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A Review of the Durability and Performance Assessment of Pavement Quality Concrete (PQC) Using Mineral Admixtures

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Abstract

This review examines the current state of knowledge regarding the performance and durability characteristics of Pavement Quality Concrete (PQC) incorporating mineral admixtures. With increasing emphasis on sustainable construction practices and the need for durable pavements, mineral admixtures have emerged as crucial components in modern concrete technology. This paper synthesizes recent research findings on various mineral admixtures' effects on PQC properties, evaluation methodologies, and long-term performance implications.

1. Introduction

Pavement Quality Concrete represents a specialized concrete formulation designed to withstand the demanding conditions of highway and airport applications. Recent studies have shown that PQC specifications typically require a minimum grade of M40, reflecting the material's critical role in infrastructure development. The incorporation of mineral admixtures has revolutionized PQC technology, offering enhanced performance characteristics while addressing sustainability concerns.

Pavement quality concrete is a critical component of infrastructure development, as it directly impacts the longevity and performance of roadways, bridges, and other concrete structures. The use of mineral admixtures, such as fly ash, slag, and silica fume, has become increasingly common in the production of PQC due to their ability to enhance the concrete's durability and sustainability. This study aims to evaluate the performance and durability of PQC incorporating various mineral admixtures.

2. Types and Properties of Mineral Admixtures in PQC

2.1 Common Mineral Admixtures

The most frequently employed mineral admixtures in PQC include:

1. Fly ash: Fly ash, a byproduct of coal combustion, has been extensively studied as a supplementary cementitious material in PQC. (Mukherjee & Vesmawala, 2017) mentions the exploration of fly ash utilization in highway construction. Its incorporation in concrete mixes has been shown to improve workability, reduce permeability, and increase long-term strength. The spherical particles of fly

ash fill voids in the cement matrix, leading to a denser and more compact structure. This densification contributes to reduced permeability, enhancing the resistance of PQC to water ingress and chemical attack. Additionally, the pozzolanic reaction of fly ash with cement over time contributes to increased strength development.

2. Silica fume: Silica fume, a byproduct of silicon and ferrosilicon alloy production, is a highly reactive pozzolanic material. Its extremely fine particles and high silica content contribute to significant improvements in PQC properties. Studies have shown that silica fume enhances both compressive and flexural strength, reduces porosity, and improves resistance to chloride penetration. The enhanced strength and reduced porosity are attributed to the filler effect and pozzolanic reaction of silica fume, which refines the pore structure and strengthens the interfacial zone between cement paste and aggregates.

3. Ground granulated blast furnace slag (GGBS) :GGBS, a byproduct of iron production, is another widely used mineral admixture in PQC. It exhibits cementitious properties and contributes to improved durability, particularly increased resistance to sulfate attack and alkali-silica reaction. The slower hydration rate of GGBS compared to cement results in lower heat of hydration, which can be beneficial in mitigating thermal cracking in massive concrete structures. Moreover, GGBS improves the microstructure of concrete, leading to reduced permeability and enhanced resistance to chemical attack.

4. Steel fibers : Steel fibers have been shown to improve the compressive strength of pavement quality concrete. (T.V & Pavithra, 2023) found that adding steel fibers at a volume fraction of 0.5% increased compressive strength by 10%. The steel fibers act as reinforcement, providing additional strength and resisting crack propagation. (Murthi et al., 2020) also investigated the correlation between rebound hammer number and mechanical properties of steel fiber reinforced PQC.

Admixture	**Effect on PQC**
Fly Ash	Improved workability, reduced permeability, increased strength
Silica Fume	Enhanced compressive and flexural strength, reduced porosity
Ground Granulated Blast Furnace Slag	Improved durability, increased resistance to sulfate attack

Recent investigations have demonstrated that high pozzolanic mineral admixtures like fly ash and silica fume significantly enhance the performance characteristics of PQC. These materials contribute to both fresh and hardened concrete properties through their physical and chemical interactions.

