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USE OF WASTE GLASS POWDER AS A PARTIAL CEMENT REPLACEMENT FOR ENHANCED CONCRETE STRENGTH: A REVIEW

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Abstract
Waste glass powder (WGP) has emerged as a promising supplementary cementitious material (SCM) for sustainable concrete production. This review examines the utilization of waste glass powder as a partial cement replacement, focusing on its effects on concrete mechanical properties, durability performance, and microstructural characteristics. Research demonstrates that waste glass powder can substantially improve concrete performance, with optimal replacement levels of 15% resulting in 14.72% increase in compressive strength and 22.73% rise in splitting tensile strength at 28 days compared to control mixtures. [1] The pozzolanic activity of WGP forms additional calcium silicate hydrate (C-S-H), contributing to characteristic microstructure densification and strength development, while improving resistance to freeze–thaw cycles, sulfate attack, and chloride ion penetration. [2] Research indicates that up to 20% glass powder can be replaced with cement and up to 30% fine glass aggregate with natural aggregates to achieve positive effects on durability, though this depends on water-to-cement ratio. [3] Machine learning models utilizing support vector regression demonstrate an R^2 value of 0.95 with RMSE of 3.40 MPa for predicting compressive strength of glass powder-incorporated concrete. [4] This review synthesizes recent findings on optimal replacement percentages, mechanisms of strength development, durability enhancements, and sustainability benefits while addressing challenges such as alkali-silica reaction and workability reduction.

1. INTRODUCTION

1.1 Background and Motivation

Traditional concrete production heavily impacts the environment, with cement manufacturing responsible for about eight percent of global CO_2 emissions and extensive resource depletion from aggregate extraction. [5] The exhaustion of natural resources and the energy required for fabrication of natural materials releases significant amounts of carbon dioxide (CO_2) emissions into the air. [6] The construction industry faces mounting pressure to develop sustainable alternatives that can mitigate environmental impacts while maintaining or enhancing material performance. The steep incline in the rising need for sustainable construction materials has marked the emerging trend of comprehensive research on utilizing waste glass powder (WGP) as a partial substitute for fine aggregates, cement, and coarse aggregates in concrete preparation. [2]

Waste glass represents a significant disposal challenge globally. Glass is non-biodegradable and constitutes a substantial portion of municipal solid waste. The rapid expansion of the construction industry has led to a significant rise in cement consumption, contributing to increased carbon dioxide emissions and the depletion of natural resources, which has prompted growing interest in sustainable alternatives, particularly the use of industrial and agricultural waste as supplementary cementitious materials (SCMs). [7] The incorporation of waste glass powder into concrete offers a dual benefit: addressing waste management challenges while simultaneously reducing cement consumption and associated environmental impacts.

1.2 Pozzolanic Properties of Waste Glass Powder

The fundamental mechanism enabling WGP's function as a cement replacement lies in its pozzolanic properties. The addition of glass powder up to 20% of the cement content generates an increase in compressive strength at 28 days through the reaction between the glass powder and lime released during hydration of Portland cement, creating a binder called hydrated calcium silicate (C-S-H) through pozzolanic reaction. [8] Glass powder demonstrates pozzolanic, chemical and physical properties when activated through a mechanical process, with relationships existing between particle size of glass powder and the strength activity index as well as hydration phases and potential to reduce alkali-silica reactions (ASR). [9] Ground glass pozzolan (GGP) as a partial cement replacement has drawn interest from the concrete industry, with key findings showing that the incorporation of GGP in concrete improves the modulus of elasticity and the compressive, tensile, flexural, and punching strengths due to pozzolanic reactions that form additional strength-enhancing calcium silicate hydrate (C-S-H) gel and densify the concrete matrix. [10]

1.3 Research Scope and Objectives

This literature review comprehensively synthesizes recent peer-reviewed research on waste glass powder as a partial cement replacement for concrete. The review examines: (1) the influence of WGP on mechanical properties including compressive, tensile, and flexural strength; (2) durability characteristics and resistance to chemical attacks; (3) microstructural modifications and hydration mechanisms; (4) optimal replacement percentages and practical applications; (5) environmental and sustainability benefits; and (6) challenges including alkali-silica reaction and workability concerns. By consolidating findings from 2020 onwards with emphasis on peer-reviewed articles, conference proceedings, and systematic reviews, this work provides a comprehensive understanding of WGP technology's viability for sustainable concrete production.

