

Review

Enhancing Concrete Performance through Sustainable Utilization of Class-C and Class-F Fly Ash: A Comprehensive Review

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Abstract: Integrating class-C and class-F fly ash (FA) as supplementary cementitious materials (SCMs) in concrete offers a promising pathway for sustainable construction practices. This study explores the pivotal role of FA in reducing carbon dioxide (CO₂) emissions and improving concrete's durability and mechanical properties through a comprehensive life cycle analysis (LCA). By blending FA with cement, significant reductions in CO₂ emissions are achieved, alongside enhancements in the workability, compressive strength, and permeability resistance of the concrete matrix. This research elucidates the pozzolanic reaction between FA and calcium hydroxide (CH) during cement hydration, highlighting its contribution to concrete strength and durability. Through a range of comprehensive analysis techniques, including mechanical testing and environmental impact assessment, this study demonstrates the substantial benefits of prioritizing the utilization of class-C and class-F FA in sustainable construction. The findings underscore the industry's commitment to environmentally conscious practices, promoting structural integrity and reducing ecological impacts. Overall, this research emphasizes class-C and class-F FA as critical components in achieving sustainable construction goals and advancing towards a more environmentally responsible built environment.

Keywords: sustainable cementitious materials; fly ash; CO₂ emissions reduction; sustainability in construction



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1. Introduction

The annual consumption of cement worldwide is a significant source of CO₂ emissions, posing a primary concern for sustainability. Cement production involves the transformation of limestone and clay into calcium silicates at high temperatures, requiring substantial energy and leading to CO₂ emissions through the combustion of fossil fuels. This sector accounts for approximately 8% of global CO₂ emissions, which can considerably impact climate change [1–3]. Table 1 provides an overview of the environmental impacts and CO₂ emissions throughout various stages of cement production.

Cement production typically involves high-temperature calcination, a primary source of CO₂ emissions. Additionally, raw material acquisition, energy usage, transportation, and waste management contribute significantly to environmental pollution and CO₂ emissions. The rising annual demand for cement further deepens these concerns and results in the excessive use of natural resources. However, alternative approaches are being developed to reduce cement consumption for sustainability. One alternative involves using SCMs

or other byproducts (FA, SF, GBFS, or volcanic ash) instead of cement in concrete production. These materials can react with cement to enhance the durability of concrete while simultaneously reducing cement usage and lowering CO₂ emissions. Figure 1 illustrates a schematic emphasizing the significance of utilizing waste materials in cement production to enhance sustainability.

Table 1. Summary of environmental impact and CO₂ emissions in cement production processes.

Process	Environmental Pollution	CO ₂ Emissions
Raw Material Acquisition	Land Alteration and Destruction	High
Clinker Production	High Calcination Temperature	Primary Emission Source
Combustion and Energy Usage	Fuel Combustion	High
Transportation	Fuel Usage and Carbon Footprint	Moderate to High
Waste Management	Waste Disposal and Recycling	Moderate

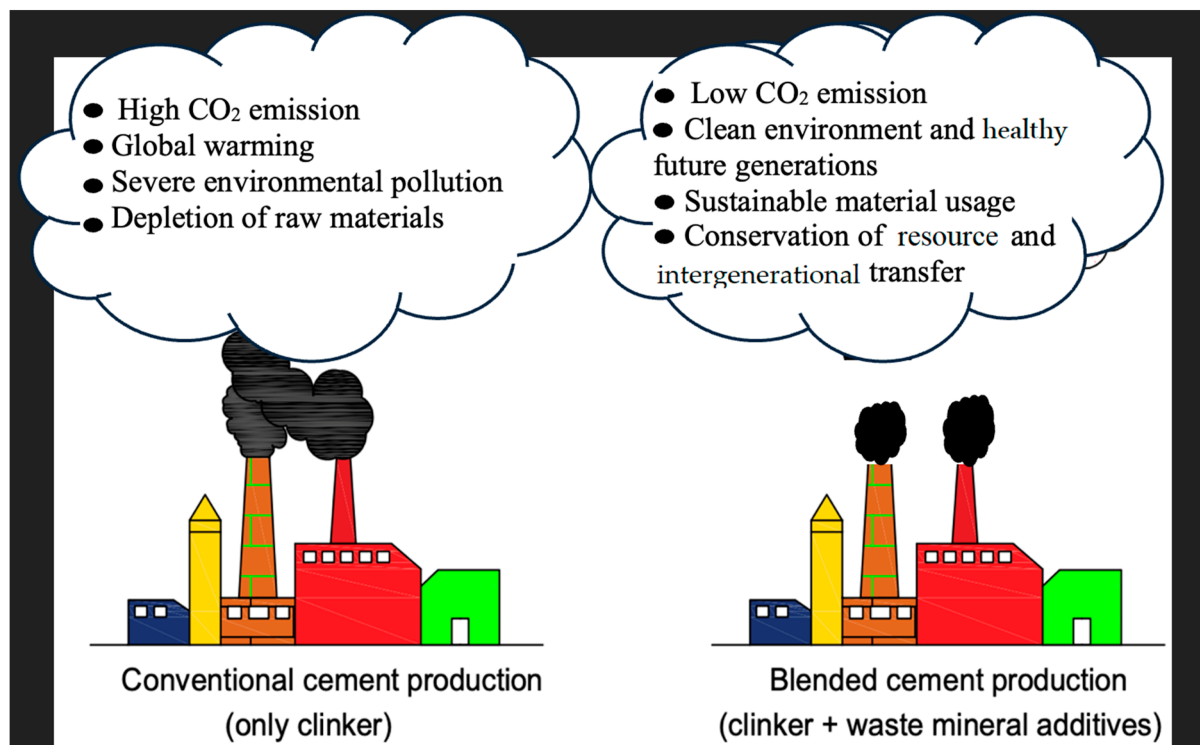


Figure 1. A schematic diagram emphasizing the critical role of incorporating waste materials in cement production, elucidating its profound significance for sustainability endeavors.

The cement industry and the construction sector are working toward more sustainable production and building processes by implementing these changes in cement consumption. These efforts play a critical role in achieving global targets for reducing CO₂ emissions stemming from cement consumption and aim to establish a greener and more environmentally friendly construction sector by promoting the widespread adoption of sustainable building materials [4–6]. Using recycled resources in construction, especially in concrete production, is a successful method for advancing sustainable development. Concrete is the predominant construction material worldwide, and its production significantly contributes to the release of greenhouse gases. Utilizing recycled resources in concrete production can effectively reduce the carbon footprint of the construction sector. Steel waste (SW), waste rubber (WR), waste plastic (WP), waste glass (WG), fly ash (FA), recycled coarse aggregates (RCA), and other industrial and natural byproducts (such as palm oil fuel ash (POFA)) can be used in concrete production as substitutes for cement and natural aggre-

gates [7,8]. Therefore, it is necessary to use effective material management strategies such as enhancement, recycling, substitution, and resource optimization to mitigate environmental issues. Figure 2 illustrates a schematic representation emphasizing the significance of using class-C and class-F FA in enhancing concrete's strength and durability properties and their relevance to sustainability in concrete mixtures.



