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A Critical Review on Use of Supplementary Cementitious Materials in Ultra-High Performance Concrete to Enhance Rheological Parameters

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Ultra-High Performance Concrete (UHPC) represents a revolutionary advancement in concrete technology, characterized by exceptional mechanical properties, durability, and workability. This review paper critically examines the use of Supplementary Cementitious Materials (SCMs) in UHPC formulations, with a specific focus on their impact on rheological parameters. By analyzing recent developments from 2005 to 2024, the paper systematically evaluates how various SCMs including silica fume, fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, and rice husk ash affect the flow behavior, viscosity, yield stress, and overall workability of UHPC mixtures. The review identifies significant research gaps, particularly in understanding the synergistic effects of multiple SCMs on rheological behavior under varying environmental conditions and with different fiber reinforcement systems. This paper also highlights the need for standardized testing protocols for rheological assessment of UHPC incorporating SCMs. Based on the comprehensive literature analysis, future research directions are proposed, focusing on developing optimization models for SCM combinations that simultaneously enhance rheological properties while maintaining the superior mechanical and durability characteristics of UHPC.

Keywords: Ultra-High Performance Concrete; Supplementary Cementitious Materials; Rheology; Workability; Silica Fume; GGBFS; Fly Ash; Sustainability.

1. Introduction

Ultra-High Performance Concrete (UHPC) has emerged as an innovative construction material with exceptional mechanical and durability properties, including compressive strengths typically exceeding 150 MPa, enhanced tensile strength, improved ductility, and superior resistance to environmental degradation (Schmidt and Fehling, 2005). While these properties make UHPC highly desirable for critical infrastructure applications, its commercial viability and widespread adoption face several challenges, including high material costs, complex production requirements, and specific rheological demands.

The rheological properties of UHPC play a crucial role in its successful implementation, affecting placement techniques, consolidation requirements, fiber distribution, and ultimately the mechanical performance of the hardened concrete (Khayat et al., 2019). Unlike conventional concrete, UHPC typically contains a high binder content, low water-to-binder ratio, specialized aggregates, and often incorporates fiber reinforcement, all of which significantly influence its flow behavior.

Supplementary Cementitious Materials (SCMs) have been increasingly incorporated into UHPC formulations to address multiple objectives: reducing the environmental footprint associated with high cement content, enhancing specific performance characteristics, and potentially improving rheological behavior (Kim et al., 2016). However, the effects of different SCMs on the rheological parameters of UHPC are complex and multifaceted, involving interactions with superplasticizers, fiber reinforcement, and other mixture components.

This review paper aims to provide a comprehensive and critical analysis of recent advancements in understanding how various SCMs influence the rheological properties of UHPC. By systematically examining the literature from 2005 to 2024, this review will:

1. Categorize the types of SCMs commonly used in UHPC formulations and their general effects on fresh concrete properties

2. Analyze the specific impacts of various SCMs on key rheological parameters including yield stress, plastic viscosity, thixotropy, and overall workability

3. Examine the interaction effects between SCMs and other UHPC ingredients (superplasticizers, fibers, aggregates)

4. Identify current research gaps and propose future research directions

The findings of this review are expected to provide valuable insights for researchers and practitioners seeking to optimize UHPC formulations with enhanced rheological performance through the strategic incorporation of SCMs.

2. Ultra-High Performance Concrete: Composition and Properties

2.1 Definition and Characteristics of UHPC

UHPC represents a specialized class of cementitious materials characterized by exceptional mechanical properties, durability, and performance characteristics. According to various standards and researchers, UHPC is defined by compressive strengths typically exceeding 150 MPa, enhanced tensile capacity, improved ductility, and superior resistance to environmental degradation (ASTM C1856/M-17, 2017). The superior performance of UHPC stems from its optimized particle packing density, extremely low water-to-binder ratio (typically between 0.15 and 0.25), elimination of coarse aggregates, incorporation of high-range water-reducing admixtures, and often the addition of fiber reinforcement (Richard and Cheyrezy, 1995).

