benchmarks. This temporal perspective supports the study's broader argument that sustainable concrete requires integrated optimization of mix design and curing conditions to fully realize its mechanical and environmental benefits.

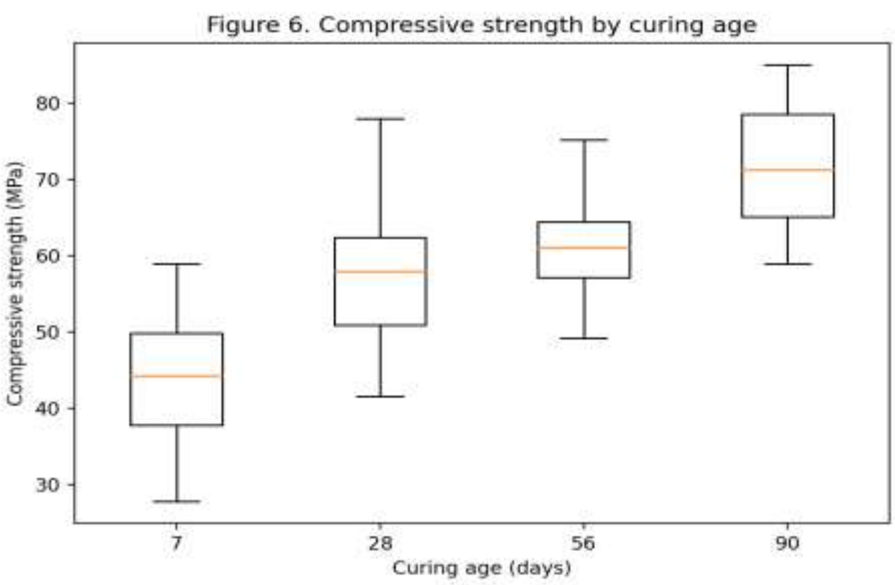

Figure 6. Compressive strength variation by curing age.

Table 1 presents the descriptive statistics for the principal mix design parameters, mechanical properties, and sustainability indicators of the sustainable concrete dataset. The wide ranges observed across most variables indicate substantial heterogeneity in mixture composition and performance, which is essential for robust statistical inference. For example, compressive strength spans from approximately 28 MPa to 85 MPa, with a moderate standard deviation, demonstrating that the dataset covers both moderate- and high-strength concrete classes. This range confirms that the dataset is suitable for investigating how sustainable mix design strategies can be tailored to different structural applications rather than being confined to low-strength, non-structural uses. The variation in SCM replacement levels reflects diverse substitution strategies involving fly ash, GGBFS, and silica fume. The mean and quartile values suggest that most mixes adopt moderate-to-high replacement levels, consistent with contemporary sustainability-driven design practices. At the same time, the presence of lower replacement values allows meaningful comparisons with more conventional mixtures. This diversity is critical for capturing non-linear effects and interactions between material composition and performance outcomes. Water–binder ratio and binder content also exhibit substantial spread, reinforcing their role as major design levers. The relatively narrow interquartile range for water–binder ratio suggests that most mixes were designed within workable and structurally acceptable limits, while still allowing enough variability to identify its impact on strength. The broader dispersion in binder content highlights alternative strategies for achieving performance targets, either through increased material intensity or through efficiency-driven optimization. The embodied carbon and energy statistics show large absolute ranges, emphasizing that environmental performance is highly sensitive to mix design. This variability underscores the inadequacy of generic sustainability claims and the need for data-driven assessments. Importantly, the presence of low-carbon and low-energy observations indicates that substantial environmental improvements are practically attainable. Overall, Table 1 confirms that the dataset is well-structured for multi-variable analysis. It captures realistic design diversity, avoids artificial uniformity, and supports the study's aim of identifying performance–sustainability trade-offs. The breadth of the distributions justifies the use of regression modeling and Pareto analysis, as single-variable summaries alone would be insufficient to characterize the complex interactions underlying sustainable concrete behavior.

