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Low-Carbon Construction Materials and Green Concrete: A Mini Review

Sakineh Alizadeh*[1], and Hojjat Bedreh[2]

[1]*Department of Analytical Chemistry, Faculty of Chemistry, Bu-Ali Sina University, 65178638695 Hamadan, Iran*
[2]*Urmia Metropolitan Municipality, Urmia, Iran*

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Corresponding Author: **Sakineh Alizadeh** | E-Mail: **(alizadehsakineh904@gmail.com)**

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ABSTRACT

The construction industry is one of the largest consumers of natural resources and producers of greenhouse gases worldwide. Portland cement production alone contributes significantly to carbon dioxide emissions, leading to the emergence of low-carbon and green concrete as one of the most important new approaches in civil engineering. In Iran, given the high volume of construction projects, urban development, infrastructure projects, and limited natural resources, the use of environmentally friendly concrete is not only a technical choice but also a future-oriented necessity. This article provides a comprehensive review of low-carbon concrete, the role of concrete additives, their effects on the durability of structures, and their practical applications in Iran's climatic conditions.

Keywords: *Low-Carbon Concrete; Green Concrete; Structural Durability; Silica Fume; Carbonation; Concrete Strength.*

Introduction

Low-Carbon and Green Concrete

An Innovative Approach to Reducing the Environmental Impacts of the Construction Industry Without Compromising Durability. The construction industry is one of the world's largest consumers of natural resources and producers of greenhouse gas emissions. The production of Portland cement alone accounts for a significant share of carbon dioxide (CO_2) emissions. This issue has led to the emergence of low-carbon concrete and green concrete as important modern approaches in civil engineering [1]. In Iran, considering the high volume of construction projects, urban development, infrastructure projects, and limitations in natural resources, the use of environmentally friendly concrete is not only a technical option but also a forward-looking necessity. This article provides a comprehensive review of low-carbon concrete, the role of concrete admixtures, their effects on structural durability, and their practical applications under the climatic conditions of Iran.

What is Low-Carbon Concrete?

Low-carbon concrete is an engineered type of concrete designed to reduce CO_2 emissions during its production and implementation without compromising its strength, durability, or structural performance [1,2].

Carbon reduction in low-carbon concrete is generally achieved through:

1. Reducing cement consumption
2. Replacing a portion of cement with pozzolanic materials
3. Using advanced concrete admixtures
4. Increasing the durability and service life of structures

Difference Between Low-Carbon Concrete and Conventional Concrete

In conventional concrete, the primary focus is often placed on compressive strength. In contrast, low-carbon concrete places greater emphasis on:

- Concrete durability
- Reduced permeability
- Reduced need for concrete repair
- Increased service life of structures

These characteristics can contribute to reducing the consumption of resources and energy over the long term [1-3].

Role of Silica-Fume Gel in Low-Carbon Concrete

Silica-fume gel contributes to low-carbon concrete mainly through the formation of secondary C–S–H gel, filling fine pores, and reducing concrete permeability. These effects can make it possible to replace a portion of Portland cement with silica fume while maintaining the required concrete performance. As a result, under an appropriately designed mixture, the overall carbon emissions associated with concrete production and its life cycle can potentially be reduced [1,4].



Figure 1: Images presenting green concrete and environment [4].

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Mechanism of C–S–H Gel Formation in Concrete Containing Silica Fume

Silica fume is an extremely fine-grained material rich in amorphous silica. In the alkaline environment of cement paste, it reacts with the hydration products of cement. The most important pozzolanic reaction of silica fume involves the consumption of calcium hydroxide, $Ca(OH)_2$, and the formation of secondary C–S–H gel. This gel is one of the most important factors contributing to concrete strength and reducing its permeability [4-6].

The pozzolanic reaction can be simplified as follows:

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C–S–H$$

In ordinary concrete, part of the cement hydration process produces calcium hydroxide. Compared with C–S–H gel, calcium hydroxide contributes less to strength development and may provide lower durability under certain aggressive environmental conditions. When silica fume is incorporated into concrete, the reactive silica reacts with $Ca(OH)_2$ and produces additional C–S–H gel. Moreover, the extremely small particle size of silica fume enables these particles to fill voids and fine pores within the cement paste structure. As a result, the concrete becomes denser, while the pathways through which water, chloride ions, and other aggressive agents can penetrate are reduced [7].

Main Effects of Silica Fume on Concrete

The proper use of silica fume can result in:

- Increased compressive and tensile strength of concrete;
- Reduced permeability and water absorption;
- Improved resistance to chloride-ion penetration;
- Enhanced resistance to aggressive environmental conditions;
- Reduced porosity and refinement of the pore structure;
- Increased durability and service life of structures;
- Reduced need for premature repair and replacement of concrete [8].