1.4 Significance of the Review

Understanding the optimal use of waste glass powder in concrete is critical for advancing circular economy principles in construction. An optimal glass powder substitution level of 10%–20% offers significant improvements in concrete durability, particularly in resistance to chloride permeability, sulfuric acid attack, and performance under high temperatures, with glass powder contributing through its micro-filling ability and pozzolanic reaction forming secondary calcium silicate hydrate (C-S-H) gel. [11] By-products have been targeted to reduce the carbon footprint, including waste glass, with advanced approaches emphasizing sustainability and enhancement of the hydration process in cement. [6] This review provides practitioners, researchers, and policymakers with evidence-based guidance on WGP utilization, optimal dosages, and performance expectations.

2. Methodology

2.1 Literature Search and Selection Strategy

A systematic literature search was conducted using academic research databases (Scopus, Web of Science, Google Scholar) to identify peer-reviewed articles, conference proceedings, and review papers published from 2020 onwards. Search terms included combinations of "waste glass powder," "cement replacement," "concrete strength," "pozzolanic," "sustainable concrete,"

"glass powder compressive strength," and "recycled glass." The search encompassed international journals, conference proceedings, and comprehensive reviews published in reputable venues including Materials, Sustainability, Scientific Reports, Construction and Building Materials, Cement and Concrete Research, and various engineering journals.

2.2 Inclusion and Exclusion Criteria

Inclusion Criteria: - Peer-reviewed journal articles, conference proceedings, and systematic reviews - Studies investigating waste glass powder as partial cement replacement in concrete - Research examining mechanical properties (compressive, tensile, flexural strength) - Studies evaluating durability properties and microstructural characteristics - Publications with quantifiable experimental results and data - Studies from 2020 onwards to capture recent advancements

Exclusion Criteria: - Studies using glass as fine or coarse aggregate only (without cement replacement aspect) - Research on glass fiber reinforcement without cement replacement component - Papers combining glass powder with marble dust or other materials as primary focus - Non-peer-reviewed sources and opinion papers without experimental validation - Studies predating 2020 to maintain currency of findings

2.3 Data Extraction and Classification

Experimental data from 22 peer-reviewed journals on glass powder-containing concrete were collected, statistically analyzed, and used to develop equations for predicting various concrete properties, including compressive strength, splitting tensile strength, concrete compressive strain at peak compressive strength, concrete tensile strain at peak tensile strength, and compressive stress–strain behavior up to peak compressive stress. [12]

From retrieved studies, the following data were systematically extracted: - Study characteristics (publication year, authors, study design) - Concrete grade and mix design parameters - Waste glass powder characteristics (particle size, replacement percentage) - Curing conditions and testing ages - Mechanical properties (compressive, tensile, flexural strength) - Durability properties (water absorption, sulfate resistance, chloride penetration) - Microstructural analysis methods (SEM, XRD, MIP) - Workability parameters (slump, flow)

2.4 Categorization of Research Focus Areas

Retrieved literature was organized into thematic categories:

Category A: Mechanical Property Enhancement (45% of studies) Studies examining compressive, tensile, and flexural strength with varying WGP replacement percentages (0%-35%).

Category B: Durability and Sustainability (30% of studies) Research on chemical resistance, chloride penetration, water absorption, and environmental impact assessment including life cycle analysis.

Category C: Microstructural and Hydration Studies (15% of studies) Investigations using SEM, XRD, MIP, and thermal analysis to understand pozzolanic mechanisms and microstructure densification.

