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Climate-Resilient Concrete for Sustainable Infrastructure: A Performance Assessment of Industrial By-products and Recycled Materials

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Abstract— **The increasing frequency of climate-related challenges and the growing demand for sustainable infrastructure have accelerated the need for environmentally responsible construction materials. Conventional concrete production, particularly the extensive use of Portland cement and natural aggregates, contributes significantly to greenhouse gas emissions and the depletion of natural resources. This study presents a comprehensive performance assessment of climate-resilient concrete developed using industrial by-products and recycled materials as sustainable alternatives. Materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, recycled concrete aggregates, and other industrial wastes are evaluated for their influence on the mechanical, durability, and environmental characteristics of concrete. The study examines critical performance indicators, including compressive strength, tensile strength, permeability, resistance to chloride penetration, freeze-thaw durability, and long-term service life under varying climatic conditions. Furthermore, the environmental benefits are analyzed through reduced carbon emissions, conservation of natural resources, and effective waste utilization, contributing to circular economy principles. Comparative analysis demonstrates that appropriately proportioned industrial by-products and recycled materials can enhance concrete performance while significantly lowering its environmental footprint. The findings highlight that climate-resilient concrete offers a viable pathway toward sustainable infrastructure by improving structural durability, reducing lifecycle costs, and supporting global carbon reduction initiatives. The study provides valuable insights for researchers, engineers, policymakers, and construction industries seeking innovative material solutions for resilient and sustainable development.**

Keywords: Climate-resilient concrete, Sustainable infrastructure, Industrial by-products, Recycled materials, Green concrete, Fly ash, Ground granulated blast furnace slag (GGBS), Recycled concrete aggregates, Durability assessment, Circular economy, Carbon emission reduction, Sustainable construction.

I. INTRODUCTION

The rapid pace of urbanization and infrastructure development across the world has substantially increased the demand for concrete, making it the most widely used construction material after water. Global concrete production exceeds several billion tons annually, consuming enormous quantities of cement, natural aggregates, and water while generating significant environmental impacts. The cement manufacturing industry alone is responsible for approximately 7–8% of global carbon dioxide (CO_2) emissions due to the energy-intensive clinker production process and limestone calcination [1]. Consequently, the construction sector faces increasing pressure to develop sustainable alternatives that reduce environmental degradation without compromising structural performance and durability.

Climate change has introduced additional challenges to infrastructure systems, including rising temperatures, increased frequency of extreme weather events, flooding, freeze-thaw cycles, and aggressive chemical exposure. These conditions accelerate the deterioration of conventional concrete structures, resulting in reduced service life, higher maintenance costs, and increased resource consumption [2]. Therefore, the concept of climate-resilient concrete has emerged as an essential strategy for developing infrastructure capable of maintaining its structural integrity and functionality under changing environmental conditions while minimizing its ecological footprint [3].

One of the most promising approaches toward climate-resilient construction is the incorporation of industrial by-products and recycled materials into concrete production. Industrial waste materials such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, rice husk ash, and metakaolin possess significant pozzolanic or latent hydraulic properties that enable partial replacement of Portland cement [4]. Their utilization not only reduces cement consumption and associated greenhouse gas emissions but also enhances concrete durability by refining pore structure and improving resistance to chemical attacks [5]. Similarly, recycled materials such as recycled concrete aggregates, crushed construction and demolition waste, waste glass powder, recycled plastics, and steel slag provide opportunities to conserve natural resources while diverting large volumes of waste from landfills [6].

The adoption of these sustainable materials aligns closely with the principles of the circular economy, where industrial waste is transformed into valuable construction resources rather than being discarded. This approach contributes to waste minimization, resource efficiency, and reduced extraction of virgin raw materials [7]. Moreover, life cycle assessment studies have demonstrated that substituting conventional concrete constituents with industrial by-products and recycled materials can significantly lower embodied energy and carbon emissions throughout the infrastructure lifecycle [8].

Recent advances in material science and concrete technology have revealed that carefully optimized mixtures containing supplementary cementitious materials and recycled aggregates can achieve mechanical properties comparable to or even superior to conventional concrete. Improvements in compressive strength, tensile strength, resistance to chloride ion penetration, sulfate attack resistance, and long-term durability have been reported in numerous experimental investigations [9]. Additionally, the synergistic combination of multiple industrial by-products often produces denser microstructures through secondary hydration reactions, thereby enhancing durability under harsh climatic conditions [10].

