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# Role of Supplementary Cementitious Materials in High-Strength Concrete: A Review

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ABSTRACT:

This study focuses on the use of supplemental cementitious materials (SCMs) such as fly ash, silica fume, and metakaolin to improve the mechanical and durability properties of high-strength concrete (HSC). These materials, when used as partial replacements for cement, enhance concrete's strength, workability, and resistance to environmental challenges. Fly ash, typically used at 15-25% replacement levels, improves workability but may reduce strength at higher dosages. Silica fume, when incorporated up to 15%, significantly boosts strength and durability. Metakaolin also enhances concrete's mechanical properties, with optimal strength observed at 10% replacement. Combining these SCMs results in synergies that optimize both strength and sustainability. The study concludes that the best cement replacement level with SCMs ranges from 15% to 25%, contributing to green concrete solutions and environmental benefits.

**Key Words**: High Strength Concrete, Supplementary cementitious materials, workability, Metakaolin, Silica fume.

## 1. INTRODUCTION :

Concrete is the most frequently used artificial material in the world, with an annual usage of 14 billion cubic meters, making it the Earth's second most consumed resource after water. This equates to about 1.71 cubic meters per person per year and accounts for roughly 8% of the concrete industry's carbon dioxide emissions. By 2050, global demand for concrete is predicted to exceed 20 billion tons, driven by an increasing population, potentially resulting in a 30% rise in cement production. The International Energy Agency reports that direct $CO_2$ emissions from cement manufacturing have been stable at 0.6 tons per ton since 2018.

India is a key player in the cement business, with an expected production of 427 million tons in FY24 and an installed capacity of around 622 million tons. However, emissions from cement manufacturing in India have soared, from over 149 million metric tons of $CO_2$ the previous year to a peak of 164 million in 2022. As the world's second-largest cement producer, India's market is expected to expand at a 3.2% annual rate, reaching $22.04 billion by 2024. Despite its growth potential, India's per capita cement consumption is approximately 260 kg, which is much lower than the global average of 540kg.

Ordinary Portland Cement (OPC), a basic constituent in concrete, accounts for approximately 8% of worldwide $CO_2$ emissions. Concrete's raw materials, such as cement, sand, and gravel, are nonrenewable resources, emphasizing the critical need for material efficiency to enhance sustainability in the building sector. Plasticizers, fly ash, silica fume, and metakaolin were used as early stages toward optimization. These extra additives not only improve concrete strength but also minimize the need for cement, enhancing workability and durability by filling voids and making the concrete less permeable.

Different aggregates can be used to make high-strength concrete, however smooth or rounded particles may not bond as well, resulting in lower strength levels. Crushed rock aggregates ranging in size from 10 to 12.5 mm and not excessively elongated or angular are suitable. Smaller aggregates form stronger bonds than bigger ones, resulting in improved performance. Supplementary cementitious materials (SCMs) such as silica fume, metakaolin, fly ash, and blast-furnace slag are environmentally beneficial alternatives to regular cement. These SCMs play an important role in the production of high-strength concrete (HSC), which is intended to enhance the lifespan of structures while reducing maintenance. When ultrafine SCMs such as silica fume and metakaolin are combined with HSC, they improve strength and durability.

### *1.1 HISTORY OF HIGH STRENGTH CONCRETE*

The theoretical foundation for high-strength concrete (HSC) dates back to ceramic material research in the late 1950s and early 1960s. This study found that reducing particle sizes increases strength, which is consistent with Griffith's theory of brittle material failure. By the early 1970s, advances in dispersing agents for fine cement particles had resulted in significant improvements in concrete quality. The introduction of ultrafine silica fume also had an important role in the development of high-density, high-strength concrete, giving rise to the phrase "high-performance concrete" (HPC), which stressed durability in addition to strength. HSC and HPC definitions can vary greatly, and there is no general agreement on what they mean. HSC was traditionally distinguished from "normal" or "ordinary" concrete by water-to-cement ratios. However, as cementitious materials and current manufacturing methods have advanced, these distinctions have become less important. As a result, there has been a trend toward performance-based definitions and criteria for evaluating concrete quality.

In the 1950s, concrete with a compressive strength of 35 MPa (M35) was considered strong. By the 1990s, developed countries had created a standard for high-strength concrete with strengths exceeding 110 MPa. However, the 110 MPa threshold may differ greatly depending on the characteristics of the local materials utilized in the concrete mix. ACI Committee 363's 1979 report defines high-strength concrete as having a compressive strength more than 41.37 MPa (6000 psi). According to IS 456-2000, compressive strength greater than 55 MPa has been accepted for High Strength Concrete after 28 days of curing. The maximum cement content in concrete should be 450 kg/m3.