Figure 2. Optimizing sustainability: exploring the role of FA in concrete mixtures for environmental conservation and enhanced performance [9].

SCMs contribute significantly to the sustainability of concrete by displacing cement in its formulation [10]. This displacement is pivotal in reducing the environmental impact associated with cement production, which is characterized by high energy consumption and substantial CO₂ emissions [11,12]. Integrating pozzolans into concrete mixtures mitigates these ecological ramifications and augments the material's durability, extending the structures' lifespan [7–9]. Table 2 describes the contribution of SCMs in reducing CO₂ emissions and mitigating environmental pollution, considering both economic and technical aspects. This comprehensive table delineates various SCMs' diverse aspects, including their capacity for reducing CO₂ emissions, environmental contributions such as recycling of resources or waste management, economic considerations in terms of cost-effectiveness, and the technical advantages they offer in terms of enhanced durability, strength, chemical resistance, and thermal performance in concrete production.

Table 2. Summary of SCMs' contribution to CO₂ emission reduction and environmental mitigation in concrete production: an economic and technical overview [13].

Type of SCM	CO ₂ Reduction	Environmental Contributions	Economic Benefits	Technical Advantages
Fly Ash	Moderate to High	Resource Recycling	Cost-effective	Enhanced Durability and Strength
Silica Fume	High	Reduced Carbon Footprint	Higher Cost	Increased Strength and Density
Ground Granulated Blast Furnace Slag	High	Waste Management	Moderate Cost	Chemical Resistance and Thermal Performance

Reducing the cement content by incorporating supplementary cementitious materials (SCMs) correlates with a decline in concrete's overall carbon footprint. Cement production, being energy-intensive, contributes significantly to global CO₂ emissions [14]. The use of SCMs relies on conventional cement, thus reducing CO₂ emissions and environmental impact. Additionally, including SCMs enhances the concluding properties through the pozzolanic reaction with calcium hydroxide (CH) formed during cement hydration [15–17]. This reaction yields additional binding compounds, resulting in denser concrete with improved strength and reduced permeability, enhancing its resistance to various detrimental factors like chemical attacks and cracking. The increased durability of concrete structures incorporating pozzolans prolongs their service life, reducing the need for frequent maintenance or premature replacement [15–17]. Consequently, this approach minimizes life cycle costs and mitigates the resource consumption associated with recurrent reconstruction activities, aligning with sustainable construction practices. In essence, utilizing SCMs in concrete offers a multifaceted approach to sustainability by addressing environmental concerns, enhancing structural integrity, and promoting longevity in concrete structures [18,19].

This research conducted a comprehensive assessment regarding the definition of class-C and class-F FA, their significance in the concrete industry for sustainability, and the alterations they bring about in the workability, physical characteristics, strength, and durability of concrete. This research aims to underline the pivotal role of these specific classes of FA in advancing sustainable practices within the concrete sector. The significance lies in elucidating how using class-C and class-F FA contributes to sustainable concrete production. By exploring their distinct properties and impacts on concrete, this inquiry sheds light on their potential to mitigate its environmental impact, enhance its performance, and extend the lifespan of concrete structures. The detailed analysis delves into how these materials, known for their pozzolanic properties, can effectively reduce the reliance on traditional cement, thereby curbing carbon emissions and conserving natural resources. This evaluation examines their effects on the workability, physical attributes such as particle size distribution and water demand, mechanical strength, and long-term durability against freeze–thaw cycles and chemical attacks. This research emphasizes the importance of deliberate material selection and optimized mix designs in achieving more sustainable and resilient concrete formulations by providing a nuanced understanding of these effects. Ultimately, this investigation highlights the pivotal role of class-C and class-F FA in promoting a more sustainable, durable, and environmentally conscious approach within the concrete industry. By emphasizing their multifaceted impact on concrete properties, this research encourages informed decision-making and innovation for enhanced sustainability in construction practices.

2. Exploring FA: Definition and Uses in Concrete Industry

Class-C and class-F fly ash (FA) is a byproduct of coal combustion in thermal power plants. When coal is burned in these facilities, a process that occurs at high temperatures with limited oxygen, some of the organic and mineral constituents of the coal undergo

gasification [10,11]. In contrast, others remain unburned, dispersing into the atmosphere as fine particles known as FA. Typically captured and separated through filtration systems in thermal power plants, FA's chemical and physical properties can vary based on factors such as the composition of the coal and combustion conditions [20,21]. Table 3 demonstrates that the FA key component is silicon dioxide (SiO_2), enabling its application in concrete production as a partial replacement for cement. Based on the research conducted by Rafieizonooz et al. [22], the yearly global output of FA corresponds to around 600 to 800 million tonnes. As the electricity demand grows, the issue of disposing of FA is expected to increase. For example, Taiwan relies on imported coal for almost 95% of its energy production. According to Lo et al. [23], Taiwan imported about 47 million tons of coal in 2018. According to data from the Ministry of Energy and Natural Resources, Turkey's gross electrical energy consumption stood at 257.2 billion kWh in 2014, experiencing a 2.7% increase compared to the previous year, reaching 264.1 billion kWh in 2015. Concurrently, electricity production, which totaled 252 billion kWh in 2014, witnessed a 3.1% rise in 2015, reaching 259.7 billion kWh. Notably, coal and natural gas are the primary sources of electricity production [24].

Table 3. FA chemical composition overview.

References	SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	SO_3	K_2O	Na_2O	LOI	Others
Lin et al. [25]	29.47	35.54	3.49	19.27	1.82	7.96	–	–	–	–
Subramaniam and Sathiparan [26]	50.8	6.3	6.8	29.1	1.9	1.9	0.9	2.2	–	1.2
Hwang and Yeon [27]	30.8	5	39.6	9.9	0.4	11.4	1.0	0.9	7.6	0.6
Ni et al. [28]	42.1	11.7	3.5	19.3	1.8	7.4	–	–	–	3.1
Singh et al. [29]	57.4	0.3	28.5	9.1	9.7	3.0	0.6	–	16.0	0.9
Wang et al. [30]	56.2	3.8	22.4	14.1	2.6	1.0	2.1	0.2	1.5	–
Saboo et al. [31]	47.5	11.3	8.2	21.7	2.5	1.7	–	–	2.5	–
Opiso et al. [32]	23.9	23.3	4.4	26.7	0.1	–	–	1.3	–	0.1
Liu et al. [33]	51.3	10.7	7.2	23.2	2.9	1.9	–	–	2.5	–
Muthaiyan and Thirumalai [34]	51.6	10.8	13.2	24.2	2.2	2.8	2.6	0.7	0.4	0.7
Swe et al. [35]	41.7	11.1	7.0	28.0	1.2	0.4	1.9	1.5	–	1.0
Shafabakhsh and Ahmadi [36]	50.9	1.6	4.7	27.9	2.3	–	–	–	3.7	–
Peng et al. [37]	50.2	12.5	7.2	23.2	2.9	–	–	–	2.5	–
Soto-Pérez and Hwang [38]	30.8	39.6	5.0	9.9	0.4	11.4	1.0	0.9	7.6	0.6
Mohammed et al. [39]	36.4	17.5	18.2	17.8	0.95	2.59	2.16	0.59	1.49	–
Ong et al. [40]	46.0	8.4	2.1	30.5	0.1	0.4	–	1.3	1.1	1.8