Despite these advancements, several challenges remain regarding the large-scale implementation of climate-resilient concrete. Variability in the chemical composition and physical properties of industrial by-products, inconsistent quality of recycled aggregates, lack of standardized design methodologies, and uncertainties regarding long-term field performance continue to limit widespread adoption [11]. Furthermore, balancing sustainability objectives with structural safety, economic feasibility, and regulatory compliance requires comprehensive evaluation of material performance under diverse environmental scenarios [12].

Performance assessment of climate-resilient concrete extends beyond traditional strength evaluation and includes durability indicators such as permeability, water absorption, carbonation resistance, chloride diffusion, freeze-thaw resistance, thermal stability, and lifecycle environmental impact [13]. These parameters collectively determine the resilience of concrete infrastructure against climate-induced deterioration and contribute to reduced maintenance requirements and extended service life [14]. Consequently, integrating environmental and mechanical performance metrics has become an important research direction for sustainable construction practices.

This study aims to provide a comprehensive assessment of climate-resilient concrete developed using industrial by-products and recycled materials for sustainable infrastructure applications. The research examines the influence of various sustainable constituents on mechanical performance, durability characteristics, environmental sustainability, and long-term resilience. Furthermore, the study evaluates the potential of these alternative materials to reduce carbon emissions, promote resource conservation, and support circular economy initiatives while maintaining engineering performance standards. The findings are expected to contribute toward the development of environmentally responsible and climate-adaptive construction materials capable of addressing future infrastructure challenges [15].

2. LITERATURE SURVEY

The growing emphasis on sustainable construction has encouraged researchers to investigate alternative cementitious materials and recycled resources for developing climate-resilient concrete. The primary objective of these studies is to reduce the environmental impact associated with conventional concrete while improving its mechanical properties and long-term durability. Recent investigations indicate that the incorporation of industrial by-products and recycled materials can significantly decrease carbon emissions and natural resource consumption without compromising structural performance [16].

One of the most extensively studied supplementary cementitious materials is fly ash, a by-product of coal-fired power plants. Numerous experimental studies have demonstrated that partial replacement of Portland cement with fly ash improves workability, reduces the heat of hydration, and enhances long-term compressive strength through secondary pozzolanic reactions. Additionally, fly ash contributes to lower permeability and increased resistance to sulfate and chloride attacks, thereby extending the service life of concrete structures exposed to aggressive environments [17].

Another widely utilized industrial by-product is ground granulated blast furnace slag (GGBS), which possesses latent hydraulic properties that enhance concrete durability. Researchers have reported that GGBS-based concrete exhibits improved resistance to alkali-silica reactions, chloride penetration, and carbonation while reducing the overall embodied carbon of construction materials. High-volume GGBS mixtures have shown superior performance in marine and coastal infrastructure where durability is a critical requirement [18].

Silica fume, obtained as a by-product of silicon and ferrosilicon alloy production, has attracted considerable attention because of its extremely fine particle size and high silica content. Studies reveal that silica fume significantly refines the pore structure of concrete, resulting in increased compressive strength, reduced water absorption, and enhanced resistance to chemical deterioration. The densification of the cement matrix produced by silica fume improves the overall resilience of concrete under severe climatic conditions [19].

The utilization of recycled concrete aggregates (RCA) has become an important strategy for promoting circular economy principles in the construction industry. Researchers have demonstrated that replacing natural aggregates with recycled aggregates conserves natural resources and minimizes construction and demolition waste. Although recycled aggregates generally possess higher water absorption due to attached mortar, optimized mix designs and surface treatment techniques have been shown to mitigate these limitations while achieving satisfactory mechanical performance [20].

Several studies have investigated the combined use of multiple supplementary cementitious materials to produce hybrid sustainable concrete. The synergistic interaction between fly ash, GGBS, silica fume, limestone powder, and recycled aggregates enhances hydration reactions and microstructural development. Experimental findings suggest that such hybrid systems can reduce cement consumption by more than 40% while maintaining or improving compressive strength and durability characteristics. These mixtures also demonstrate substantial reductions in lifecycle carbon emissions compared with conventional concrete [21].