2.2 Conventional Composition of UHPC

The typical composition of UHPC includes:

- Cementitious Materials: High proportions of Portland cement (900-1000 kg/m³), often supplemented with reactive powders such as silica fume (Richard and Cheyrezy, 1994)
- Fine Aggregates: Optimized gradation of quartz sand with particle sizes typically below 600 μm (Wille and Boisvert-Cotulio, 2015)
- Chemical Admixtures: High-performance superplasticizers to achieve workability despite low water content (Dils et al., 2013)
- Fiber Reinforcement: Steel, synthetic, or hybrid fibers to enhance tensile behavior and ductility (Meng et al., 2018)
- Water: Extremely low water content, resulting in water-to-binder ratios typically below 0.25 (Schmidt and Fehling, 2005)

2.3 Engineering Properties of UHPC

The exceptional properties of UHPC include:

1. Mechanical Performance: Compressive strengths ranging from 150 to 250 MPa, flexural strengths of 15-50 MPa, and enhanced tensile capacity when fiber-reinforced (Wu et al., 2017)
2. Durability: Superior resistance to chloride penetration, freeze-thaw damage, abrasion, and chemical attack (Graybeal and Tanesi, 2007; Piérard et al., 2012)
3. Volume Stability: Reduced shrinkage and creep compared to conventional concrete (Pyo et al., 2015)
4. Rheological Behavior: Generally self-consolidating characteristics with specific flow properties that enable proper placement and fiber distribution (Khayat et al., 2019)

2.4 Applications of UHPC

The exceptional properties of UHPC have led to its application in:

1. Bridge Construction: Precast bridge elements, field-cast connections, overlays (Xue et al., 2020)
2. Infrastructure Components: Railway sleepers, marine structures, protective elements (Bae and Pyo, 2020a)
3. Architectural Applications: Façade panels, decorative elements (Bajaber and Hakeem, 2021)
4. Repair and Rehabilitation: Thin overlays, joint filling (Abbas et al., 2015)

3. Rheological Parameters of UHPC

3.1 Importance of Rheology in UHPC Performance

The rheological behavior of UHPC plays a critical role in its placement, consolidation, and ultimately its hardened properties. Unlike conventional concrete, UHPC requires specific flow characteristics to ensure proper placement, especially considering its often self-consolidating nature and the need for uniform fiber distribution when fiber-reinforced (Khayat et al., 2019).

3.2 Key Rheological Parameters

3.2.1 Yield Stress

Yield stress represents the minimum shear stress required to initiate flow in UHPC. This parameter significantly affects the material's ability to fill formwork and self-level (Choi et al., 2016). In UHPC, the high binder content and low water-to-binder ratio typically result in higher yield stress compared to conventional concrete, which must be carefully managed through mix design and admixture content.

3.2.2 Plastic Viscosity

Plastic viscosity describes the resistance to flow once the yield stress has been exceeded. In UHPC, high plastic viscosity can impede proper placement but is often necessary to prevent segregation of components and maintain fiber suspension (Wang et al., 2017). The balance between adequate flowability and stability is particularly critical in UHPC formulations.

3.2.3 Thixotropy

Thixotropy, the time-dependent change in rheological properties, is particularly relevant for UHPC due to its high fines content. UHPC mixtures often exhibit significant structural buildup at rest, which affects placing operations, layer-to-layer bonding in sequential casting, and formwork pressure (Lowke et al., 2012).

3.2.4 Workability Retention

The ability of UHPC to maintain its rheological properties over time is crucial for practical applications, especially considering the often extended mixing times required and potential delays between mixing and placement (Meng and Khayat, 2017).

3.3 Measurement Techniques for UHPC Rheology

Several specialized techniques have been developed or adapted to assess the rheological parameters of UHPC:

1. Rotational Rheometry: Provides fundamental rheological parameters but requires specialized equipment (Khayat et al., 2019)

2. Mini-Slump Tests: Simplified field tests that correlate with yield stress (Choi et al., 2016)

3. Flow Table Tests: Standardized methods adapted for UHPC to assess flowability (ASTM C1856/M-17, 2017)

4. V-Funnel and L-Box Tests: Evaluates passing ability and flow characteristics, particularly relevant for fiber-reinforced UHPC (Lowke et al., 2012)

3.4 Factors Affecting UHPC Rheology

The rheological behavior of UHPC is influenced by multiple factors:

1. Mixture Composition: Water content, binder type and content, aggregate characteristics, and admixture dosages (Dils et al., 2013)

2. Fiber Content and Geometry: Type, volume fraction, aspect ratio, and distribution of fibers significantly affect flow behavior (Wang et al., 2017)

3. Mixing Procedures: Mixing energy, sequence, and duration (Dils et al., 2013)

4. Temperature and Environmental Conditions: Ambient conditions affecting reaction rates and water evaporation (Meng and Khayat, 2017)

5. Supplementary Cementitious Materials: Type, fineness, reactivity, and proportion of SCMs (Kim et al., 2016)

4. Supplementary Cementitious Materials in UHPC

4.1 Types and Characteristics of SCMs Used in UHPC

4.1.1 Silica Fume

Silica fume, an ultrafine pozzolanic material, is arguably the most common SCM in UHPC formulations. Its extremely small particle size (typically 0.1-1 μm) and high silica content contribute to UHPC's dense microstructure through pozzolanic reactions and physical filler effects (Alkaysi et al., 2016). Typical incorporation rates range from 20-30% by weight of cement in UHPC mixtures.