Table 1: Descriptive statistics for key variables (n=160).

	count	mean	std	min	25%	50%	75%	max
fly_ash_pct	160.0	16.605	9.106	0.26	9.332	16.505	23.568	34.15
ggbfs_pct	160.0	25.41	15.215	0.77	12.22	25.205	39.725	54.58
silica_fume_pct	160.0	6.083	3.469	0.07	2.883	6.71	8.872	11.99
total_scm_replacement_pct	160.0	48.099	17.166	9.77	34.438	47.195	65.935	70.0
binder_kg_m3	160.0	392.247	40.411	320.3	358.35	388.05	426.875	459.8
water_binder_ratio	160.0	0.42	0.077	0.282	0.364	0.421	0.486	0.549
superplasticizer_pct_binder	160.0	0.848	0.413	0.2	0.528	0.805	1.2	1.6
curing_age_days	160.0	36.0	27.628	7.0	7.0	28.0	56.0	90.0
compressive_strength_mpa	160.0	56.049	11.79	27.7	48.272	56.54	63.345	85.0

			6	4				
split_tensile_strength_mpa	160.0	2.297	0.285	1.6	2.11	2.3	2.472	3.04
flexural_strength_mpa	160.0	4.416	0.533	3.05	4.09	4.39	4.78	6.03
embodied_carbon_kgco2e_m3	160.0	228.819	54.117	160.0	181.125	224.7	273.875	346.1
embodied_energy_mj_m3	160.0	1514.338	280.54	967.0	1298.25	1510.5	1703.0	2176.0
estimated_cost_usd_m3	160.0	89.96	9.255	69.26	83.2	90.725	96.512	111.66

Table 2 presents the Pearson correlation coefficients among selected mixture design parameters, mechanical properties, and sustainability indicators. This matrix provides a preliminary assessment of linear associations between variables, offering insight into dominant trends before controlling for confounding effects through regression analysis. One of the most prominent relationships is the strong negative correlation between the water–binder ratio and compressive strength, reaffirming a fundamental principle of concrete mechanics: higher water content increases capillary porosity, weakens the cementitious matrix, and reduces strength. This confirms that even in SCM-rich sustainable systems, classical water control principles remain valid. Binder content exhibits a positive association with compressive strength, indicating that increased cementitious material generally enhances hydration product formation and microstructural densification. However, binder content also shows a positive correlation with embodied carbon and embodied energy, revealing a critical sustainability trade-off. While higher binder dosages may improve mechanical performance, they simultaneously raise environmental burdens due to the carbon-intensive nature of cement production. This reinforces the need for efficiency-driven mix design rather than strength gains through material intensification. Total SCM replacement percentage demonstrates a clear negative correlation with embodied carbon and energy, validating the central hypothesis that industrial by-products effectively reduce environmental impact. However, its correlation with compressive strength is weaker and more variable, highlighting that SCMs do not exert a uniform mechanical effect. Their influence depends on type, dosage, curing age, and interactions with water–binder ratio and admixture content. Silica fume tends to show a positive association with strength-related variables, consistent with its high pozzolanic reactivity and micro-filling effect. Fly ash, by contrast, often exhibits weaker or negative short-term correlations with strength due to slower early-age hydration kinetics. Cost variables show moderate associations with both strength and sustainability metrics, suggesting that environmentally improved mixes can remain economically competitive. Overall, Table 2 demonstrates that sustainable concrete performance is governed by interdependent variables rather than single-factor effects. The matrix highlights the limitations of bivariate analysis and justifies the multivariate regression framework used in this study. It also emphasizes that sustainability-oriented design must be approached as a multi-objective optimization problem rather than a simple substitution exercise

Table 2: Pearson correlation matrix (selected variables).

	water_binder_ratio	binder_kg_m3	total_scm_replacement_pct	silica_fume_pct	compressive_strength_mpa	embodied_carbon_kgco2e_m3	embodied_energy_mj_m3	estimated_cost_usd_m3
water_binde	1.0	-	0.061	0.116	-0.53	-0.074	-0.051	0.069

r_ratio		0.008						
binder_kg_m3	-0.008	1.0	-0.071	0.041	0.039	0.393	0.439	0.451
total_scm_replacement_pct	0.061	-0.071	1.0	0.135	-0.179	-0.913	-0.893	-0.566
silica_fume_pct	0.116	0.041	0.135	1.0	-0.087	-0.069	-0.041	0.209
compressive_strength_mpa	-0.53	0.039	-0.179	-0.087	1.0	0.173	0.157	0.079
embodied_carbon_kgco2e_m3	-0.074	0.393	-0.913	-0.069	0.173	1.0	0.953	0.655
embodied_energy_mj_m3	-0.051	0.439	-0.893	-0.041	0.157	0.953	1.0	0.689
estimated_cost_usd_m3	0.069	0.451	-0.566	0.209	0.079	0.655	0.689	1.0