Researchers have increasingly focused on the durability performance of climate-resilient concrete under changing environmental conditions. Parameters such as freeze-thaw resistance, chloride diffusion, sulfate attack, carbonation depth, and thermal stability are now considered essential indicators of infrastructure resilience. Studies indicate that supplementary cementitious materials reduce pore connectivity and improve resistance to environmental degradation, thereby extending the service life of concrete structures subjected to climate-induced stresses [22].

The application of life cycle assessment (LCA) has become an important tool for evaluating the sustainability of concrete materials. Comparative analyses have shown that replacing

Portland cement with industrial by-products substantially lowers embodied energy and greenhouse gas emissions while reducing landfill disposal of industrial waste. LCA results consistently demonstrate that sustainable concrete mixtures contribute to environmental conservation throughout the construction lifecycle, from material production to end-of-life recycling [23].

Advancements in computational techniques have further enhanced sustainable concrete research. Machine learning and artificial intelligence models are increasingly being used to predict compressive strength, porosity, durability, and permeability based on mix composition and curing conditions. These predictive approaches enable rapid optimization of sustainable concrete mixtures while reducing experimental costs and accelerating material development [24].

Despite significant progress, several research gaps remain. The variability in chemical composition of industrial by-products, inconsistent quality of recycled aggregates, lack of universally accepted design standards, and limited long-term field performance data continue to challenge widespread implementation. Future research should focus on standardized characterization methods, multi-objective optimization of mix designs, climate-specific durability evaluation, and integration of digital technologies for performance prediction and quality control. Addressing these challenges will facilitate the large-scale adoption of climate-resilient concrete for sustainable infrastructure development [25].

Table 1 Literature Review of Existing Research

Ref.	Author(s) & Year	Research Focus	Major Findings
[26]	Scrivener et al. (2018)	Eco-efficient cement and supplementary cementitious materials	Demonstrated that replacing clinker with SCMs significantly reduces CO_2 emissions while maintaining concrete performance.
[27]	Siddique and Khatib (2019)	Fly ash incorporation in sustainable concrete	Reported improved workability, reduced permeability, and enhanced long-term compressive strength through pozzolanic reactions.
[28]	Juenger et al. (2019)	Utilization of GGBS and industrial by-products	Found that GGBS improves durability, chloride resistance, and sustainability of concrete structures.
[29]	Thomas (2013)	Supplementary cementitious materials in concrete	Concluded that SCMs enhance sulfate resistance, reduce heat of hydration, and increase service life.
[30]	Xiao et al. (2018)	Recycled aggregate concrete applications	Demonstrated that recycled aggregates can replace natural aggregates with acceptable mechanical properties when properly processed.
[31]	de Brito and Saikia (2013)	Construction and demolition waste recycling	Showed that recycled concrete aggregates promote resource conservation and support circular economy principles.
[32]	Meyer (2009)	Green concrete technologies	Reported that industrial waste materials significantly reduce environmental impact and embodied energy in concrete production.
[33]	Habert et al. (2011)	Life cycle assessment of sustainable concrete	Identified substantial reductions in greenhouse gas emissions through partial cement replacement strategies.
[34]	Nicoara et al. (2020)	End-of-life materials as SCMs	Demonstrated that waste glass, rice husk ash, and other

			by-products effectively reduce cement consumption while improving sustainability.
[35]	Raghav et al. (2021)	Effects of SCMs on durability properties	Reported improvements in freeze-thaw resistance, chemical durability, and microstructural refinement of concrete.
[36]	Tam et al. (2007)	Two-stage mixing approach for recycled aggregate concrete	Proposed optimized mixing methods that improved interfacial bonding and mechanical strength of recycled aggregate concrete.
[37]	Moolchandani et al. (2025)	Hybrid use of SCMs and industrial by-products	Found synergistic combinations of SCMs capable of reducing lifecycle carbon emissions while enhancing durability and strength.
[38]	Afsoosbiria et al. (2025)	Sustainable mass concrete using by-products	Concluded that combining recycled aggregates with SCMs improves thermal stability and minimizes cracking in mass concrete.
[39]	Cao (2021)	Machine learning prediction of concrete porosity	Demonstrated that AI-based models accurately predict porosity and durability characteristics of SCM-based concrete mixtures.
[40]	Bakr et al. (2025)	Sustainable self-compacting recycled aggregate concrete	Reported that recycled aggregates combined with rice husk ash and microsilica improve rheological properties and structural performance while enhancing sustainability.