2.2 Performance Characteristics

Mineral admixtures, such as fly ash, slag, silica fume, and natural pozzolans, play a significant role in influencing the fresh properties of concrete. These materials are typically used in combination with cement to enhance concrete's performance, especially in terms of workability, setting time, and heat generation. Here’s how mineral admixtures impact the fresh properties of concrete:

2.2.1. Workability:

Fly ash generally improves the workability of concrete by making it more cohesive and reducing the water demand. It can help improve the flowability of the mix, especially for high-strength or self-consolidating concrete.Slag can enhance the workability, similar to fly ash, by improving the paste quality. It helps reduce the friction between particles and can lead to smoother mixing and placement. Silica fume, while improving strength and durability, can reduce workability. Its fine particles require more water to achieve a workable mix, so superplasticizers are often used to compensate for this.Natural Pozzolans: These typically have similar effects to fly ash in improving workability, though their impact can vary based on the specific pozzolan type and fineness.

2.2.2. Setting Time:

Fly ash can delay the setting time of concrete. The delay occurs because fly ash particles are less reactive than cement particles. This is beneficial in hot weather conditions where premature setting can occur, but it may also require adjustments in mix design. Similar to fly ash, slag tends to extend the setting time, particularly in higher dosages. This can improve workability over extended periods and provide more time for placement and finishing. Silica fume may slightly accelerate the setting time due to its high reactivity with calcium hydroxide (a byproduct of cement hydration), but this effect is not as pronounced as in the case of accelerators. These materials also tend to delay the setting time, though the effect varies based on the specific material used.

2.2.3. Heat of Hydration:

Fly ash generally produces a lower heat of hydration compared to Portland cement. This can be advantageous in mass concrete structures, where excessive heat generation can lead to cracking due to thermal stresses. Slag also reduces the heat of hydration, making it beneficial for large pours or areas with potential temperature-induced cracking. Silica fume can increase the heat of hydration slightly, as it reacts quickly with calcium hydroxide. However, the overall effect is minor compared to the benefits it provides in strength and durability. These may either increase or decrease the heat of hydration depending on their composition and reactivity.

2.2.4. Bleeding and Segregation:

Fly ash can reduce bleeding (the rise of water to the surface of concrete) due to its ability to absorb some of the mixing water. This leads to better surface finish and fewer problems with segregation. Slag can also reduce bleeding and segregation by improving the paste and the cohesion of the mix. Silica fume is fine and highly reactive, which can help reduce bleeding, but its tendency to absorb water may lead to increased demand for water or plasticizers. These materials may show similar effects to fly ash, reducing bleeding and helping maintain a stable mix.

2.2.5. Viscosity:

Fly ash can help control the viscosity of the concrete mix, making it less prone to segregation and easier to handle, particularly in high-performance mixes. Similar to fly ash, slag contributes to a stable mix with improved viscosity characteristics, particularly in self-compacting concretes. Silica fume, due to its very fine particle size, can increase viscosity, which may require careful water content adjustments to maintain workability.

2.3Mineral admixtures significantly affect the hardened properties of concrete:

Mineral admixtures significantly affect the hardened properties of concrete, including strength, durability, and resistance to environmental factors. These admixtures, such as fly ash, slag, silica fume, and natural pozzolans, alter the hydration process and microstructure of concrete, leading to improved performance.

2.3.1. Compressive Strength :Fly ash improves the long-term strength of concrete due to its pozzolanic reaction, which consumes calcium hydroxide and forms additional calcium silicate hydrate (C-S-H). Early strength may be slightly reduced due to slower reactivity. Slag increases strength in both the medium and long term. It has a latent hydraulic property that becomes active in the presence of calcium hydroxide and water, producing additional C-S-H. Silica fume enhances the early and long-term strength of concrete significantly. Its ultrafine particles fill voids between cement particles and produce dense, high-strength concrete. These generally enhance long-term strength due to their pozzolanic reaction, though early strength may be slower compared to plain concrete.

2.3.2. Tensile and Flexural Strength: Fly Ash and Slag,these improve the tensile and flexural strength of concrete over time by enhancing the microstructure and reducing the presence of weak zones like pores and microcracks. Silica fume is particularly effective in increasing tensile and flexural strength due to its ability to refine the microstructure and bridge microcracks. These materials contribute to improved tensile and flexural strength over the long term, depending on their reactivity.