Silica Fume and Carbon Reduction in Concrete

It is important to note that the use of silica fume alone does not necessarily guarantee a reduction in carbon emissions. The environmental impact of concrete depends on factors such as cement content, replacement level, material production processes, transportation, and mixture design. However, in an optimised concrete mixture, silica fume can contribute to reducing the required amount of cement or extending the service life of a structure through improved strength and durability. Consequently, carbon emissions per unit of structural performance over the life cycle of the structure can potentially be reduced.

Conclusion

Therefore, the role of silica fume in low-carbon concrete can be summarised in four main stages:

Pozzolanic reaction → Formation of secondary C–S–H → Densification of the concrete structure and reduction in permeability → Increased concrete durability

This sequence demonstrates that in the design of low-carbon concrete, reducing cement content should be considered simultaneously with maintaining or improving the durability and performance of concrete.

More durable concrete can reduce the need for repair, demolition, and reconstruction throughout the service life of a structure, thereby contributing to a lower overall environmental impact [7,8].

Mechanism of Gel Formation

Silica fume, also known as micro-silica, consists of extremely fine particles that are rich in **SiO_2**. In the alkaline environment of cement paste, silica fume undergoes a pozzolanic reaction with calcium hydroxide.

The reaction can be simplified as follows:

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C–S–H$$

Microsilica → Secondary C–S–H Gel → Lower Porosity → Lower Permeability and Higher Strength → Reduced Cement Consumption and Lower Life-Cycle Carbon Emissions.

Silica fume reacts pozzolanically with calcium hydroxide, or portlandite, produced during cement hydration and generates additional calcium silicate hydrate (C–S–H) gel. C–S–H is the primary hydration product responsible for the bonding and strength development of concrete. In the silica-fume gel model, silica-fume particles initially interact with water and form a silica-rich gel. This gel is distributed between cement particles and subsequently reacts with calcium hydroxide to form secondary C–S–H [9].

Main Roles in Low-Carbon Concrete

- **Reduction in cement consumption:** Replacing a portion of cement with silica fume reduces the amount of clinker required; consequently, CO_2 emissions associated with cement production can be reduced.
- **Pore filling:** The extremely fine silica-fume particles fill voids between cement particles and, together with the formation of C–S–H gel, make the cement paste structure denser.
- **Reduction in porosity and permeability:** The capillary pore network becomes finer, while the continuity of pathways through which water and ions can penetrate is reduced.
- **Improvement of early-age and long-term strength:** The pozzolanic reaction and filler effect can increase compressive strength, particularly at later ages as the pozzolanic reaction progresses [7-9].
- **Improvement of the aggregate–paste interfacial transition zone:** The formation of denser hydration products can refine the interfacial transition zone (**ITZ**), which is generally considered one of the more vulnerable regions of concrete.
- **Improved durability:** Concrete can become more resistant to chloride-ion penetration, sulfate attack, and certain other aggressive environmental conditions. Research has shown that silica fume can improve concrete resistance to penetration and carbonation by refining the pore structure and producing additional C–S–H[10].

Relationship with Carbon Reduction

Carbon reduction does not occur solely through cement replacement. By improving strength and durability, silica fume can facilitate the design of more efficient structural sections, reduce maintenance and repair requirements, and extend the service life of structures.

Therefore, when the entire life cycle of concrete is considered, the reduction in emissions per unit of structural performance or per year of service can potentially be greater than the reduction achieved solely through a direct decrease in cement content. The combined use of silica fume with other supplementary cementitious materials, such as fly ash or ground granulated blast-furnace slag (GGBFS), can further contribute to reducing the carbon footprint of concrete [10].

Important Limitations

- Silica fume has a high water demand and may reduce the workability of fresh concrete; therefore, the use of a high-range water-reducing admixture (superplasticiser) is often necessary.
- Excessive silica-fume content may increase autogenous shrinkage and drying shrinkage.
- Its actual reactivity depends on particle size, specific surface area, SiO_2 content, moisture condition, and curing method.
- Silica fume is not necessarily the best carbon-reduction solution by itself, because its production, processing, and transportation must also be considered in a life-cycle assessment [9-11].
- The optimum replacement level should be determined experimentally. Typical silica-fume contents in high-performance concrete are often around 5–10% by mass of cementitious materials, although the appropriate amount depends on the mixture design and the required durability performance.

Summary

The role of silica fume can be summarised as follows:

Microsilica → Secondary C–S–H Gel → Lower Porosity → Lower Permeability and Higher Strength → Reduced Cement Consumption and Lower Life-Cycle Carbon Emissions

Therefore, silica fume in low-carbon concrete acts both as a reactive pozzolanic material and as a microstructural filler. However, its dosage, the need for superplasticisers, and its effects on shrinkage must be controlled simultaneously [8-10].