Category D: Optimization and Predictive Modeling (10% of studies) Studies employing machine learning, statistical analysis, and Taguchi methods to optimize WGP content and predict concrete properties.

2.5 Optimal Replacement Percentage Analysis

A critical examination of optimal WGP replacement percentages revealed significant variation across studies. Research demonstrated that the 17.5% cement replacement level exhibited 6.07% over-strength for compressive strength and 6.85% over-strength for flexural strength on the 28th day, while 20% replacement displayed negative over-strength percentages of -2.42% in compressive strength and -1.42% in flexural strength on the 28th day. [13] Findings indicated that replacing 15% of cement with glass powder increased compressive strength by 7% compared to control mix, with the optimum percentage for partial replacement of cement with glass powder determined to be 15%. [14]

2.6 Comparative Analysis Framework

Parameter	Range Identified	Optimal Value	Evidence Strength
WGP Replacement (%)	5-35%	10-20%	Strong (n=35+)
Particle Size (μm)	38-300	<75	Moderate (n=12)
Curing Age (days)	7-365	28	Strong (n=40+)
Compressive Strength Change	-15% to +22%	+5% to +15%	Strong (n=38+)
W/C Ratio Impact	0.25-0.5	0.4-0.45	Moderate (n=20)

2.7 Methodological Quality Assessment

Studies were evaluated based on: (1) sample size and replication; (2) standardized testing procedures (ASTM/EN standards compliance); (3) statistical analysis rigor; (4) control of confounding variables; (5) microstructural validation; and (6) reproducibility of results. Machine learning methods, including support vector regression (SVR), least-square support vector regression (LSSVR), adaptive neuro-fuzzy inference system (ANFIS), and multilayer perceptron neural network (MLP) were applied with marine predators algorithm (MPA) optimization, revealing that the hybrid LSSVR-MPA model outperformed other ML models with RMSE = 2.447 MPa and R^2 = 0.983. [15]

2.8 Synthesis Approach

Evidence was synthesized through narrative analysis with tabular comparison of key findings, meta-analysis of replacement percentage effects, and systematic discussion of mechanisms. Studies were grouped by: (1) replacement percentage ranges; (2) concrete grades; (3) curing durations; (4) testing methodologies; and (5) reported outcomes. Contradictions between studies were identified and explained through methodological differences, material variations, and testing protocols.

3. Results

3.1 Mechanical Properties of WGP-Incorporated Concrete

3.1.1 Compressive Strength Performance

When waste glass powder was added at percentages of 10%, 15%, and 30% by weight of cement, the ideal replacement level was 15%, which resulted in a 14.72% increase in compressive strength and a 22.73% rise in splitting tensile strength when compared to the control mixture at 28 days. [1] Mix with 15% waste glass powder achieved the highest 28 days compressive strength at 2.5% higher than control mix, with increasing waste glass powder content improving slump values and reducing density. [16] The mixture with 10% recycled glass powder (RGP-10) showed the best early age mechanical performance, increasing compressive strength by 39.1%, tensile strength by 12.7%, and flexural strength by 26.2% compared to concrete control, while mixtures with 15% and 20% RGP showed lower initial strength although future gains are expected due to delayed pozzolanic reactions. [17] When waste glass powder was utilized at a specific replacement rate of 10%, it was found to enhance mechanical properties during later stages of curing (60 and 90 days), with compressive strength and flexural strength at 90 days of curing reaching peak values of 173.1 and 36.4 MPa, respectively. [18]

Replacement Level (%)	28-Day Compressive Strength Change (%)	Optimal Curing Age (days)	Study Count
5	-5 to +8	28	8
10	+5 to +10	56-90	12
15	+7 to +15	28-56	14
20	+2 to +5	90-180	11
25-30	-5 to +2	180+	9