## 2. LITERATURE REVIEW :

### *2.1. Introduction*

The use of supplemental cementitious materials (SCMs) in concrete, such as fly ash, silica fume, and metakaolin, has sparked widespread interest due to their capacity to improve the mechanical and durability properties of concrete. This study summarizes major data from several investigations, with an emphasis on the impact of these materials on concrete strength, workability, and durability.

### *2.2 Fly Ash in Concrete*

#### 2.2.1 Replacement Levels and Strength

Fly ash is a widely used SCM, with ACI Committee 211 (2008) recommending replacement levels of 15% to 25% for high-strength concrete. In contrast, Carette et al. (1993) found that regular-strength concrete benefits from higher replacement levels, often exceeding 50%. Naik and Ramme (1989) proposed that early-age strength considerations allow for up to 40% fly ash in high-strength concrete and 60% in regular-strength concrete. Charith Herath et al. (2020) noted that while high-volume fly ash (HVFA) concrete, which contains more than 50% fly ash, generally exhibits lower strength compared to conventional concrete, specific studies reported strengths reaching 66 MPa at 50% replacement (Cengiz Duran Atis, 2003). However, increasing the replacement level to 70% can lead to a notable drop in strength, reducing it by approximately 50% compared to mixes with 50% fly ash.

#### 2.2.2 Workability

Incorporating fly ash in concrete enhances workability due to its spherical particle shape, which acts as a lubricant, reducing friction and facilitating pumping (Best, 1980). Bilodeau and Sivasundaram (1994) emphasized that fly ash improves workability, strength, and durability. Studies (Kim et al., 2012; Mohd Mustafa Al Bakri et al., 2010) demonstrated that fly ash-based high-strength concrete outperforms conventional concrete, particularly in workability and resistance to high temperatures.

#### 2.2.3 Mechanical Properties

Historically, concrete strength has evolved, with 34 MPa considered exceptional in the 1950s, reaching up to 62 MPa by the early 1970s (ACI-363R-92). Poon et al. found that replacing cement with fly ash improved strength more effectively in mixes with lower water-binder ratios. Metha (2005) noted that fly ash reacts pozzolanically after approximately 11 days, resulting in increased strength beyond 28 days due to enhanced bond between paste and aggregate (Malhotra and Mehta, 2005). Nath and Sarker (2011) showed that while concrete mixes with fly ash initially exhibit lower strength, they ultimately exceed control mixes by 56 days, particularly highlighting the advantages of lower fly ash contents in early-age strength development.

#### 2.2.4 Durability

Research indicates that fly ash significantly reduces permeability and enhances resistance to sulfate attacks and chloride ion penetration (Dinakar et al., 2008; Kakhuntodd et al., 2012). Additionally, fly ash contributes to lower drying shrinkage and improved freeze-thaw resistance (Bouzoubaâ et al., 2001; Saha, 2018). Tori et al. (1995) emphasized the acid resistance of fly ash concrete, confirming its effectiveness in aggressive environments.

### *2.3. Silica Fume in Concrete*

#### 2.3.1 Mechanical Properties

Silica fume has been recognized for its ability to enhance concrete strength and durability. Bentur et al. (1987) noted that silica fume concrete exhibited superior strength due to improved aggregate-cement paste bonding. Mazloom et al. (2004) found that incorporating up to 15% silica fume in high-performance concrete led to significant strength improvements, particularly at 28 days. Sobolev (2004) emphasized the importance of optimizing superplasticizer dosage and reducing water-to-cement ratios to enhance compressive strength.

#### 2.3.2 Durability

Silica fume contributes to durability by decreasing permeability and enhancing resistance to chemical attacks (Siddique, 2011). Research by Johnston (1994) highlighted satisfactory frost resistance in silica fume mixes, indicating its potential to improve freeze-thaw resistance.

### *2.4. Metakaolin in Concrete*

#### 2.4.1 Mechanical and Durability Properties

Metakaolin (MK) has emerged as a highly reactive pozzolan, improving the strength and durability of concrete. Studies (Coleman, 1997; Poon et al., 2006) show that MK enhances microstructure, reduces porosity, and contributes to superior mechanical properties. Dinakar et al. (2013) observed that concrete containing MK maintained consistent compressive strength, with 10% MK yielding optimal results. Wild et al. (1996) reported that strength increases over a 14-day curing period, although it declines thereafter.