ASTM C618-15 [41] categorizes fly ash (FA) into class-C and class-F FA. The characteristics of class-C and class-F FA are depicted in Figure 3.



Figure 3. A view of class-C and class-F fly ash (FA). (a) Class-C FA [42]. (b) Class-F FA.

Conversely, Australia, Russia, Indonesia, South Africa, and Canada rank among the top five coal-exporting nations, with Australia leading at 59%, followed by Russia at 20%, Indonesia at 11%, South Africa at 6%, and Canada at 2.5%. These coal exports may contain elevated silica, alumina, and iron oxide levels, potentially exhibiting pozzolanic properties.

XRD and SEM images of class-C and class-F FA are shown in Figures 4 and 5, respectively. The phase analysis of the class-C FA was investigated by XRD (Model: Rigaku, D/MAX, Ultima III, Japan) at a scan speed of $10^\circ/\text{minute}$ and step size of 0.02 for a scan range of from 10° to 80° [43]. XRD patterns of class-F FA samples were performed on a MiniFlex600 diffractometer (Japan Rigaku Co., Ltd., Akishima, Japan) with Cu K α radiation (50 KV, 200 mA) [44]. The combined Fe_2O_3 , Al_2O_3 , and SiO_2 concentrations in both FA classes must exceed 50%. The quantity must fall between 50% and 70% for class-C FA, but it should exceed 70% for class-F FA. Furthermore, the calcium oxide (CaO) concentration in class-C FA must exceed 18%, but it should be below 18% for class-F FA.

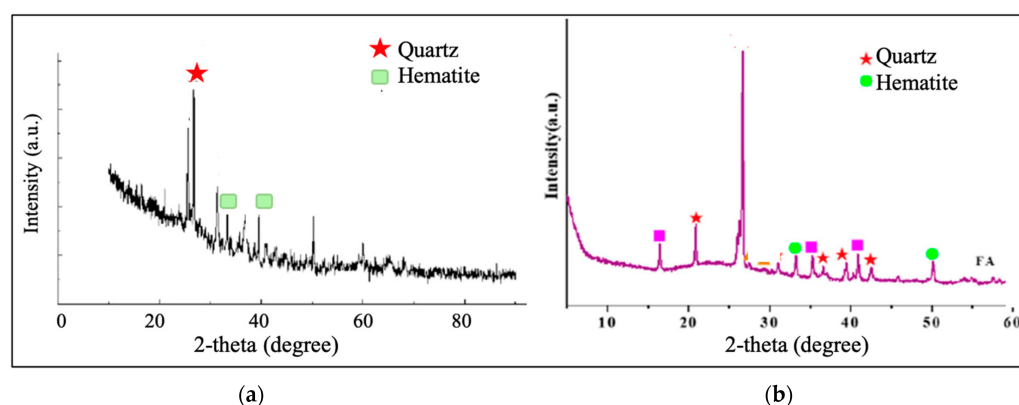


Figure 4. The XRD spectrums of class-C and class-F FA [43,44]. (a) Class-C FA [43]. (b) Class-F FA [44].

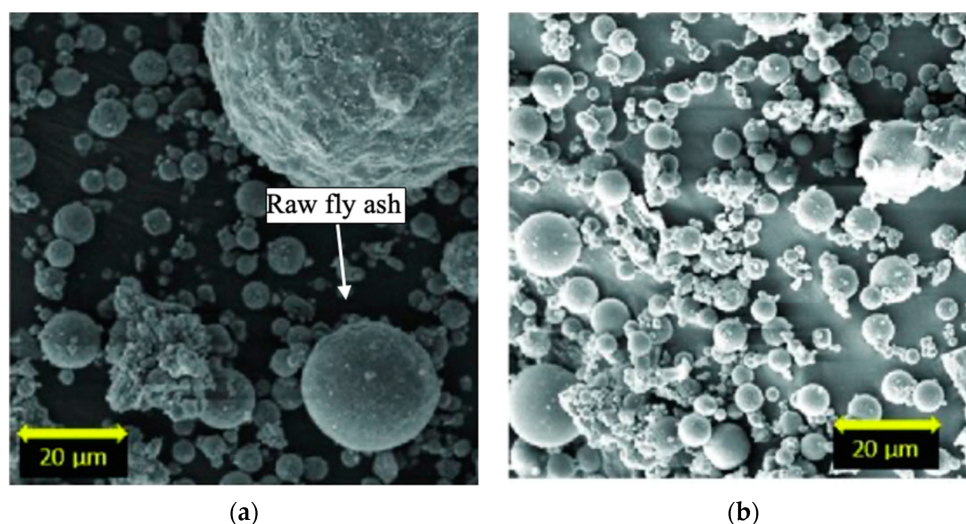


Figure 5. SEM images of class-C and class-F FA [45]. (a) Class-C FA. (b) Class-F FA.

Class-C FA, derived from the combustion of low-rank coals, has a significant quantity of calcium and exhibits more excellent cementitious characteristics than class-F FA. As a result, concrete made with class-C FA demonstrates superior early strength compared to conventional concrete. Its pozzolanic characteristics stem from its ability to react with cement-based binding materials.

Figure 5 shows SEM images of class-C and class-F FA. The class-C and class-F FA microstructural investigation was carried out using a TESCAN Vega 3 SEM. When used in

concrete production, FA interacts with the cement during hydration. This reaction leads to the formation of hydration products, contributing additional binding components within the concrete matrix. As a result, it enhances the concrete's mechanical properties, durability, and chemical resistance. FA finds application in producing sustainable building materials and in eco-friendly construction practices. However, carefully assessing FA's properties is essential before its use, and it should be incorporated into concrete mixtures at optimal ratios. The composition and attributes of FA can significantly impact concrete's mechanical performance and workability [46].