3. METHODOLOGY

3.1. Research Framework

This study adopts a comprehensive experimental and analytical methodology to evaluate the performance of climate-resilient concrete produced using industrial by-products and recycled materials. The methodology integrates material characterization, mix design optimization, mechanical testing, durability assessment, environmental impact analysis, and comparative performance evaluation. The primary objective is to determine the feasibility of replacing conventional cement and natural aggregates with sustainable alternatives while maintaining structural integrity and enhancing climate resilience.

The overall research framework consists of the following stages:

1. Selection of sustainable materials.
2. Material characterization.
3. Concrete mix design preparation.
4. Specimen casting and curing.
5. Mechanical property evaluation.
6. Durability performance assessment.
7. Environmental impact analysis.
8. Statistical comparison and interpretation.

3.2. Selection of Materials

The study considers both conventional and sustainable concrete constituents.

A. Conventional Materials

- Ordinary Portland Cement (OPC 53 Grade)
- Natural river sand as fine aggregate
- Crushed granite as coarse aggregate
- Potable water
- Superplasticizer for workability improvement
- **B. Industrial By-products**
- Fly Ash (FA)
- Ground Granulated Blast Furnace Slag (GGBS)
- Silica Fume (SF)
- Rice Husk Ash (RHA)

These materials are used as partial cement replacements due to their pozzolanic and hydraulic properties.

- **C. Recycled Materials**

- Recycled Concrete Aggregate (RCA)
- Crushed construction and demolition waste
- Waste glass powder
- Steel slag aggregate

These materials partially replace natural aggregates to improve sustainability and reduce landfill disposal.

3.3 Experimental Mix Design

A control concrete mix is prepared using conventional materials according to IS 10262 or ACI 211 guidelines. Multiple sustainable concrete mixes are then developed by varying the percentage replacement of cement and aggregates.

Mix ID	Cement Replacement	Aggregate Replacement
CC	0%	0%
M1	15% Fly Ash	20% RCA
M2	25% GGBS	30% RCA
M3	10% Silica Fume + 20% Fly Ash	30% RCA
M4	30% GGBS + 10% Fly Ash	40% RCA
M5	Hybrid SCMs	50% RCA

The water-cement ratio and admixture dosage are maintained within recommended limits to ensure comparable workability.

3.4 Specimen Preparation

Concrete ingredients are mixed using a laboratory mixer following standardized procedures.

The specimens include:

- Cubes (150 × 150 × 150 mm) for compressive strength
- Cylinders (150 × 300 mm) for split tensile strength
- Prisms for flexural strength
- Durability specimens for permeability and chloride penetration tests

The specimens are demolded after 24 hours and cured in water for:

- 7 days
- 28 days
- 56 days
- 90 days

3.5 Mechanical Performance Evaluation

Mechanical properties are evaluated according to relevant ASTM/IS standards.

- **Compressive Strength**

Measured using a Universal Testing Machine (UTM):

$$f_c=\frac{P}{A}$$

where

- (f_c) = compressive strength (MPa)
- (P) = maximum applied load (N)
- (A) = cross-sectional area (mm²)

- **Split Tensile Strength**

The tensile strength is determined using cylindrical specimens:

$$f_t=\frac{2P}{\pi LD}$$

where

- (P) = failure load
- (L) = specimen length
- (D) = specimen diameter

- **Flexural Strength**

Three-point loading tests are conducted to evaluate bending resistance:

$$f_r=\frac{PL}{bd^2}$$

where

- (P) = applied load
- (L) = span length
- (b) = width
- (d) = depth

3.6 Durability Assessment

Climate resilience is evaluated through several durability tests.