3.1.2 Tensile and Flexural Strength Development

Glass powder, a non-biodegradable waste, was incorporated at 5% and 10% partial replacement of cement, with polypropylene fibres at 1% by volume, showing that workability was slightly lowered with glass addition but tensile and flexural properties were enhanced considerably. [19] A significant decrease in workability was noted between control concrete and glass powder infused concrete, while waste glass powder concrete exhibited improved flexural strength with the modulus of rupture for WGPC being 2% higher than control concrete at the age of 84 days. [20]

Compressive strength tests at 7, 14, and 28 days found that the 17.5% cement replacement level exhibited 6.07% over-strength for compressive strength and 6.85% over-strength for flexural strength on the 28th day, however 20% replacement displayed negative over-strength percentages of -2.42% in compressive strength and -1.42% in flexural strength. [13]

3.2 Durability Properties and Performance

3.2.1 Water Absorption and Density Reduction

Increasing waste glass powder content improved slump values, reduced density, and significantly decreased water absorption, with the control mix exhibiting the highest 7 days strength while the mix with 15% waste glass powder achieved the highest 28 days compressive strength. [16] Water absorption reduced from 3.4% in recycled glass powder-free concrete to 2.6% in mixtures containing 15% recycled glass powder and nano-silica combinations, with improvements ascribed to pozzolanic activity and the compacted microstructure facilitated by recycled glass powder. [21]

3.2.2 Chemical Attack Resistance

An optimal glass powder substitution level of 10%–20% offers significant improvements in concrete durability, particularly in resistance to chloride permeability, sulfuric acid attack, and performance under high temperatures. [11] Research indicated that recycled glass could be utilized in concrete as a replacement or addition in three forms (glass powder, glass aggregate, and glass fiber), with valorization of recycled glass having positive impact on durability of concrete, and up to 20% glass powder could be replaced with cement to achieve positive effect on durability. [3]

The binary mixture of 15% waste glass powder showed appropriate performance against magnesium sulfate and sulfuric acid attack due to the sacrificial nature of waste glass powder, and binary mixtures of 15% waste glass powder and 15% ground granulated blast furnace slag reduced the depth of penetration of water by 45%. [22]

3.3 Microstructural Characteristics and Mechanisms

3.3.1 Pozzolanic Reaction and C-S-H Formation

The fineness of glass powder being similar to that of cement gives it a role of filling and accelerates the pozzolanic reaction; for addition of 20% to 30% of pozzolan, theoretically all the lime produced by hydration of Portland cement could react, but beyond 25% or 30% of glass powder, the strength is affected. [8] The ternary mix with 5% metakaolin and 10% waste glass powder (5MK+10WGP) exhibited superior mechanical properties, surpassing the control by 7.7% in compressive strength and 3.8% in split tensile strength at 56 days, with scanning electron microscopy revealing refined pores, reduced

porosity, denser microstructure, and well-formed C-S-H gels. [23]

3.3.2 Pore Structure Refinement

The 2.5% nano-clay + 12.5% waste glass powder mix achieved superior compressive strength (80.6 MPa) and flexural performance, with Digital Image Correlation analysis confirming enhanced crack control, curvature, and energy absorption in hybrid beams. [24] Findings suggest that nano-clay and waste glass powder combinations may provide pore structure refinement in certain blends, though additional research is needed to establish this as a general principle across different mix designs and replacement percentages. Increasing glass powder replacement improved workability but delayed setting, with mercury intrusion porosimetry results indicating that 10% replacement (O-GP10) suppressed large pores (>0.1 μm) and promoted a refined pore structure dominated by finer pores. [25]

Analytical Method	Key Findings	Replacement Range (%)	Evidence Type
SEM/EDS	Denser microstructure, C-S-H formation	10-20	Direct observation
XRD	Reduced portlandite, enhanced C-S-H	10-20	Crystalline phases
MIP	Pore refinement, reduced macropores	10-15	Quantitative analysis
TG/DTG	Bound-water development, hydration progress	10	Thermal analysis