2.3.3. Durability: Resistance to Chloride Penetration,mineral admixtures such as fly ash, slag, and silica fume improve resistance to chloride ingress by densifying the pore structure and reducing permeability.Alkali-Silica Reaction (ASR), silica fume and fly ash are effective in mitigating ASR by consuming alkalis and reducing the reactive silica available for the reaction.Sulphate Resistance,slag and fly ash improve resistance to sulphate attack by reducing permeability and altering the chemical composition of the hardened cement paste to resist aggressive ions.Freeze-Thaw Resistance, mineral admixtures enhance freeze-thaw resistance by reducing water penetration and refining pore structure. However, proper air entrainment is necessary for optimal performance.

2.3.4. Permeability: Fly Ash, reduces permeability by producing additional C-S-H, which fills capillary pores and blocks pathways for water and ions. Slag significantly reduces permeability due to its fine particle size and reactivity, leading to a denser microstructure. Extremely fine particles of silica fume significantly decrease permeability, making concrete highly resistant to water and ion ingress. Natural Pozzolans, reduce permeability, though their effectiveness depends on their reactivity and fineness.

2.3.5. Shrinkage and Creep: Fly ash generally reduces drying shrinkage and creep due to the lower heat of hydration and slower reaction rate, leading to less thermal stress during curing. Slag can reduce shrinkage in the long term, though it may increase early-age shrinkage if the replacement level is high. Silica fume may increase drying shrinkage due to its high surface area and increased water demand. Proper curing is essential to mitigate this effect. Similar to fly ash, they generally help reduce long-term creep and shrinkage.

2.3.6. Heat of Hydration: Fly Ash and Slag, both materials reduce the heat of hydration, making them suitable for mass concrete applications to minimize thermal cracking. Silica slightly increases the heat of hydration due to its rapid pozzolanic reaction but typically not to the extent that it causes significant thermal stresses.Natural Pozzolans, reduce the heat of hydration, similar to fly ash, which is beneficial in large pours.

2.3.7. Microstructure and Density: Fly Ash and Slag, improve the microstructure by refining pore sizes and reducing the overall porosity, resulting in denser and more durable concrete.Silica Fume, creates an extremely dense microstructure due to its particle size and reactivity, which fills even the smallest voids between cement particles.Natural Pozzolans, enhance microstructure by reducing calcium hydroxide content and increasing C-S-H formation.

2.3.8. Resistance to Chemical Attack: Fly Ash, improves resistance to chemical attack by reducing permeability and enhancing the concrete matrix.Slag, provides excellent resistance to chemical attacks, including sulphate and acid exposure, due to its dense microstructure and reduced ion ingress.Silica Fume, enhances resistance to aggressive environments, especially chloride-rich conditions, by minimizing permeability. Natural Pozzolans, contribute to chemical resistance by densifying the concrete and reducing free calcium hydroxide.

The use of mineral admixtures significantly improves the hardened properties of concrete. They enhance strength, reduce permeability, and increase durability against chemical and environmental attacks. However, the effectiveness depends on the type, dosage, and compatibility of the admixture with the cement and aggregates used. Careful mix design and proper curing are essential to maximize these benefits.

3. Performance Evaluation Methods

3.1 Mechanical Performance Testing: Mechanical performance testing of concrete is essential to assess its suitability for construction applications. The American Society for Testing and Materials (ASTM) has established several standards to guide these evaluations. Recent ASTM standards pertinent to mechanical performance testing of concrete include:

3.1.1. Compressive Strength Testing :ASTM C39/C39M-21;this standard outlines the procedure for determining the compressive strength of cylindrical concrete specimens, such as molded cylinders and drilled cores. It is applicable to concrete with a density exceeding 800 kg/m^3 (50 lb/ft^3).