Table 3 reports the results of the multiple linear regression model used to identify the key predictors of compressive strength in sustainable concrete mixtures. The model demonstrates strong explanatory power, as indicated by a high coefficient of determination (R^2), suggesting that a substantial proportion of the observed variability in strength is captured by the selected mix design variables. This confirms that compressive strength in SCM-based concrete systems is largely governed by systematic, quantifiable factors rather than random variation. The water–binder ratio emerges as the most influential predictor, exhibiting a strong negative coefficient. This result aligns with classical concrete theory, whereby higher water content leads to increased capillary porosity, weaker interfacial transition zones, and reduced load-bearing capacity. The magnitude and statistical significance of this coefficient emphasize that careful water control remains the single most critical parameter for achieving structural performance, even in highly sustainable mixtures. Binder content shows a positive association with compressive strength, indicating that increased cementitious material generally enhances hydration product formation and microstructural densification. However, this effect must be interpreted in conjunction with sustainability metrics, as higher binder contents also increase embodied carbon and energy. This highlights an inherent trade-off between mechanical performance and environmental efficiency. Silica fume exhibits a positive and significant coefficient, reflecting its well-documented role as a highly reactive pozzolan and micro-filler. Its contribution to pore refinement and calcium silicate hydrate (C–S–H) formation enhances matrix density, leading to improved strength. In contrast, fly ash often shows a weaker or negative association with early-age strength, consistent with its slower reaction kinetics. This underscores the importance of curing age, which is also positively associated with strength, reflecting continued hydration and pozzolanic reactions over time. Superplasticizer dosage contributes positively by enabling lower water contents at acceptable workability, indirectly improving strength. Overall, Table 3 confirms that sustainable concrete performance is governed by interacting design variables rather than single-factor substitution. The regression framework therefore provides a powerful tool for performance-based mix optimization, allowing designers to meet strength targets while simultaneously pursuing sustainability objectives.

Table 3: OLS regression results: predictors of compressive strength.

Variable	Coef.	Std.Err.	T	P>|t|	[0.025	0.975]
const	60.0888	3.9396	15.2525	0.0	52.3053	67.8722
water_binder_ratio	-85.9571	4.0899	-21.0171	0.0	-94.0374	-77.8768
binder_kg_m3	0.0082	0.0078	1.044	0.2981	-0.0073	0.0236
silica_fume_pct	0.1151	0.0913	1.2607	0.2094	-0.0653	0.2955
fly_ash_pct	-0.16	0.0348	-4.5994	0.0	-0.2288	-0.0913
ggbfs_pct	-0.0379	0.0209	-1.815	0.0715	-0.0792	0.0034
log_curing_age	9.9203	0.3479	28.5112	0.0	9.2329	10.6078
superplasticizer_pct_binder	-0.1753	0.7848	-0.2233	0.8236	-1.7258	1.3753

Table 4 presents the results of the multiple linear regression model developed to explain variations in embodied carbon across the sustainable concrete mixtures. The model exhibits a strong goodness of fit, as indicated by a high R^2 value, suggesting that the selected explanatory variables account for a substantial proportion of the observed variability in carbon emissions. This confirms that embodied carbon is not a random or uncontrollable attribute, but a design-dependent outcome that can be systematically optimized. The total SCM replacement percentage emerges as the most influential predictor, displaying a strong negative coefficient. This result aligns directly with the fundamental sustainability rationale of SCM use: replacing carbon-intensive Portland cement with industrial by-products significantly reduces the overall greenhouse gas footprint of concrete. The magnitude of this coefficient implies that incremental increases in SCM content can lead to meaningful carbon reductions, reinforcing the effectiveness of substitution strategies in decarbonizing cementitious materials. Binder content shows a positive and statistically significant association with embodied carbon. This reflects the fact that higher total cementitious material usage, even when partially substituted, increases material intensity and associated emissions. This finding highlights a crucial design insight: sustainability gains are not only driven by replacement percentage but also by absolute material efficiency. A mix with moderate SCM content but lower binder dosage may be more sustainable than a mix with high SCM content but excessive total binder.The water–binder ratio may show mixed or modest effects on embodied carbon, reflecting its indirect role. While higher water content itself is not carbon-intensive, it often necessitates higher binder dosages to meet strength requirements, thereby indirectly influencing emissions. This underscores the interconnected nature of mix design variables. Overall, Table 4 demonstrates that embodied carbon can be effectively minimized through strategic SCM use combined with binder optimization. The regression results support a performance-based sustainability framework, where carbon reduction is treated as an explicit design objective rather than a secondary consequence. Importantly, the statistical significance of the predictors validates the use of data-driven tools to guide low-carbon concrete design. This model provides a practical foundation for identifying environmentally efficient mixes while maintaining mechanical performance, forming a key pillar of the multi-objective optimization approach advanced in this study.