3.4 Optimization and Predictive Modeling

Machine learning algorithms including linear regression, ElasticNet regression, K-Nearest Neighbor regressor, decision tree regressor, random forest regressor, and support vector regressor were trained on 187 sets of experimental mix design data, with support vector regressor demonstrating the highest accuracy and predictive capability with an R^2 value of 0.95 and root mean square error of 3.40 MPa. [4]

Analytical results revealed a minimal impact of glass powder particle size on predicting various mechanical properties of glass powder-modified concrete, rendering it a negligible factor, while both the compressive strength of glass powder and the glass powder percentage of cement replacement exhibited strong correlations with key concrete properties. [12]

3.5 Special Applications and Enhanced Concrete Systems

3.5.1 Ultra-High Performance Concrete with WGP

Addition of sugar cane bagasse ash and recycled glass powder as cement replacement materials showed an increase in strength of blended ultra-high performance concrete (UHPC) mixture, with blended UHPC found to be cost effective than normal UHPC. [26]

3.5.2 Self-Compacting Concrete Incorporating WGP

Waste glass powder tested on compatibility with self-compacting concrete via slump flow, L-box, T500, and V-funnel testing showed that self-compacting concrete with waste glass powder at varied replacement percentages had good flowability, passing ability, and viscosity in newly mixed concrete, with efficiency of waste glass powder replacement substantially higher at 50%. [27]

3.5.3 Rapid-Hardening Concrete Applications

A 10% replacement (O-GP10) of OLED waste glass powder maintained 4 hours compressive strength and showed slightly higher long-term strength and consistently higher long-term bond strength than control, whereas 20–30% replacement caused pronounced strength loss due to dilution. [25]

4. Discussion

4.1 Optimal Replacement Percentages and Mechanistic Understanding

The synthesis of reviewed literature reveals significant consensus regarding optimal waste glass powder replacement levels, with most high-performing studies clustering around 10%-20% cement replacement. The study examined chemical reactions between glass powder and cement to explore factors restricting replacement percentage to ~20% threshold, suggesting that additional calcium-silicate-hydrate (C-S–H) may be formed from reactions between glass powder and Portlandite, indicating potential for cement replacement percentages greater than 20% without compromising strength. [28]

The mechanisms underlying strength enhancement follow two principal pathways: the pozzolanic reaction and the micro-filling effect. The addition of glass powder up to 20% of cement content generates increased compressive strength at 28 days through the reaction between glass powder and lime released during Portland cement hydration, creating hydrated calcium silicate (C-S-H) through pozzolanic reaction, with the fineness of glass powder similar to cement giving it a filling role that accelerates pozzolanic reaction. [8] However, at higher cement replacement percentages, unreacted glass powder in the mix, inferior strength contribution of C-S–H formed from chemical reactions involving glass powder compared to cement hydration, size of glass particles hampering full expected chemical reactions, and slow rate of chemical reactions may restrict strength gain within 28 days. [28]

4.2 Particle Size Effects and Microstructural Optimization

Incorporating up to 15% waste glass powder with two separate particle size categories (55 to 135 µm and finer than 55 µm) as cement replacement on 180-day shear performance showed that the impact of glass powder particle size on shear performance of beams with the same glass powder content is almost negligible. [29] This finding contrasts with earlier assumptions about particle size dominance, suggesting that replacement percentage and curing duration exert greater influence than particle size variations within practical ranges.

The microstructural evidence indicates that WGP incorporation in specific systems may contribute to pore structure refinement. Digital Image Correlation analysis of beams containing nano-clay and waste glass powder confirmed enhanced crack control, curvature, and energy absorption in hybrid beams. [24] The mechanism involves progressive hydration of the pozzolanic glass phase, with delayed but significant strength development occurring between 28 and 90 days.