Consequently, understanding the role of FA in concrete production remains a crucial area of research concerning its properties, advantages, and appropriate utilization methods. Olarewaju [47] reveals that India is the leading global producer of coal fly ash (CFA), with a yearly production of 112 million tonnes and a utilization rate of 38%. China follows closely with a production of around 100 million tonnes and a utilization rate of 45%. The National Development and Reform Commission (NDRC) annual report of China provides data on the production and utilization of FA, indicating a significant production of coal fly ash (CFA) in China and its many applications, as shown in Figure 6. China is the leading producer of cement and concrete using CFA as a source. In addition, according to the latest Central Electricity Authority (CEA) data available for 2016–2017, thermal power plants in India generated almost 169 million tones (mt) of FA. Figure 7 displays the FA utilization and generation patterns from 2012 to 2017 in India.

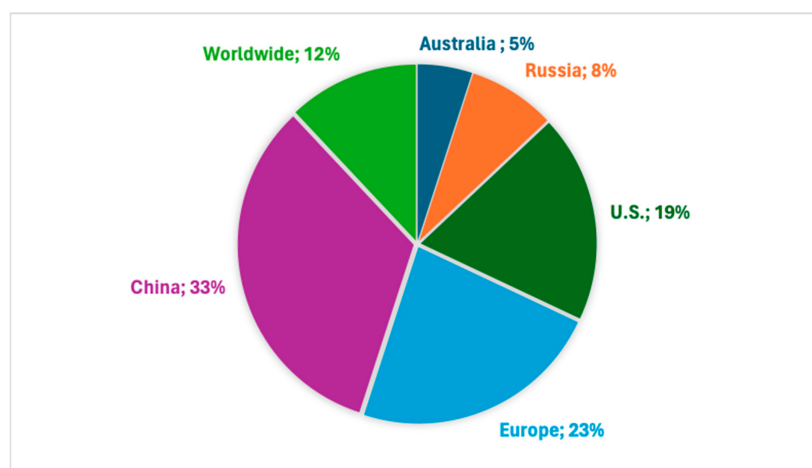


Figure 6. Global trends in fly ash (FA) utilization for concrete manufacturing [48].

On the other hand, class-F FA results from burning bituminous coal, which generally contains lower amounts of calcium oxide [49–54]. It does not exhibit self-cementing properties to the same extent as class-C FA. Class-F FA relies on external sources of CH to initiate the pozzolanic reaction. It tends to have finer particles and may require more time to develop strength than class-C FA [12–14]. The differences between class-C and class-F FA primarily stem from their chemical compositions, specifically regarding the calcium oxide content and reactivity. These variations affect their behavior in concrete mixtures, influencing factors like the setting time, early strength development, and overall performance. Understanding these distinctions is crucial for selecting the appropriate class of FA based on the desired concrete properties and performance criteria in construction applications.

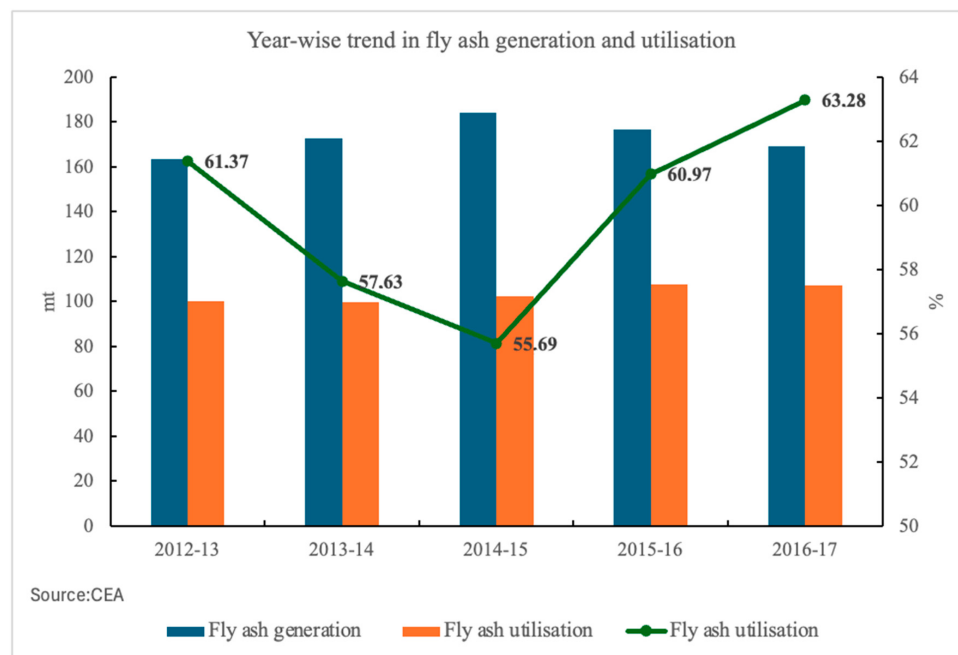


Figure 7. Temporal analysis of FA: utilization and generation patterns over the years in India [55].

The specific gravity of fly ashes (FAs) typically ranges from 1.3 to 4.8, a variance attributed to particle morphology, chemical composition, and color. For instance, American-produced FAs exhibit specific gravities of between 2.14 and 2.69, whereas those from Turkey range from 1.83 to 2.99. Various parameters, including the content of amorphous phases, fineness, chemical composition, and residual carbon content, govern the pozzolanic reactivity of FAs [56–58]. While many studies affirm that fine grinding significantly enhances the pozzolanic activity, it is noted that increases beyond 6000 cm²/g yield marginal improvements [59,60]. In Turkey, FA is predominantly generated as a byproduct of coal combustion in thermal power plants. The country possesses significant coal reserves, leading to a considerable annual FA production. This byproduct is actively used in the construction sector, particularly in the concrete industry. FA is an SCM in concrete output due to its pozzolanic properties, enhancing various characteristics of concrete mixtures. Its utilization helps to improve concrete structures' workability, durability, and long-term strength [15–17].

Furthermore, it reduces the demand for cement, thereby diminishing carbon emissions and promoting sustainability in the construction industry. However, despite its advantageous uses, challenges persist regarding the consistent quality and classification of FA, which may vary based on its source and composition. Additionally, efforts are ongoing to optimize the incorporation of FA into concrete mixtures, ensuring its compatibility and effectiveness in diverse construction applications. Turkey actively utilizes FA in the concrete industry as a sustainable solution, although continued research and standardization efforts are essential to maximize its benefits and address associated challenges [18–20].