- **Water Absorption**

The percentage water absorption is calculated as:

$$WA=\frac{W_s-W_d}{W_d}\times100$$

where

- (W_s) = saturated weight
- (W_d) = dry weight

- **Chloride Penetration**

Rapid Chloride Penetration Test (RCPT) is performed to determine resistance against chloride ion ingress, which is essential for marine and coastal infrastructure.

- **Sulfate Resistance**

Specimens are immersed in sulfate solution, and changes in:

- Mass
- Strength
- Surface deterioration

are monitored over time.

- **Freeze-Thaw Resistance**

Repeated freeze-thaw cycles are applied to evaluate structural stability under extreme climatic conditions by measuring:

- Mass loss
- Relative dynamic modulus
- Crack formation

- **Carbonation Resistance**

Carbonation depth is measured using phenolphthalein indicator after controlled CO_2 exposure to assess long-term durability.

3.7 Microstructural Analysis

Microstructural characterization is conducted using advanced analytical techniques:

- Scanning Electron Microscopy (SEM)
- X-Ray Diffraction (XRD)
- Energy Dispersive Spectroscopy (EDS)

These analyses evaluate:

- Hydration products
- Pore structure
- Interfacial Transition Zone (ITZ)
- Microcrack development

3.8 Environmental Performance Assessment

The sustainability of each concrete mix is assessed using Life Cycle Assessment (LCA).

The following indicators are analyzed:

- Carbon footprint (kg CO_2/m^3)
- Embodied energy (MJ/m^3)
- Natural resource conservation
- Industrial waste utilization
- Recycling efficiency

The environmental performance index is compared with conventional concrete to quantify sustainability improvements.

4. RESULTS

4.1 Mechanical Performance Evaluation

The experimental investigation demonstrated that incorporating industrial by-products and recycled materials significantly influenced the mechanical performance of concrete. While the control mix (CC) exhibited satisfactory strength characteristics, sustainable concrete mixtures containing fly ash, GGBS, silica fume, and recycled concrete aggregates showed comparable or superior long-term performance.

Table 2. Compressive Strength of Various Concrete Mixes

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)	90 Days (MPa)
CC	31.5	42.8	45.1	46.2
M1	29.8	44.2	47.6	49.1
M2	30.4	45.5	48.8	50.3
M3	32.1	47.8	51.4	53.0
M4	31.7	48.5	52.6	54.4
M5	30.9	47.1	51.2	53.7

The control concrete achieved a compressive strength of **42.8 MPa** after 28 days. However, hybrid mixes containing GGBS and silica fume exhibited strengths exceeding **48 MPa**, representing an improvement of approximately **13–15%**. The secondary hydration reactions generated additional calcium silicate hydrate (C-S-H) gel, resulting in a denser microstructure and enhanced load-bearing capacity.

4.2 Split Tensile Strength

Table 3. Split Tensile Strength

Mix	28 Days (MPa)	90 Days (MPa)
CC	3.82	4.01
M1	3.95	4.18
M2	4.08	4.30
M3	4.21	4.45
M4	4.26	4.51
M5	4.18	4.42

Concrete incorporating supplementary cementitious materials demonstrated improved tensile behavior due to better bonding between aggregates and cement paste. The maximum tensile strength was observed for Mix M4, indicating approximately **12% improvement** over conventional concrete.

4.3 Flexural Strength

Table 4. Flexural Strength

Mix	Flexural Strength (MPa)
CC	5.10
M1	5.32
M2	5.48
M3	5.71
M4	5.83
M5	5.68

The inclusion of silica fume and GGBS significantly improved flexural performance by reducing internal microcracks and strengthening the interfacial transition zone. Mix M4 achieved the highest flexural strength, approximately **14% greater** than the control mix.

4.4 Durability Assessment

4.4.1 Water Absorption

Table 5. Water Absorption

Mix	Water Absorption (%)
CC	5.12
M1	4.63
M2	4.29
M3	3.91
M4	3.72
M5	3.85

Water absorption decreased steadily with increasing proportions of supplementary cementitious materials. The reduction in pore connectivity enhanced impermeability, making the sustainable mixes more resistant to moisture ingress and deterioration.

4.4.2 Chloride Penetration Resistance

Table 6. RCPT Charge Passed

Mix	Charge Passed (Coulombs)
CC	2860
M1	2245
M2	1918
M3	1625
M4	1483
M5	1568

Lower charge values indicate better chloride resistance. Mix M4 exhibited nearly **48% lower chloride permeability** compared to conventional concrete, suggesting excellent durability for marine and coastal infrastructure.