4.1.2 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS is increasingly utilized in UHPC to partially replace Portland cement. Its latent hydraulic properties, fineness, and chemical composition make it suitable for enhancing specific properties of UHPC while potentially reducing cost and environmental impact (Kim et al., 2016). Incorporation rates in UHPC typically range from 20-50% replacement of cement.

4.1.3 Fly Ash

Fly ash, particularly low-calcium (Class F) fly ash, has been incorporated into UHPC formulations to improve workability, reduce heat of hydration, and enhance long-term strength development through pozzolanic reactions (Yu et al., 2014). Replacement rates in UHPC typically range from 15-30% of cement weight.

4.1.4 Metakaolin

Metakaolin, produced by calcining kaolin clay, offers high pozzolanic reactivity and can contribute to early strength development in UHPC. Its plate-like particle shape and high alumina content influence both fresh and hardened properties (Korpa et al., 2009).

4.1.5 Rice Husk Ash (RHA)

RHA, when properly processed to achieve high amorphous silica content, can serve as an effective pozzolan in UHPC formulations, potentially improving rheological behavior while contributing to sustainability objectives (Li et al., 2020).

4.2 Motivations for SCM Incorporation in UHPC

4.2.1 Sustainability Considerations

The high cement content in conventional UHPC formulations raises significant environmental concerns, particularly regarding CO_2 emissions (Worrell et al., 2001). SCMs, many of which are industrial by-products, can reduce the carbon footprint of UHPC while potentially enhancing specific performance characteristics.

4.2.2 Economic Factors

The high cost of UHPC, largely attributed to its high cement content and specialized ingredients, has limited its widespread application. SCMs typically cost less than Portland cement and can reduce overall material costs (Wille and Boisvert-Cotulio, 2015).

4.2.3 Performance Enhancement

Beyond environmental and economic benefits, certain SCMs can enhance specific properties of UHPC, including rheological behavior, durability, and long-term strength development (Pyo et al., 2018).

5. Influence of SCMs on Rheological Parameters of UHPC

5.1 Literature Review of SCMs' Effects on UHPC Rheology

A comprehensive analysis of the literature from 2005-2024 reveals significant research into the effects of various SCMs on UHPC rheological parameters. Table 1 summarizes key research contributions in chronological order, highlighting the SCM types studied and their observed effects on rheological properties.

Table 1: Chronological Summary of Research on SCM Effects on UHPC Rheology (2005-2024)

Year	Authors	SCM Type	Replacement Level	Key Findings on Rheological Effects
2005	Schmidt and Fehling	Silica Fume	20-30%	Increased water demand but essential for strength development
2009	Korpa et al.	Metakaolin	10-15%	Increased viscosity due to plate-like particle shape
2012	Lowke et al.	Silica Fume	25-35%	Significant impact on yield stress and thixotropic behavior
2013	Dils et al.	GGBFS	20-40%	Improved flowability at moderate replacement levels
2014	Yu et al.	Fly Ash	15-30%	Enhanced flow properties due to spherical particle shape
2015	Wille and Boisvert-Cotulio	Multiple SCMs	Various	Particle packing optimization critical for rheological control

2016	Kim et al.	GGBFS	30-60%	Significantly enhanced flowability at higher replacement levels
2016	Alkaysi et al.	Silica Fume	15-25%	Increased water demand but critical for microstructure development
2017	Meng and Khayat	Silica Fume	20-25%	Rheology control critical for fiber distribution and flexural performance
2017	Wang et al.	Multiple SCMs	Various	SCM type and dosage significantly affect fiber distribution
2018	Pyo et al.	Mining Tailings	20-40%	Alternative siliceous materials can improve flow characteristics
2019	Khayat et al.	Review of Multiple SCMs	Various	Comprehensive review of rheological effects of various SCMs
2020	Li et al.	Steel Slag Powder	20-30%	Modified rheological properties while maintaining strength
2021	Bajaber and Hakeem	Review of Multiple SCMs	Various	Highlighted importance of SCM selection for workability