3.1.2. Flexural Strength Testing: ASTM C78/C78M; this test method covers the determination of the flexural strength of concrete by using a simple beam with third-point loading. It is commonly used to assess the tensile strength of concrete indirectly.ASTM C293/C293M; this standard specifies the procedure for determining the flexural strength of concrete using a simple beam with center-point loading. It provides an alternative method to ASTM C78/C78M.

3.1.3. Splitting Tensile Strength Testing: ASTM C496/C496M, this test method covers the determination of the splitting tensile strength of cylindrical concrete specimens. It is used to evaluate the tensile strength of concrete, which is crucial for understanding its behavior under tensile stresses.

3.1.4. Elastic Modulus Testing: ASTM C469/C469M, this standard outlines the procedure for determining the static modulus of elasticity and Poisson's ratio of concrete in compression. These properties are vital for structural analysis and design.

3.1.5. Ultrasonic Pulse Velocity Testing: ASTM C597-09; this test method covers the determination of the pulse velocity of ultrasonic waves passing through concrete. It is a non-destructive test used to assess the uniformity and quality of concrete.

3.1.6. Fracture Toughness Testing: ASTM C1421; this standard provides a test method for determining the fracture toughness of advanced ceramics at ambient temperature. While primarily for ceramics, it can be applicable to certain high-strength concrete materials.

3.2 Durability Assessment: The durability assessment of Pavement Quality Concrete (PQC) is critical to ensure long-term performance under traffic loads and exposure to environmental factors. PQC, typically used for heavy-duty pavements like highways and airfields, must resist physical and chemical degradation over time.

Modern durability testing protocols include:

3.2.1 Freeze-thaw resistance: PQC specimens are subjected to repeated freeze-thaw cycles, and the loss in weight or reduction in strength is evaluated.
3.2.2 Chloride penetration: Electrical charge passed through a concrete specimen is measured to assess its resistance to chloride penetration.
3.2.3 Sulfateresistance: PQC specimens are immersed in sulphate solutions, and expansion or loss of strength is monitored.
3.2.4 Carbonation resistance: Specimens are exposed to controlled carbon dioxide environments, and the carbonation depth is measured.
3.2.5 Water absorption: Specimens are subjected to water pressure, and the depth of water penetration is measured.
3.2.6 Resistance to Chemical Attack: Specimens are immersed in chemical solutions, and changes in weight or strength are monitored.

4. Performance Optimization Strategies: Pavement Quality Concrete (PQC) is subjected to heavy traffic loads and harsh environmental conditions, requiring optimized performance to ensure durability, strength, and service life. Below are key strategies to enhance PQC performance:

4.1. Material Selection and Proportioning

4.1.1 Cement: Use high-quality Ordinary Portland Cement (OPC) or blended cements (e.g., Portland Pozzolana Cement, Portland Slag Cement) for enhanced durability and reduced permeability. Select low-alkali cement to mitigate alkali-silica reactions (ASR). Aggregates: Use well-graded, clean, and durable aggregates to minimize voids and ensure uniform compaction. Ensure the maximum size of aggregates is suitable for the pavement thickness (typically 20–40 mm).
4.1.2 Admixtures: Incorporate mineral admixtures like fly ash, slag, or silica fume to improve workability, durability, and long-term strength. Use chemical admixtures such as superplasticizers to achieve desired workability at a low water-cement ratio.

4.2 Mix Design Optimization

4.2.1 Water-Cement Ratio: Maintain a low water-cement ratio (0.35–0.45) to reduce permeability and enhance strength and durability. Concrete Consistency, ensure appropriate slump values (25–75 mm) for PQC, balancing workability and stability. Target Strength, design the mix to achieve a target compressive strength that exceeds the specified characteristic strength, ensuring safety margins.

4.3. Durability Enhancements

4.3.1 Low Permeability: Use supplementary cementitious materials (SCMs) like fly ash and silica fume to refine the pore structure and reduce water ingress.

4.3.2 Chloride and Sulphate Resistance: Incorporate slag and pozzolanic materials to enhance resistance against chloride and sulphate attacks.