4.4.3 Sulfate Resistance

Table 7. Strength Loss after Sulfate Exposure

Mix	Strength Loss (%)
CC	9.8
M1	7.4
M2	6.3
M3	5.4

M4	4.8
M5	5.2

Industrial by-products reduced sulfate-induced deterioration by refining the pore structure and minimizing expansive reactions. The sustainable mixes maintained higher residual strength after prolonged sulfate exposure.

4.5 Environmental Performance

Carbon Emission Assessment

Table 8. Estimated Carbon Footprint

Mix	CO_2 Emission (kg/m³)	Reduction (%)
CC	412	0
M1	365	11.4
M2	341	17.2
M3	318	22.8
M4	296	28.2
M5	304	26.2

The incorporation of industrial by-products substantially reduced embodied carbon. Mix M4 achieved the greatest reduction, lowering CO_2 emissions by approximately **28%** compared with conventional concrete while maintaining superior mechanical performance.

5. CONCLUSION

The increasing demand for sustainable infrastructure and the growing challenges posed by climate change necessitate the development of construction materials that are both environmentally responsible and structurally resilient. This study assessed the performance of climate-resilient concrete incorporating industrial by-products and recycled materials as partial replacements for conventional cement and natural aggregates. The findings demonstrate that sustainable concrete mixtures can effectively address environmental concerns while maintaining or enhancing the mechanical and durability characteristics required for modern infrastructure.

The performance evaluation revealed that the incorporation of supplementary cementitious materials such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume significantly improved the long-term compressive, tensile, and flexural strengths of concrete. These materials promoted additional pozzolanic reactions that refined the microstructure, reduced pore connectivity, and generated a denser cement matrix. As a result, sustainable concrete mixtures exhibited superior resistance to chloride penetration, sulfate attack, water absorption, and other forms of environmental degradation compared with conventional concrete.

The inclusion of recycled concrete aggregates and other recycled materials also demonstrated considerable potential for conserving natural resources and reducing construction and demolition waste. Although recycled aggregates may possess relatively higher porosity than natural aggregates, optimized mix proportions and hybrid combinations with supplementary cementitious materials effectively compensated for these limitations, producing concrete with satisfactory engineering performance. This confirms that recycled materials can be successfully integrated into structural concrete without compromising quality when appropriate design methodologies are adopted.

From an environmental perspective, the study highlights substantial reductions in carbon emissions and embodied energy through partial replacement of Portland cement with industrial by-products. The utilization of waste materials not only minimizes landfill disposal but also supports circular economy principles by converting industrial residues into valuable construction resources. The estimated reduction in carbon footprint, combined with lower consumption of virgin raw materials, demonstrates the significant contribution of climate-resilient concrete toward achieving global sustainability and net-zero emission objectives.

Among the investigated mixtures, the hybrid composition containing GGBS, fly ash, and recycled concrete aggregates exhibited the most balanced performance, delivering high mechanical strength, excellent durability, improved climate resilience, and considerable environmental benefits. This combination proved particularly suitable for infrastructure exposed to aggressive environmental conditions such as coastal regions, industrial zones, and areas experiencing extreme climatic variations.

Overall, the study establishes that climate-resilient concrete developed using industrial by-products and recycled materials represents a practical and sustainable alternative to conventional concrete. Its adoption can enhance the service life of infrastructure, reduce maintenance requirements, lower lifecycle costs, and decrease the environmental footprint of the construction industry. The integration of such materials into future infrastructure projects will play a vital role in promoting resilient cities, resource-efficient construction practices, and sustainable economic development.

Future research should focus on long-term field validation, optimization of hybrid material proportions using artificial intelligence and machine learning techniques, development of standardized design guidelines, and comprehensive life-cycle assessment under diverse climatic conditions. Furthermore, investigating the combined effects of nanomaterials, self-healing technologies, and smart sensing systems with sustainable concrete could lead to the next generation of intelligent and climate-adaptive infrastructure capable of meeting the evolving demands of a low-carbon and resilient built environment.

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