5.2 Effects of Specific SCMs on UHPC Rheology

5.2.1 Silica Fume

Silica fume significantly influences UHPC rheology, with complex and sometimes contradictory effects:

- Yield Stress: Generally increases yield stress due to high specific surface area and water demand (Lowke et al., 2012)
- Plastic Viscosity: Typically increases viscosity, particularly at higher dosages (Alkaysi et al., 2016)
- Thixotropy: Enhances thixotropic behavior due to strong particle interactions (Khayat et al., 2019)
- Workability Retention: May accelerate workability loss due to rapid water adsorption (Meng and Khayat, 2017)

5.2.2 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS generally improves the rheological behavior of UHPC:

- Yield Stress: Typically reduces yield stress compared to equivalent cement content (Kim et al., 2016)
- Plastic Viscosity: Moderate reductions in plastic viscosity at typical replacement levels (Dils et al., 2013)
- Thixotropy: Less pronounced thixotropic behavior compared to silica fume-only formulations (Khayat et al., 2019)
- Workability Retention: Often improves workability retention due to slower reaction kinetics (Kim et al., 2016)

5.2.3 Fly Ash

Fly ash, particularly Class F fly ash, typically enhances the flow properties of UHPC:

- Yield Stress: Reduces yield stress due to spherical particle shape ("ball-bearing effect") (Yu et al., 2014)
- Plastic Viscosity: Generally decreases plastic viscosity, enhancing flowability (Yu et al., 2014)
- Thixotropy: Reduces thixotropic behavior compared to silica fume (Khayat et al., 2019)
- Workability Retention: Typically improves workability retention due to slower pozzolanic reaction (Yu et al., 2014)

5.2.4 Other SCMs

- Metakaolin: Generally increases water demand and plastic viscosity due to plate-like particle shape, but can enhance stability (Korpa et al., 2009)
- Rice Husk Ash: Effects largely dependent on fineness and processing method, with properly processed RHA potentially improving flow characteristics (Li et al., 2020)
- Quartz Powder: Often used as a filler material, contributing to particle packing density with minimal chemical activity, generally improving rheological behavior (Pyo et al., 2018)

5.3 Interaction Effects with Other UHPC Components

5.3.1 SCM-Superplasticizer Interactions

The compatibility between SCMs and superplasticizers significantly influences UHPC rheology. Different SCMs show varying adsorption behaviors with polycarboxylate-based superplasticizers, affecting dispersing efficiency (Khayat et al., 2019):

- Silica fume may compete with superplasticizers for adsorption sites on cement particles
- GGBFS typically shows good compatibility with most superplasticizers
- The carbon content in fly ash can adsorb superplasticizer molecules, potentially reducing effectiveness

5.3.2 SCM-Fiber Interactions

SCMs influence fiber distribution and orientation in UHPC through their effects on matrix rheology:

- Higher viscosity matrices (e.g., with high silica fume content) may better suspend fibers but could impede proper distribution (Wang et al., 2017)
- Reduced yield stress (e.g., with GGBFS or fly ash) may facilitate fiber distribution but could increase settlement risk (Wille et al., 2014)
- Optimized SCM combinations can create rheological windows that enable proper fiber distribution while maintaining stability (Meng and Khayat, 2017)

6. Experimental Techniques for Rheological Assessment

6.1 Conventional Rheological Measurements

Traditional rheological measurement techniques adapted for UHPC include:

- Rotational Rheometry: Provides fundamental parameters (yield stress, plastic viscosity) but requires specialized equipment and careful interpretation for fiber-reinforced UHPC (Khayat et al., 2019)
- Flow Table Tests: Modified for UHPC to assess static and dynamic flow characteristics (ASTM C1856/M-17, 2017)
- V-Funnel Tests: Evaluates flow time as an indirect measure of viscosity, particularly relevant for self-consolidating UHPC formulations (Lowke et al., 2012)

6.2 Emerging Techniques for UHPC Rheology

Recent advancements in rheological assessment of UHPC include:

- Mini-Slump Tests: Simplified field tests with strong correlations to fundamental rheological parameters (Choi et al., 2016)
- Ultrasonic Monitoring: Non-destructive techniques to monitor structural buildup and setting behavior (indirectly related to rheological evolution)
- Image Analysis: Advanced techniques to quantify fiber orientation and distribution as influenced by matrix rheology (Wang et al., 2017)