3. Effects of FA on the Workability and Physical, Mechanical, and Durability Properties of Concrete

3.1. Utilizing FA for Enhanced Concrete Workability

Class-C and class-F fly ash (FA), derived from coal combustion, play pivotal roles in concrete workability owing to their distinct properties. Class-C FA, originating from burning sub-bituminous or lignite coals, exhibits self-cementing properties due to its high calcium oxide content, enabling it to react with water and facilitate early strength development [61–66]. This enhances the workability by lubricating the mixture, improving cohesiveness, and contributing to better concrete finishing [67–69]. Conversely, class-F FA, typically derived from burning bituminous coal, lacks inherent self-cementing properties but enhances the workability through the particle size distribution and shape [70–72]. Its

fine particles fill the voids between larger particles, enhancing the flowability and reducing the water demand. Both types of FA significantly impact concrete's rheology through their pozzolanic reactivity, which alters the setting time, water demand, and viscosity [73]. However, an excessive incorporation of FA can pose challenges to the workability, potentially requiring the addition of water-reducing admixtures or leading to increased water demand. Consequently, optimizing the proportion of class-C or class-F FA in concrete mixtures is essential in harnessing their positive effects on the workability without compromising the desired properties of fresh concrete [74–76]. High levels of FA replacement (>50%) may decrease the slump flow in self-compacting concrete (SCC) due to excessive superplasticizer use, which reduces fluidity [77–80]. This underscores the importance of striking a balance in the FA content to ensure the efficient utilization of this supplementary material while promoting sustainable construction practices. By understanding the unique influences of class-C and class-F FA on workability, concrete producers can make informed decisions regarding their incorporation, ultimately contributing to more efficient and sustainable concrete production processes.

3.2. Influence of FA on Concrete's Apparent Porosity

Class-C and class-F fly ash (FA), commonly utilized as supplementary cementitious materials (SCMs) in concrete, influence the total porosity of concrete matrices. Originating from sub-bituminous or lignite coal combustion, class-C FA triggers pozzolanic reactions with its higher calcium oxide content, leading to additional hydration products that refine the concrete's pore structure. This refinement reduces the total porosity due to the finer particles filling voids between the cementitious materials, resulting in a denser microstructure [81]. In contrast, class-F FA, derived from bituminous coal, possesses fewer self-cementing properties but still exhibits pozzolanic reactivity. While it reduces the total porosity, its impact may be less pronounced than class-C FA due to its finer particle size, partially filling the voids in the concrete matrix [82]. Incorporating either type of FA alters the pore size distribution and connectivity. Class-C FA generally refines the pore structure more effectively, leading to a more interconnected yet smaller pore network.

Optimizing the FA content and selection based on project-specific requirements are essential for achieving desired improvements in the total porosity and, consequently, enhancing the durability and performance of concrete structures [83–88]. Studies have shown that the porosity of concrete mixtures varies based on factors such as the FA substitution rate, particle size, and curing time, highlighting the need for careful consideration when integrating FA into concrete formulations.

3.3. Compressive Strength Analysis: Concrete Performance with FA Admixtures

Class-F and class-C fly ash (FA) affect concrete's compressive strength differently due to their chemical compositions and reactivities. Class-C FA, from sub-bituminous or lignite coal, has higher calcium oxide levels, leading to robust pozzolanic reactions that enhance the early and long-term strength [89–91]. It forms additional cementitious compounds, refining the microstructure and improving the compressive strength. Conversely, class-F FA, from bituminous coal, with its lower calcium oxide content, relies more on its fine particle size and pozzolanic reactivity to bolster the compressive strength [92,93]. While it may not exhibit strong self-cementing properties, it densifies the matrix and reduces pore connectivity, enhancing the long-term strength. Both FA types fill voids, reduce porosity, and promote additional cementitious compound formation, bolstering concrete's resistance to compressive stresses. Selection depends on the project needs and regional availability, offering distinct advantages based on chemical composition and reactivity. Optimizing the dosage and selection ensures improved compressive strength while maintaining the concrete's durability [94–96]. Harison et al. [94] reported that in mixtures utilizing class-C fly ash (FA), the 7-day compressive strengths decreased due to slow hydration. Still, with increasing curing durations, the rate of strength gain increased. It was observed that the 56-day samples exhibited higher compressive strengths compared

to the control mixture. However, for replacement rates exceeding 20% (specifically for 30%, 40%, 50%, and 60% replacements), the compressive strength was lower even at later ages compared to the control sample. Cho et al. [95] examined cement pastes' compressive strengths using 16 types of class-F FA with distinct chemical compositions. They noted that with prolonged curing durations, the compressive strengths increased, but variations were observed depending on the kind of FA used. FA13, with the lowest CaO content (2.54%), exhibited the lowest compressive strength, while FA8, with the highest CaO content (6.17%), showed the highest compressive strength. Additionally, when examining the 28-day compressive strengths, the difference between the highest and lowest strengths was 10.4 MPa. In contrast, this value increased to 14.8 MPa for the 91-day samples, indicating denser matrix formation due to progressing hydration. Sun et al. [96] indicated that in high-FA-content concretes where class-F FA was used instead of cement at replacement rates of 40%, 55%, and 70%, the early-age compressive strengths decreased with increasing FA replacement ratios. As the hydration progressed, the compressive strength increased due to the pozzolanic effect of the FA, but the specimens failed to match the control's strength. Following 180 days of curing, the compressive strengths of the control and the 40% FA, 55% FA, and 70% FA mixtures were reported as 59.4 MPa, 58.7 MPa, 41.2 MPa, and 28.1 MPa, respectively. The relationship between FA utilization and the compressive strength of concrete obtained from some recent studies is depicted in Figure 8 [97–101].

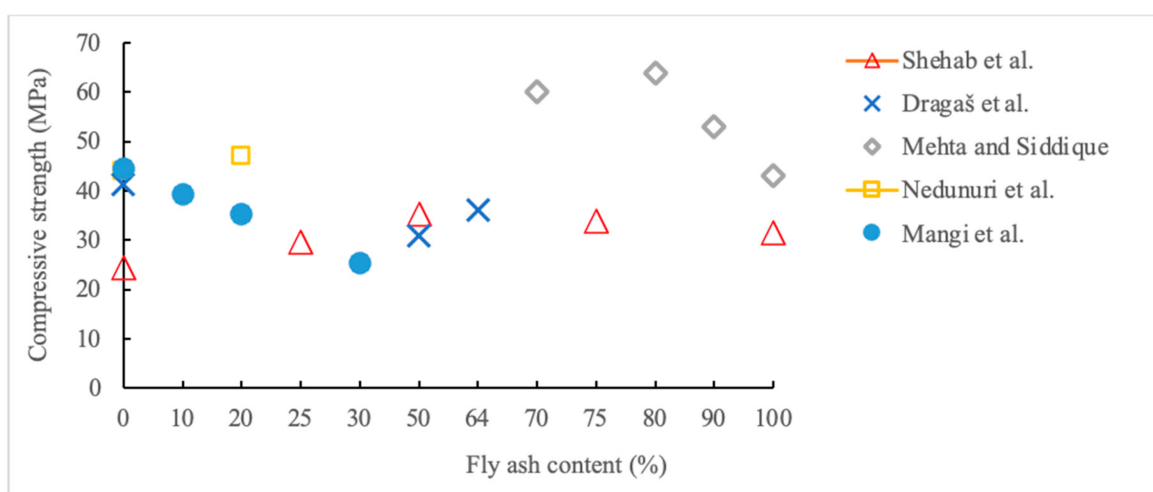


Figure 8. Recent studies depicting the correlation between the use of FA and the resulting compressive strength of concrete [60–64].