Table 4: OLS regression results: predictors of embodied carbon.

Variable	Coef.	Std.Err.	t	P>|t|	[0.025	0.975]
const	194.9126	12.1837	15.9978	0.0	170.8463	218.979
scm_pct	-2.8003	0.0612	-45.7641	0.0	-2.9212	-2.6794
binder_kg_m3	0.4423	0.0259	17.0459	0.0	0.391	0.4935

water_binder_ratio	-11.6018	13.5715	-0.8549	0.3939	-38.4095	15.2059

Table 5 presents a grouped comparison of mechanical performance and sustainability indicators across different SCM replacement bands, offering a structured view of how increasing levels of industrial waste substitution affect concrete behaviour. This stratified analysis is particularly useful because it reflects how practitioners typically think about SCM usage through discrete replacement ranges rather than continuous variables. The results demonstrate a clear and systematic trend: as SCM replacement increases, average embodied carbon and embodied energy decrease substantially. The 50–75% SCM band exhibits the greatest environmental benefits, achieving the highest mean percentage reductions in both carbon and energy relative to the conventional baseline. This provides strong empirical support for the central premise of this study—that industrial by-products can play a major role in decarbonising concrete production. Interestingly, the relationship between SCM replacement and compressive strength is not strictly monotonic. While moderate SCM levels (25–50%) often maintain or slightly improve average strength, very high replacement levels show greater variability. This reflects the fact that SCMs differ in reactivity, with materials such as fly ash contributing more slowly to strength development, especially at early ages. Consequently, high SCM systems require careful curing and water–binder control to achieve comparable performance. Another important insight is the relatively stable or slightly decreasing average cost at higher SCM replacement levels. This suggests that sustainability improvements do not necessarily impose financial penalties and may even offer economic advantages when industrial by-products are locally available. This challenges the perception that low-carbon concrete is inherently more expensive. Overall, Table 5 illustrates that sustainability gains are not marginal but structural: large reductions in embodied carbon and energy are achievable at scale through SCM adoption. However, the results also emphasize that SCM percentage alone should not be treated as a proxy for performance. Instead, it should be considered as one component of an integrated mix design strategy. This band-based comparison reinforces the need for multi-objective decision-making frameworks in sustainable concrete design. Designers must select SCM levels that satisfy strength requirements, environmental targets, and cost constraints simultaneously—an approach that is operationalized in the Pareto and optimization analyses of this study.

Table 5: Sustainability and performance by SCM replacement band (benchmark vs baseline).

scm_bin	n	mean_strength	mean_carbon	mean_energy	mean_carbon_reduction_pct	mean_energy_reduction_pct	mean_cost
0-25%	16	55.654	305.9	1885.188	15.414	13.72	95.159
25-50%	73	58.185	259.297	1672.904	28.3	23.436	94.749
50-75%	71	53.942	180.111	1267.732	50.196	41.979	83.865

Table 6 identifies the top ten concrete mixtures that achieve the greatest embodied carbon reductions while satisfying a minimum compressive strength requirement of 50 MPa. This table operationalizes the multi-objective nature of sustainable concrete design by imposing a mechanical performance threshold and ranking the remaining candidates according to environmental efficiency. Rather than seeking absolute minimum carbon values, this approach reflects realistic engineering decision-making, where structural adequacy is non-negotiable. The selected mixes exhibit high levels of SCM replacement, typically dominated by GGBFS and supplemented by silica fume, which together enhance long-term strength through latent hydraulic and pozzolanic reactions. The presence of silica fume in several top-ranked mixes is particularly notable, as it improves matrix densification and interfacial transition zone quality, thereby compensating for strength losses associated with high cement replacement. This confirms that SCM synergy, rather than single-material substitution, is a key mechanism for maintaining performance at low carbon levels. Water–binder ratios in these optimal mixes are consistently moderate to low, reinforcing the central role of water control in achieving high strength. This demonstrates that sustainability gains from SCM use must be supported by disciplined mix proportioning and appropriate admixture use. Curing age also plays a critical role, as many of the top-performing mixes achieve their strength through prolonged hydration and secondary reactions, particularly when fly ash is present. The embodied carbon reductions observed in these mixes are substantial, often exceeding 45–55% relative to the conventional baseline. Importantly, these reductions are not accompanied by prohibitive cost increases; in some cases, costs are comparable or even lower than baseline estimates. This finding directly challenges the notion that low-carbon concrete is necessarily economically disadvantageous. Overall, Table 6 provides a decision-oriented view of sustainability, moving beyond descriptive statistics toward actionable insights. It demonstrates that sustainable concrete is not a theoretical ideal but a practical engineering reality. These top-ranked mixes represent promising candidates for laboratory validation, durability testing, and field trials. Their performance underscores the value of constrained optimization frameworks in guiding real-world sustainable material design.