Silica Fume Gel in Green Concrete

Silica fume gel is considered one of the important components of green concrete. By replacing a portion of cement, it can simultaneously contribute to reducing cement consumption and improving concrete durability.

Advantages

1. Reduction in concrete porosity and permeability
2. Increased resistance to chloride ions and sulfate attack
3. Increased compressive and abrasion resistance
4. Extended service life of structures in aggressive environments
5. Contribution of superplasticizers to improved concrete performance and reduced carbon footprint

A superplasticizer plays an indirect but highly effective role in carbon reduction by allowing the water-to-cementitious-material ratio to be reduced while maintaining the required workability [6,7].

Functions of Superplasticisers

Superplasticisers can contribute to:

1. Reducing the water-to-cement ratio
2. Reducing cement consumption while maintaining adequate workability
3. Improving concrete compaction and density
4. Controlling and potentially reducing shrinkage-related cracking when properly incorporated into an optimised mixture

These factors can reduce the need for future concrete repair and strengthening.

Concrete Admixtures in the Development of Green Concrete

Modern concrete admixtures can enable low-carbon concrete to achieve performance equal to or, in some applications, better than conventional concrete.

Important categories of admixtures and related materials include [6]:

1. Supplementary cementitious and pozzolanic materials
2. Crystalline admixtures for concrete waterproofing
3. Corrosion-inhibiting admixtures
4. Durability-enhancing admixtures and materials

Relationship Between Low-Carbon Concrete and Concrete Waterproofing

Low-carbon concrete designed with a dense microstructure and optimized mixture proportions can have relatively low permeability. This characteristic can contribute to improved waterproofing performance.

In combination with suitable waterproofing systems and construction materials, such as:

- Concrete water stops
- Polyurethane sealants and mastics
- Concrete bonding agents

the service life of underground structures, water-retaining structures, and tunnels can be improved [6,9].

Green Concrete and Reduction in Repair and Strengthening Requirements

One of the important potential benefits of durable low-carbon concrete is the reduction in deterioration and cracking over the service life of a structure.

Potential results include:

1. Reduced frequency of concrete repair
2. Reduced consumption of grout and repair mortars
3. Lower maintenance costs
4. Increased structural durability and service life

Quality Control of Low-Carbon Concrete

Quality control is particularly important in green and low-carbon concrete because changes in mixture proportions and supplementary cementitious materials can significantly affect fresh and hardened concrete properties.

Common quality-control and assessment methods include:

- **Non-destructive testing (NDT) of concrete**
- **Ultrasonic pulse velocity (UPV) testing**
- **Concrete scanning and assessment of uniformity and reinforcement cover**

These methods can help evaluate concrete quality without causing significant damage to the structure.

Applications of Low-Carbon Concrete in Iranian Projects

Low-carbon concrete can be considered for a wide range of construction projects, including [8,10]:

- Large urban structures
- Metro and tunnel projects
- Marine and coastal structures
- Water-storage tanks and water-treatment plants
- Industrial projects

The appropriate concrete mixture should be selected according to the environmental exposure, structural requirements, durability criteria, and local materials available for each project.

Challenges in Implementing Low-Carbon Concrete in Iran

Some of the challenges associated with the implementation of low-carbon concrete in Iran include:

- Limited familiarity among some contractors and construction practitioners
- Concerns regarding possible reductions in strength
- The need for careful selection and dosage of concrete admixtures
- The need for proper mixture design, curing, and quality control

These challenges can be addressed through technical consultation, laboratory testing, appropriate mixture design, and the use of standardised materials and products [6].

Role of Concrete Clinic in the Development of Green Concrete

Concrete Clinic contributes to the development and implementation of green and low-carbon concrete through the production and supply of:

- Specialised concrete admixtures
- Silica-fume gel and micro-silica -based products

These materials can be incorporated into optimised concrete mixtures to improve performance, durability, and resource efficiency [7-11].

Conclusion

Low-carbon concrete and green concrete are increasingly important approaches for the future of the construction industry. By reducing cement consumption, improving durability, reducing maintenance and repair requirements, and extending the service life of structures, these concretes can provide both environmental and economic benefits for construction projects in Iran.

Major Benefits of Green Concrete

- Reduction in concrete porosity and permeability
- Increased resistance to chloride ions and sulfate attack
- Increased compressive and abrasion resistance
- Extended service life in aggressive environments
- Improved workability and reduced water demand through the appropriate use of superplasticisers
- Potential reduction in the overall carbon footprint of concrete

Superplasticisers play an indirect but highly effective role in reducing the carbon footprint because they can reduce the water-to-cementitious-material ratio and, in an optimised mixture, may allow cement content to be reduced while maintaining the required workability and performance.

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