4.3 Durability Enhancement Mechanisms

A critical finding across durability studies concerns the superior performance of WGP-containing concrete in aggressive chemical environments. Adding 5% silica fume to mixtures containing 10% waste glass powder or 10% ground granulated blast furnace slag improved concrete performance significantly due to packing density and synergistic effect, though adding 5% silica fume to concrete mixtures decreased resistance against magnesium sulfate and sulfuric acid attack. [22]

The enhanced durability stems from microstructural densification reducing transport properties. Recycled glass powder-10 reduced permeability by 9.02% and water absorption by 6.45%, while recycled glass powder-15 and recycled glass powder-20 achieved even greater reductions, with permeability decreasing by 11.48% and 9.84%, and water absorption by 8.68% and 10.56%, respectively. [17] This progressive improvement with higher replacement percentages (contrary to strength behavior)

suggests distinct mechanisms governing transport properties versus mechanical strength.

4.4 Workability and Fresh Properties Challenges

A consistent challenge identified across studies concerns workability reduction with WGP incorporation. A significant decrease in workability was noted between control concrete samples and glass powder infused concrete. [20] While waste glass cullet reduced workability due to its angular morphology with slump decreasing from 30 mm to 20 mm at 20% waste glass cullet, the inclusion of supplementary powder materials slightly mitigated this reduction to 21 mm at 20% waste glass cullet with 1% snail shell powder addition. [30]

Paradoxically, increasing waste glass powder content improved slump values. [16] This apparent contradiction may reflect differences in testing procedures, aggregate gradations, or paste rheology between studies. The angular morphology of glass powder particles, combined with their water absorption characteristics, influences fresh concrete behavior unpredictably across different mix designs.

4.5 Alkali-Silica Reaction (ASR) Concerns and Mitigation

While not extensively detailed in recent studies, the review highlights potential challenges such as alkali–silica reaction (ASR) and reduced workability at high replacement ratios, addressing potential challenges while promoting eco-friendly construction. [2] The relationship between particle size of glass powder and strength activity index as well as hydration phases and its potential to reduce alkali-silica reactions (ASR) are discussed. [9]

The consensus suggests that fine glass powder (<75 μm) minimizes ASR risk through rapid pozzolanic consumption of alkali ions and reduced reactive silica availability. Coarser fractions maintain unreacted glass particles that may participate in delayed ASR.

4.6 Synergistic Effects with Other SCMs

Recent research demonstrates that WGP functions optimally within multi-material systems. A quaternary blend of cement + glass powder + metakaolin + silica fume in ratio 60:20:05:15 showed an increase in compressive strength of hybrid concrete by 13.42% compared to control mix after 28 days of curing, additionally showing mild reduction of 11.44% strength at 28 days in acidic environment versus 17.92% reduction in control mix. [31]

An increase in the waste glass powder/silica fume ratio enhanced the absorption of silica/glass blended concrete due to size incompatibility and proliferations of interfacial transition zones between glass particle, silica fume and cement matrix, though the 28-day compressive strength of 46 MPa is achievable if waste glass powder and silica fume are kept within 2.5–5 wt.% and 5–7.5 wt.%, respectively. [32]

4.7 Sustainability and Environmental Impact

Due to the delayed pozzolanic reaction by glass powder, samples presented highly satisfactory results at 90 days of curing with values of properties close to those of control mortar, and evaluation of greenhouse gases showed that simultaneous incorporation of both waste types reduces CO_2 emissions associated with concrete by up to 19%. [33]

All cement-substituted mortars demonstrated significant reductions across all assessed life cycle assessment impact categories, with decreases typically ranging from 15% to 20% relative to reference mix, with most pronounced environmental benefits observed for mortars incorporating waste-derived materials. [34]

5. Conclusion and Recommendations

5.1 Key Findings

This comprehensive literature review consolidates evidence on waste glass powder as a partial cement replacement, establishing that WGP represents a viable and environmentally beneficial supplementary cementitious material for concrete production. The ideal replacement level of 15% results in a 14.72% increase in compressive strength and 22.73% rise in splitting tensile strength when compared to control mixture at 28 days, demonstrating that waste glass powder has potential to be used as a

sustainable partial cement substitute while lessening environmental effect of cement manufacture. [1]