3.4. Examining Concrete Flexural Strength with FA Addition

The impact of class-C and class-F FA on the flexural strength of concrete samples is significant, stemming from their distinct chemical compositions and pozzolanic activities. Class-C FA, typically derived from sub-bituminous or lignite coal combustion, contains higher levels of calcium oxide. Its pozzolanic reactivity and self-cementing properties improve concrete's flexural strength. Class-C FA initiates a pozzolanic reaction with calcium hydroxide formed during cement hydration when incorporated into concrete mixes. This reaction generates supplementary calcium–silicate–hydrate (C-S-H) gel, increasing the interlocking and densification within the concrete matrix. The enhanced microstructure contributes to improved flexural strength, especially during the early stages of concrete curing [21].

On the other hand, class-F FA, originating from bituminous coal combustion, contains lower levels of calcium oxide and relies more on its fine particle size and pozzolanic reactivity to enhance the flexural strength. While it may not exhibit substantial self-cementing properties, class-F FA's pozzolanic activity forms additional C-S-H gel and other cementitious compounds. This process densifies the concrete matrix, improves the bond strength,

and enhances the flexural strength of concrete over time [22]. Both class-C and class-F FA act as SCMs, refining the microstructure and enhancing the flexural strength of concrete. Their contributions include reducing voids, improving particle packing, and promoting additional cementitious compound formation, ultimately enhancing the concrete's resistance to flexural stresses. The choice between class-C and class-F FA depends on the specific project requirements, desired concrete properties, and regional availability, as each class offers unique advantages in enhancing flexural strength based on its chemical composition and pozzolanic reactivity [23,24].

3.5. Assessing Freeze–Thaw Resistance in Concrete Enhanced by FA

Freeze–thaw (F-T) cycling is a phenomenon that affects concrete durability, particularly in colder climates or regions where temperature variations lead to repeated freezing and thawing of moisture within the concrete. When the water within the concrete freezes, it expands, creating internal pressure. This expansion stresses the concrete matrix, leading to the cracking and deterioration of the material. When the ice melts during thawing, the water moves into the voids left by the ice crystals, potentially causing further damage due to volume changes [25]. A representative illustration in Figure 9 demonstrates the formation and progression of damage within the internal structure of concrete resulting from freeze–thaw cycles.

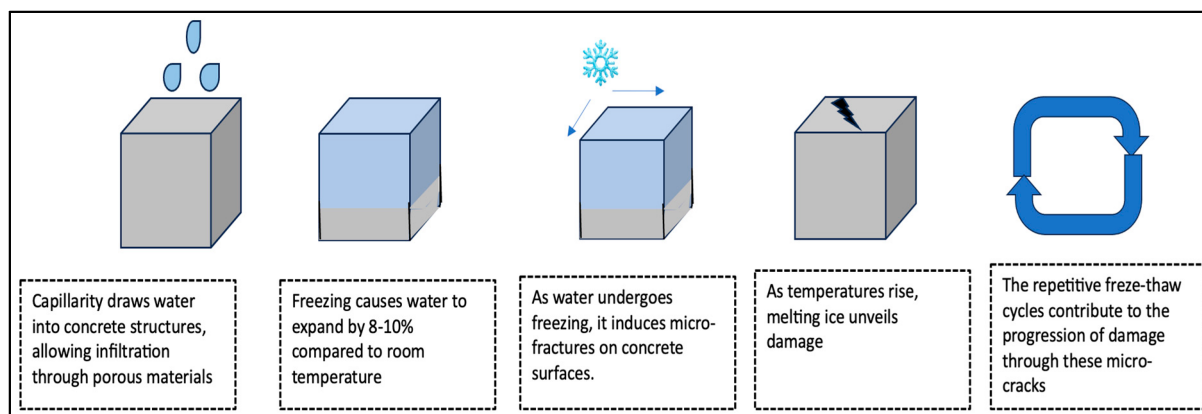


Figure 9. The evolution and propagation of damage within the internal microstructure of concrete induced by F-T cycles.

3.6. Cycles Impacting the Durability of a Concrete Structure

This cyclical process of freezing and thawing weakens the concrete over time, compromising its structural integrity and leading to surface scaling, spalling, and reduced durability. Factors such as the quality of concrete, air entrainment, porosity, and reinforcing materials influence how susceptible the concrete is to F-T damage [26]. Concrete mix designs often incorporate air-entraining admixtures to mitigate F-T damage that create tiny air bubbles within the concrete. These air voids allow water to expand during freezing, reducing internal pressures and minimizing the risk of cracking [102–107]. Regular maintenance and repair and proper construction practices are crucial in preventing and managing the effects of F-T cycles on concrete structures, particularly in areas prone to such weather conditions [27]. Islam et al. [108] investigated the use of class-F FA at four different levels of replacement (20%, 30%, 40%, and 60%) instead of cement, noting that the mixtures containing FA exhibited more excellent resistance, particularly after prolonged freeze–thaw (F-T) cycles. Some researchers have stated that the effect of FA-containing concrete against F-T cycles occurs in more extended periods [109–111]. Liu et al. [109] produced pervious concretes by substituting cement with class-C FA at 3%, 6%, 9%, and 12% replacement rates. They observed decreased compressive strengths of all the mixtures containing FA with increasing F-T cycles. At 28 days, when the addition of FA changed from 0% to 12%, the compressive strength decreased from 22.2 MPa to 14.7 MPa, and the

compressive strength reduction was 7.5 MPa with a loss ratio of 33.8%. At 150 days, the 150-day compressive strength of the FA-modified pervious concrete increased at all addition levels compared to the 28-day compressive strength. The 3% FA-modified group had the maximum levels compared to the 28-day compressive strength. The 3% FA-modified group had the maximum 150-day compressive strength of 21.5 MPa, which was comparable to the control group with a strength of 22.2 MPa. The 12% FA-modified group had a 150-day compressive strength of 17.4 MPa. This improvement was because the FA reacted with the cement hydration product (CH) and formed a pozzolanic C–S–H gel, which improved the bonding between the hardened cement binder and the aggregate [109].