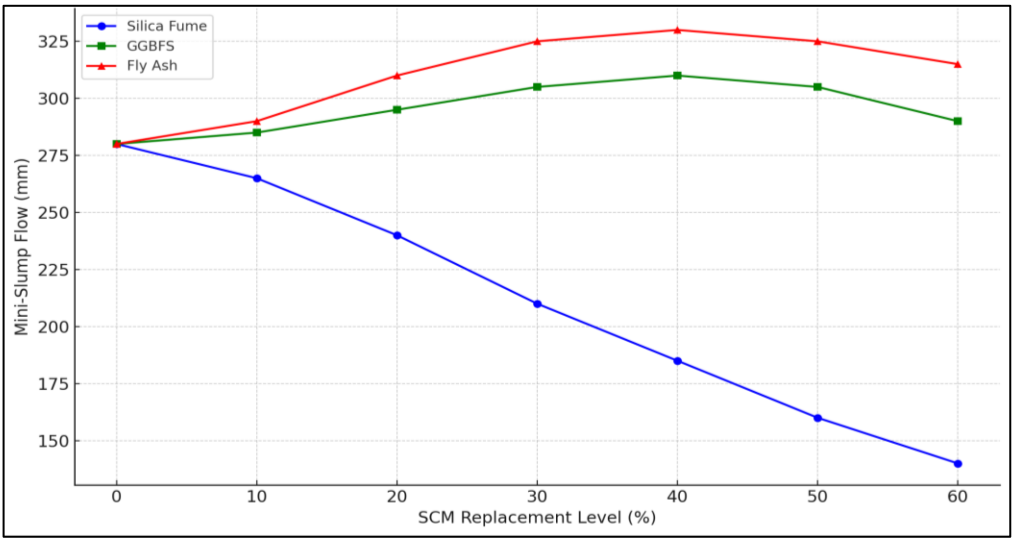

Figure 1: Relationship Between Different SCM Replacement Levels and Mini-Slump Flow of UHPC

6.3 Correlation Between Rheological Parameters and Field Performance

Establishing correlations between laboratory-measured rheological parameters and field performance remains challenging:

- Laboratory measurements may not fully capture the effects of placement methods, formwork interactions, and environmental conditions
- The dynamic nature of rheological properties during transport and placement introduces additional complexity
- Developing predictive models that link rheological parameters to field performance represents an important research direction (Meng and Khayat, 2017)

7. Optimization of SCM Combinations for Enhanced Rheology

7.1 Binary and Ternary SCM Systems

Recent research has increasingly focused on optimizing combinations of multiple SCMs to achieve desired rheological properties while maintaining or enhancing other performance characteristics:

- Silica Fume + GGBFS: Common combination that balances the negative rheological effects of silica fume with the positive effects of GGBFS (Kim et al., 2016)
- Silica Fume + Fly Ash: Combines the strength-enhancing properties of silica fume with the improved workability from fly ash (Yu et al., 2014)
- Ternary Combinations: Increasingly explored to achieve broader performance optimization (Wille and Boisvert-Cotulio, 2015)

7.2 Particle Packing Optimization

Advanced approaches to SCM selection and proportioning based on particle packing models have shown promise for optimizing rheological behavior:

- Modified Andreasen & Andersen Model: Applied to UHPC to achieve maximum packing density while maintaining workability (Yu et al., 2014)
- Compressible Packing Model: Accounts for the compressibility of fine particles under mixing energy (Wille and Boisvert-Cotulio, 2015)
- Statistical Design of Experiments: Used to identify optimal combinations of SCMs for specific rheological targets (Ghafari et al., 2014)