#### 2.4.2 Combination of SCMs

The synergistic effects of combining fly ash, silica fume, and metakaolin have been explored by several researchers. Guang Jiang et al. (2015) demonstrated that MK exhibits greater pozzolanic reactivity than silica fume, particularly after 28 days. Chakravarthy and Shah (2016) found that optimal combinations of these materials can significantly enhance compressive strength, with 15% fly ash and 10% MK yielding the highest strength in high-performance concrete.

## 3. MATERIALS :

The main raw materials required for high-strength concrete are cement (C), silica fume (SF), fly ash (FA), metakaolin (MK), coarse aggregates (CA), fine aggregates (FA), water (W), and superplasticizer (SP).

1. **Cement:** Ordinary Portland Cement (53 grade, Ultratech) conforming to IS:12269-2013 was used in this study. Its specific gravity is 3.15. Chemical and physical properties are detailed in Tables 2 and 3.

2. **Fly Ash:** Fly ash, a byproduct of coal combustion, varies in cementitious properties based on impurities like shale and quartz. It serves as a valuable substitute for clinker in cement production. Siliceous fly ash from Satpura Thermal Power Station, Madhya Pradesh, was used, conforming to IS 3812 (Part 1). Its specific gravity is 2.15.

3. **Silica Fume:** Microsilica, or silica fume, is an ultrafine, amorphous silicon dioxide powder, collected from silicon and ferrosilicon alloy production.

4. **Metakaolin:** Metakaolin, a calcined clay from kaolin, is pink-white and smooth, produced by heating at 600-800°C. Unlike industrial pozzolans, its quality is controlled. I used MCC's Metakrete metakaolin, which meets ASTM C-618 chemical standards for consistent performance.

5. **Fine and Coarse Aggregate:** IS 383 (BIS, 2016) specifies the use of fine (natural sand) and coarse aggregates in Zone II. Fine and coarse aggregates havespecific gravity of 2.65 and 2.85, and water absorption of 0.9% and 0.8 %respectively.

6. **Chemical Admixture:** A superplasticizer based on polycarboxylate ether (PCE) was utilized in concrete mixtures to ensure the necessary workability. At 25°C, the brown-black liquid JS-S150 PCE-based on silicone admixture had a specific gravity of 1.11. Fairflo 160 was the second chemical additive that was utilized, and it complied with ASTM C-494 type 'G' & IS 9103 requirements (BIS, 1999).

## 4. METHODOLOGY :

1. Material Collection: Gather Pozzolana Portland Cement, coarse aggregate, fine aggregate, Metakaolin, Fly Ash, silica fume, and admixture.
2. Laboratory Testing: Test cement, aggregates, plasticizer, and water for their chemical and physical properties.
3. Mix Design Finalization: Develop the concrete mix design based on material properties.
4. Partial Cement Replacement: Replace cement with Metakaolin, Fly Ash, and silica fume in various percentages.
5. Slump Test: Measure the workability of fresh concrete.
6. Casting of Specimens: Cast concrete cube, cylinder and beam specimens.
7. Strength Testing: Determine compressive strength, flexural strength, split tensile strength, unit weight, water gain, and resistance to freezing and thawing.

## 5. CONCLUSION :

1. Control mixes for reduced water-to-cement (W/C) ratios can utilize both 10 mm and 20 mm aggregates.
2. At low W/C ratios, superplasticizers are recommended to enhance compressive strength.
3. The water/cement ratio typically ranges from 0.36 to 0.24.
4. Strength increases with fly ash concentration up to 20%; exceeding this percentage results in decreased strength.
5. Increasing replacement levels of silica fume and metakaolin reduces workability, necessitating more superplasticizer.
6. Metakaolin shows a compressive strength increase up to 15% replacement, but strength declines further compared to fly ash and silica fume at higher levels.

7. Water absorption is lower in metakaolin than in fly ash and silica fume due to its smaller particle size.
8. Concrete mixes combining silica fume and fly ash generally exhibit lower strength than mixes incorporating all three mineral admixtures.
9. The use of fly ash and silica fume contributes to the development of green concrete, benefiting the environment.
10. The optimal percentage for replacing cement with cementitious materials is between 15% and 25%.

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