Öztürk and Kılınçkale [110] conducted a study where class-F FA was used at a replacement rate of 20% instead of cement. They reported that while the compressive strengths of the control specimens without FA decreased by 5% after F-T cycles, the decrease in the specimens containing FA was 10% at 90 days. Class-C and class-F FA are crucial in enhancing concrete performance, particularly in terms of the strength, durability against F-T cycles, prolonged service life, and economic benefits. Berry and Malhotra [111] indicated that cement replacement by FA at any percentage reduced the compressive strength up to a 90-day curing period. In contrast, greater strength was achieved at a curing time of 180 days or longer [112,113].

(a) **Strength Enhancement:** Class-C and class-F FA are SCMs that bolster concrete's compressive strength and overall durability. Their inclusion fills voids and enhances the structure's resilience.

(b) **Durability Against F-T Cycles:** The pozzolanic effect of class-F FA is particularly noteworthy, significantly reducing the harmful impact of F-T cycles. By diminishing water permeability and concrete's susceptibility to expansion during freezing, FA mitigates cracking and deterioration due to these cycles.

(c) **Extended Service Life:** Using class-C and class-F FA results in structures with prolonged longevity. Their ability to fortify concrete's resistance against weathering, including F-T cycles, preserves its structural integrity over an extended period.

(d) **Economic Benefits:** Incorporating FA, a byproduct of coal combustion, into concrete formulations provides economic advantages. It decreases the reliance on cement, reducing production costs. Moreover, the improved durability and extended service life of these structures minimize maintenance expenses, leading to long-term cost savings.

4. Environmental Impact Analysis: Concrete Incorporating FA—A Life Cycle Assessment

The use of class-C and class-F FA in concrete involves a comprehensive assessment throughout its life cycle, encompassing extraction, production, utilization, and end-of-life phases. Class-C and class-F FA, derived from coal combustion, offer substantial potential as SCMs, impacting the environmental footprint and performance of concrete structures. Figure 10 illustrates the influence of SCM incorporation in concrete through a comprehensive LCA.

In the extraction phase, the acquisition of FA involves processes related to coal combustion in thermal power plants. While this phase emits pollutants during coal combustion, using FA as a byproduct mitigates environmental burdens by diverting waste from landfills and reducing the need for virgin materials in concrete production. However, differences in class-C and class-F FA production, such as combustion temperatures and coal classes, result in distinct chemical compositions and reactivity, influencing their environmental impact. Using FA in concrete mixtures reduces cement consumption, thus decreasing greenhouse gas emissions associated with cement production. This substitution offers benefits in terms of enhanced durability, reduced energy consumption, and improved mechanical properties of concrete structures. However, the transportation of FA to concrete plants and the varying geographical availability of specific FA classes impact the overall environmental footprint and sustainability of its use in concrete. Throughout the service life of concrete structures, the performance and durability benefits provided by class-C and class-F FA reduce the need for maintenance, extending the lifespan of the structures.

However, the end-of-life phase entails considering the recycling or disposal of demolished concrete containing FA. Conclusively, incorporating class-C and class-F FA in concrete presents a promising strategy for reducing environmental impacts throughout the life cycle of concrete structures [28–30]. The ecological benefits of reduced cement consumption and the improved performance must be weighed against factors like transportation emissions and variations in FA properties. The aforementioned factors necessitate a comprehensive life cycle analysis (LCA) for informed decision-making in sustainable concrete construction practices. The utilization of SCMs in concrete production delineates various stages, and their environmental impacts are shown in Table 4.

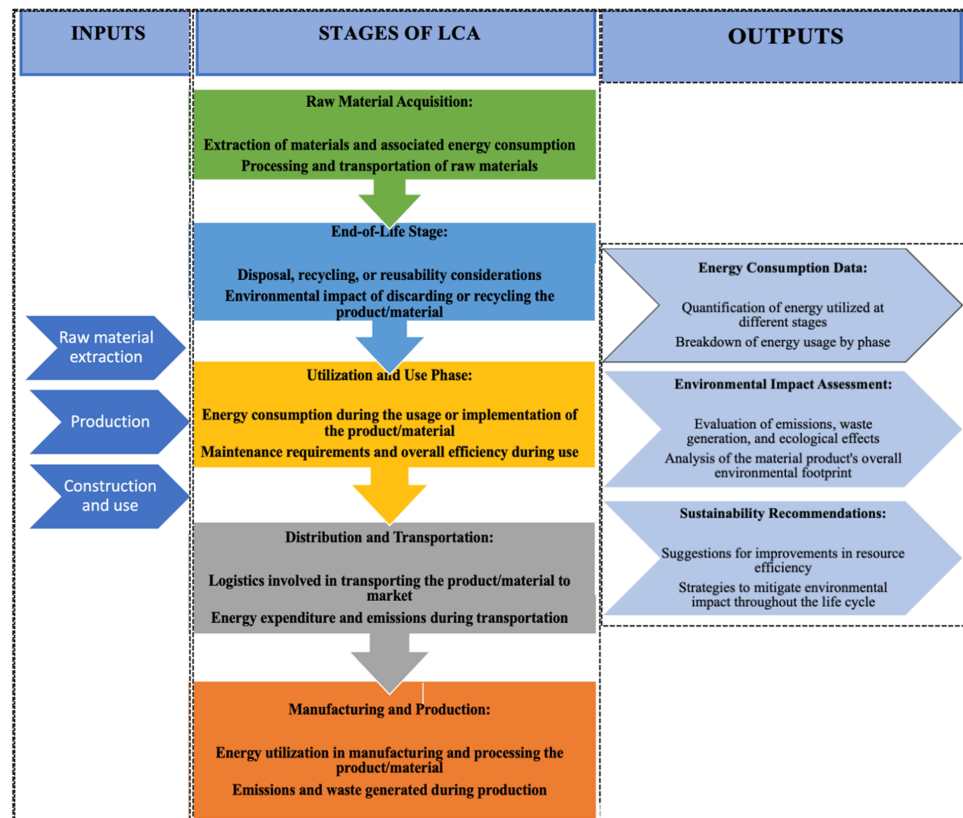


Figure 10. Assessing the impact of incorporation of supplementary cementitious materials (SCMs) in concrete using a holistic life cycle assessment (LCA).

Table 4. The significance of pozzolanic materials in concrete: a sustainability and life cycle analysis perspective.