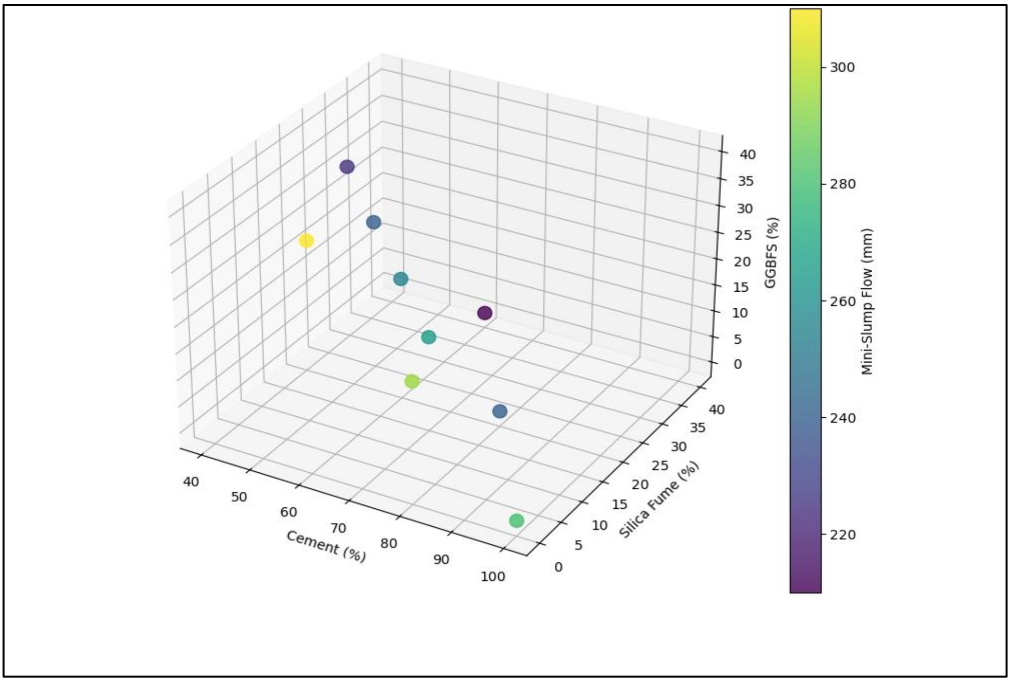

Figure 2: SCM Combinations and Their Effects on UHPC Rheological Parameters

8. Research Gaps and Future Directions

8.1 Identified Research Gaps

Based on the comprehensive literature review, several research gaps have been identified:

1. Limited Understanding of SCM Synergies: While individual SCM effects are increasingly well-documented, understanding of synergistic effects in multi-SCM systems remains limited

2. Environmental Sensitivity: Research on how SCM-modified UHPC rheology responds to varying temperature and humidity conditions is insufficient

3. Standardization Issues: Lack of standardized testing protocols specifically designed for rheological assessment of SCM-modified UHPC

4. Durability Correlations: Limited research correlating rheological modifications via SCMs with long-term durability performance

5. Large-Scale Production Challenges: Gap between laboratory-scale rheological optimization and industrial-scale production

6. Time-Dependent Behavior: Insufficient understanding of time-dependent rheological evolution in SCM-modified UHPC

8.2 Future Research Directions

Based on the identified gaps, the following future research directions are proposed:

1. Development of Comprehensive Rheological Models: Models that account for multiple SCM types, their interactions, and time-dependent behavior

2. Standardized Testing Protocols: Development of specific testing methods for rheological assessment of SCM-modified UHPC

3. Field-Scale Validation: Correlation studies between laboratory rheological parameters and field performance

4. Multi-Objective Optimization Approaches: Methodologies that simultaneously consider rheology, mechanical properties, durability, and sustainability

5. Novel SCM Types and Combinations: Exploration of emerging SCMs and unconventional combinations for rheological enhancement

6. Machine Learning Applications: Data-driven approaches to predict and optimize rheological behavior based on SCM characteristics and proportioning

9. Conclusions

This comprehensive review has examined the effects of various SCMs on the rheological properties of UHPC, drawing the following key conclusions:

1. The incorporation of SCMs in UHPC formulations significantly influences rheological behavior, with effects varying based on SCM type, characteristics, and incorporation rate

2. Silica fume, while essential for UHPC microstructure development, typically increases water demand and viscosity, potentially compromising workability

3. GGBFS and fly ash generally improve flow properties, with GGBFS offering better compatibility with UHPC's mechanical performance requirements

4. Optimized combinations of multiple SCMs show promise in achieving balanced rheological properties while maintaining or enhancing mechanical and durability characteristics

5. The interactions between SCMs and other UHPC components, particularly superplasticizers and fibers, significantly influence overall rheological behavior

6. Particle packing optimization approaches provide a theoretical framework for systematically enhancing rheological properties through SCM selection and proportioning

Despite significant advancements, important research gaps remain, particularly regarding synergistic effects in multi-SCM systems, environmental sensitivity, standardized testing protocols, and correlations between rheological modifications and long-term performance. Addressing these gaps through targeted research will contribute to more efficient and effective utilization of SCMs in UHPC, enhancing both performance and sustainability.

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