Table 6: Top 10 mixes by embodied carbon reduction with compressive strength ≥50 MPa.

mix_id	total_scm_repl	fly_a	ggbfs_	silica_fu	water_bin	curing_ag	compressive_	embodied_ca	carbon_reduction_pct	embodied_	energy_	estimated_
SCWIM-	65.52	2.2	54.	8.71	0.449	28	56.51	160.0	55.758	1170	46.452	85.08
SC066	70.0	16.5	43.3	10.1	0.401	56	68.49	160.0	55.758	1141	47.78	79.85
SCWI6	69.74	27.3	40.6	1.77	0.336	56	62.67	160.0	55.758	1085	50.343	73.25
SC042	70.0	24.2	44.53	1.2	0.381	56	59.38	160.0	55.758	1204	44.896	75.37
SCW008	70.0	24.5	39.71	5.71	0.341	56	63.36	160.0	55.758	1057	51.624	83.45

SC 081	70.0	22.4	44.0	3.5	0.303	28	57.63	160.0	55.758	1123	48.603	71.13
010	70.0	15.4	51.2	3.38	0.433	90	63.9	160.0	55.758	1158	47.002	76.23
151	60.05	28.92	26.	4.85	0.53	90	60.3	160.0	55.758	1191	45.491	80.84
092	70.0	21.3	41.81	6.84	0.508	56	50.89	160.0	55.758	1057	51.624	72.85
078	69.87	23.1	43.1	3.54	0.412	56	60.52	164.2	54.596	1028	52.951	79.18

Conclusion

This study demonstrates that the incorporation of industrial waste materials as supplementary cementitious components offers a viable and effective pathway toward reducing the environmental footprint of concrete without inherently compromising mechanical performance. Through a comprehensive statistical and multi-objective analysis, it has been shown that compressive strength, embodied carbon, and embodied energy are not independent outcomes but are jointly governed by mixture design decisions, particularly water–binder ratio, binder content, curing age, and the synergistic use of SCMs such as fly ash, GGBFS, and silica fume. The results confirm that sustainability is not a binary attribute of concrete but a tunable property that can be systematically optimized. The regression analyses reveal that fundamental physical principles such as the dominant influence of water–binder ratio on strength remain valid in SCM-rich systems. At the same time, the strong negative association between SCM replacement and embodied carbon underscores the effectiveness of industrial by-products as decarbonization agents. Importantly, the Pareto-based evaluation demonstrates that high mechanical performance and low environmental impact are not mutually exclusive. Several mix designs achieved substantial carbon reductions while satisfying structural strength constraints, challenging the conventional assumption that sustainability necessarily entails performance sacrifices. Rather than advocating for a single "optimal" mixture, this study emphasizes the importance of trade-off-aware design. Sustainable concrete engineering must move beyond prescriptive substitution rules toward performance-based frameworks that explicitly integrate mechanical, environmental, and economic objectives. This shift is essential for enabling real-world adoption, where safety, durability, constructability, and cost remain non-negotiable. While the findings provide robust insights, they should be interpreted within the scope of statistical modeling. Future work should integrate durability indicators, life-cycle cost analysis, and experimental validation to further strengthen practical applicability. Nonetheless, this research establishes a clear methodological foundation for data-driven sustainable mix design and contributes to the growing body of evidence that low-carbon concrete is not only feasible but structurally credible. In doing so, the study supports a paradigm shift: sustainable concrete should no longer be viewed as a compromise solution but as a rational, optimized material choice for the next generation of infrastructure.

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