Aspect	Impact	Detailed Description
CO ₂ Reduction	Reduced Carbon Footprint	Reduction in CO ₂ emissions through the use of pozzolans instead of cement
Conservation of Natural Resources	Efficient Utilization of Raw Materials	Pozzolans contribute to the preservation of natural resources
Durability and Service Life	Long-lasting and Durable Structures	Pozzolans enhance concrete durability, leading to longer service life
Waste Management and Recycling	Waste Reduction and Recycling Opportunities	Pozzolans contribute to reduced concrete waste and enable recycling
Energy Efficiency	Reduced Energy Consumption in Production Processes	Pozzolans lower energy consumption in concrete production

Table 5 outlines various aspects demonstrating the importance of using SCMs from the perspective of sustainability and life cycle analysis. It highlights how these materials contribute to reducing CO₂ emissions, conserving natural resources, enhancing durability, managing waste, recycling possibilities, and increasing energy efficiency in concrete production. For instance, substituting cement with class-C and class-F FA may yield energy savings and reduce CO₂ emissions during raw material acquisition. However, transportation activities might contribute to a higher carbon footprint. Incorporating class-C and class-F FA in concrete, enhancing its durability, and potentially reducing long-term maintenance needs are critical factors influencing the effectiveness of the undertaken activities. This table evaluates the environmental footprint and resource utilization throughout the concrete life cycle, emphasizing FA's role in sustainable concrete production. Table 4 describes the LCA and ecological impact of using class-C and class-F fly ash as a substitute for cement in concrete. Table 5 comprehensively overviews each stage's environmental impacts and contributions. Using class-C and class-F fly ash in concrete production presents potential for resource reduction, energy efficiency, transportation impacts, enhanced durability, recycling prospects, and waste management strategies.

Table 5. LCA and environmental impact of utilizing class-C and class-F fly ash as cement substitutes in concrete production: a comprehensive overview.

Stage	Impact	Detailed Description
Raw Material Acquisition	Resource Reduction, Waste Management	Extraction and recycling of FA, optimizing resource utilization
Production	Energy Efficiency, Carbon Reduction	Energy efficiency and CO ₂ reduction in FA incorporation in concrete
Transportation	Carbon Footprint, Transportation Costs	Impact of FA transportation on carbon footprint and costs
Construction	Increased Durability, Reduced Maintenance Needs	Improved durability of concrete and decreased maintenance requirements
Recycling	Waste Reduction, Recycling Opportunities	Recycling potential and waste reduction through reused concrete
Waste Management	Waste Disposal, Recovery Opportunities	Environmental impact and management of FA and concrete waste

Table 6 provides a comprehensive insight into the profound influence of SCMs within concrete, emphasizing their substantive impact through quantifiable metrics. It delineates their pivotal role in facilitating several critical facets of concrete production. Specifically, it elucidates the significant contributions of SCMs in curbing CO₂ emissions, meticulously conserving finite natural resources, bolstering structural longevity by enhancing durability, orchestrating effective waste management strategies, and optimizing energy efficiency throughout concrete production processes. It includes quantifiable data in percentages as an illustrative representation, showcasing SCMs' tangible effects and efficacy across each distinct aspect and underlining their multifaceted contributions to sustainable practices within concrete engineering.

Table 6. Quantified impact of pozzolanic materials in concrete: a comprehensive analysis of sustainability factors and performance metrics.

Aspect	Impact	Detailed Description	Quantitative Impact (Example)
CO ₂ Reduction	Reduced Carbon Footprint	Reduction in CO ₂ emissions through pozzolan use	25% decrease in CO ₂ emissions
Conservation of Natural Resources	Efficient Utilization of Raw Materials	Lower consumption of natural resources due to pozzolan use	30% reduction in raw material usage
Durability and Service Life	Long-lasting and Durable Structures	Increased lifespan of structures with pozzolan-enhanced concrete	40% longer service life
Waste Management and Recycling	Waste Reduction and Recycling Opportunities	Reduced concrete waste and potential for recycling	20% decrease in waste production
Energy Efficiency	Reduced Energy Consumption in Production Processes	Lower energy requirements in concrete production	15% decrease in energy consumption

5. Conclusions

Incorporating class-C and class-F FA as viable cement substitutes in concrete represents a promising avenue for mitigating CO₂ emissions, significantly contributing to environmental sustainability and human health enhancement. The culmination of our findings, particularly highlighting the reduction in porosity and improvements in mechanical strengths associated with these FA classes, paints a vivid picture of their multifaceted impact on concrete performance. The significant achievement in reducing CO₂ emissions is attributed to the decreased reliance on cement within concrete formulations. As cement production is a notorious contributor to global carbon emissions, the diminished usage of cement through the integration of FA, a byproduct of industrial processes, not only curtails CO₂ emissions but also alleviates the environmental strain associated with cement manufacturing. FA's multifaceted advantages extend beyond its mere cement-replacement role. The improvements in concrete properties, such as reduced porosity and enhanced durability, signify a paradigm shift towards longer-lasting structures. This reduction in the need for frequent repairs or replacements minimizes resource consumption and waste generation, contributing to a more sustainable construction ecosystem.

Moreover, this approach has ancillary benefits for human health. The resilience and longevity of concrete structures fortified by fly ash (FA) translate into safer and more stable infrastructures, reducing the potential hazards associated with deteriorating constructions. The overall enhancement in structural integrity and reliability safeguards public safety and potentially reduces the economic burden of maintenance and repair activities. Class-C and class-F FA in concrete reverberate with profound environmental and societal implications. Beyond the reduction in CO₂ emissions, these materials represent a transformative force in constructing more resilient, durable, and sustainable infrastructures, aligning with global sustainability initiatives while promoting the well-being of present and future generations. In the future, the utilization of FA is poised to bolster sustainability across various industries, primarily in construction and infrastructure development. FA's multifaceted contributions towards mitigating environmental impacts, optimizing resource utilization, and fostering resilient, eco-friendly practices are significant. Firstly, FA's use as a supplementary cementitious material in concrete holds immense promise. As sustainable construction practices gain prominence, reducing cement consumption for its substantial carbon footprint becomes increasingly vital. FA presents a compelling alternative to industrial processes like coal combustion. Its integration into concrete formulations effectively reduces the demand for cement, thus curtailing CO₂ emissions and lessening the environmental strain associated with traditional concrete production.

Furthermore, FA's role extends beyond emissions reduction. Its incorporation enhances concrete's properties, fostering durable and longer-lasting infrastructures. This durability reduces maintenance requirements and extends structure lifespan, aligning with sustainability goals by curbing resource depletion and minimizing waste generation. Moreover, the circular economy concept underscores FA's significance. FA exemplifies resource optimization and waste minimization by repurposing a byproduct of industrial

processes into a valuable construction material. Its integration into construction aligns with the principles of sustainability by closing the loop on material utilization, reducing reliance on finite resources, and diverting waste from landfills. In sustainable development, FA's versatility as a material extends beyond concrete. It finds applications in various sectors, including agriculture, geotechnical engineering, and waste stabilization, showcasing its potential to drive sustainability in diverse domains.

In conclusion, FA's imminent importance in promoting sustainability is multifaceted. Its role in reducing CO₂ emissions, enhancing infrastructure durability, optimizing resource utilization, and contributing to a circular economy aligns seamlessly with global sustainability agendas. As industries increasingly pivot towards eco-conscious practices, using FA is a beacon of sustainable innovation, promising a future where industrial byproducts become catalysts for a more sustainable, resilient, and environmentally conscious world.

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