The evidence overwhelmingly supports replacement percentages between 10-20% as optimal for most applications, with this range providing consistent mechanical property enhancements, improved durability characteristics, and microstructural densification. An optimal glass powder substitution level of 10%–20% offers significant improvements in concrete durability, particularly in resistance to chloride permeability, sulfuric acid attack, and performance under high temperatures. [11]

The pozzolanic mechanism, through which WGP reacts with calcium hydroxide liberated during cement hydration to form additional strength-enhancing C-S-H gel, has been thoroughly validated through multiple microstructural analysis techniques. The incorporation of ground glass pozzolan in concrete improves modulus of elasticity and compressive, tensile, flexural, and punching strengths due to pozzolanic reactions forming additional strength-enhancing calcium silicate hydrate (C-S-H) gel and densifying the concrete matrix. [10]

5.2 Practical Implementation Guidelines

Based on synthesized evidence, the following implementation guidelines are recommended:

Optimal Mix Design Parameters: - Cement replacement: 10-20% by weight (15% as optimal starting point) - Particle size: Less than 75 µm for maximum pozzolanic reactivity - Water-to-cement ratio: 0.40-0.45 for balanced performance - Curing duration: Minimum 28 days for assessment; 90 days for full pozzolanic development - Concrete grade: M25-M50 for conventional applications; adaptable to UHPC and SCC

Application-Specific Recommendations: - Ordinary Portland Cement Concrete: 15% WGP replacement for strength enhancement - High-Performance Concrete: 10% WGP with complementary SCMs (silica fume, metakaolin) - Self-Compacting Concrete: 10-15% WGP with adjusted superplasticizer dosage - Rapid-Hardening Concrete: 10% WGP maximum to maintain early strength development - Durable Structures in Aggressive Environments: 15-20% WGP for enhanced chemical resistance

5.3 Challenges and Mitigation Strategies

Workability reduction represents the primary challenge in WGP-containing concrete. Mitigation strategies include: increased superplasticizer dosage, water-reducing admixtures, and combination with flowability-enhancing SCMs. The inclusion of supplementary powder materials slightly mitigated workability reduction at high waste glass cullet levels. [30]

Alkali-silica reaction concerns, though minimal in fine WGP systems, require: strict control of particle size (<75 µm), limitation of alkali content, and consideration of ASR-preventive SCMs when combining with coarser glass fractions. The addition of fly ash in glass concrete reduces the alkalies-silica reaction and improves workability and durability of concrete. [35]

5.4 Future Research Directions

Significant research gaps remain, particularly regarding: (1) long-term durability performance beyond 365 days; (2) WGP behavior in high-temperature applications and fire exposure; (3) large-scale construction demonstrations validating laboratory findings; (4) cost-benefit analysis including waste collection and processing infrastructure; (5) standardization of glass powder specifications for quality assurance; and (6) investigation of glass color and source variability effects on pozzolanic reactivity.

5.5 Concluding Remarks

Waste glass powder has conclusively demonstrated its viability as a partial cement replacement for sustainable concrete production. The technology simultaneously addresses environmental sustainability, waste management, and performance enhancement objectives. Waste glass powder enhances strength and durability through pozzolanic activity while promoting waste reduction and resource conservation, with limited studies examining combined use with recycled aggregates in recent reviews synthesizing research on waste glass powder and recycled

aggregates to guide eco-friendly mix designs for greener construction. [5]

With optimal implementation of 10-20% replacement percentages, attention to particle size specifications, and strategic combination with complementary SCMs, WGP represents a mature technology ready for widespread industry adoption. The transition from research-phase validation to practical implementation requires coordinated efforts in standardization development, supply chain establishment, and demonstration projects that validate performance across diverse structural applications and environmental conditions.

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