4.3.3 Freeze-Thaw Resistance: Ensure proper air entrainment in concrete to improve resilience in freeze-thaw cycles.
4.3.4 Carbonation Resistance: Maintain a dense microstructure and low permeability to resist carbonation, particularly in urban environments.

4. 4 Construction Practices

4.4.1 Batching and Mixing: Use automated batching plants for consistent mix proportions.Ensure thorough mixing to achieve uniform distribution of materials.

4.4.2 Placement and Compaction: Place concrete within its initial setting time to avoid cold joints.Use vibratory equipment for proper compaction and void reduction.

4.4.3 Finishing: Ensure smooth surface finishing to enhance skid resistance and surface durability.

4.4.4 Curing: Implement adequate curing practices (e.g., water curing, curing compounds) for at least 14–28 days to prevent shrinkage cracks and ensure proper hydration.

5. Joint Design and Maintenance

5.1 Joint Placement: Provide contraction, expansion, and construction joints at appropriate intervals to control cracking.
5.2 Sealing: Use high-quality joint sealants to prevent ingress of water, debris, and contaminants.

5.3 Dowels and Tie Bars: Ensure proper placement of dowels and tie bars to maintain load transfer efficiency across joints.

6. Quality Control and Testing

6.1 Fresh Concrete: Test slump, temperature, and air content during placement.
6.2 Hardened Concrete: Conduct compressive strength, flexural strength, and non-destructive tests (NDT) like ultrasonic pulse velocity and rebound hammer tests.
6.3 Durability Tests: Perform chloride penetration, water permeability, and freeze-thaw tests to ensure long-term performance.

7. Maintenance Strategies

7.1 Periodic Inspection: Regularly monitor the pavement for cracks, spalling, and joint integrity.
7.2 Preventive Maintenance: Apply surface treatments like sealants and coatings to protect against environmental exposure.

7.3 Timely Repairs: Address minor cracks and defects promptly to prevent further deterioration.

8. Sustainability and Cost Efficiency

8.1 Recycled Materials: Incorporate recycled aggregates or industrial byproducts (e.g., fly ash, slag) to reduce environmental impact.
8.2 Energy Efficiency: Use low-energy cements and optimize transport distances to minimize the carbon footprint.

8.3 Waste Reduction: Reuse PQC waste during repairs or as sub-base material in new pavements.

9. Technological Integration

9.1 Self-Compacting Concrete (SCC): Consider SCC for ease of placement and superior surface finish, especially in congested areas.

9.2 Fiber Reinforcement: Use steel or synthetic fibers to improve tensile strength, crack resistance, and impact resistance.
9.3 Smart Materials: Explore smart concrete with self-healing capabilities or embedded sensors for real-time performance monitoring.

10. Climate-Specific Adjustments

10.1 Hot Weather Conditions: Use retarders to prevent rapid setting and reduce thermal stresses.
10.2 Cold Weather Conditions:Incorporate accelerators and insulated curing methods to ensure proper hydration in low temperatures.

Conclusions

This review demonstrates that mineral admixtures significantly enhance PQC performance and durability when properly designed and implemented. The synergistic effects of different mineral admixtures offer opportunities for optimizing concrete properties while contributing to sustainability goals. Continued research in this field will likely yield further improvements in PQC technology and applications.

In conclusion, the integration of mineral admixtures into Pavement Quality Concrete (PQC) represents a significant advancement in modern construction, offering improvements in performance, durability, and sustainability. Admixtures such as fly ash, silica fume, and ground granulated blast furnace slag enhance key properties of PQC, including strength, permeability, and resistance to environmental and chemical degradation.

Strategic performance optimization through careful material selection, mix design, and adherence to construction best practices ensures the long-term functionality of PQC under heavy traffic loads and harsh conditions. Additionally, durability assessment methodologies and regular maintenance strategies are crucial for extending the service life of pavements.

Incorporating sustainability measures, such as the use of recycled materials and energy-efficient practices, further aligns PQC development with global environmental goals. Technological innovations like self-compacting concrete and fiber reinforcement present future pathways for enhancing PQC applications, making it a resilient and sustainable solution for infrastructure development.

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