**Title 2: Enhancing Strength in High-Performance Concrete: Cement Replacement with Supplementary Materials for Superior Performance**

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**ABSTRACT**

Ultra-High-Performance Concrete (UHPC) represents a breakthrough in modern concrete technology, delivering unparalleled strength and durability compared to conventional concrete. Its remarkable performance stems from a highly refined microstructure, achieved through the integration of advanced binders and innovative additives. This research investigates the ability to achieve higher compressive strength in high-performance concrete (HPC) by replacing a portion of cement with ultra-fine mineral supplementary materials. Ultra-fine materials were employed as partial substitutes for cement to evaluate their influence on the mechanical and durability properties of concrete. Comprehensive analyses were conducted, focusing on the compressive strength development through standardized cube tests at varying curing intervals. The study offers a comprehensive evaluation of concrete mixes enhanced with ultra-fine materials, presenting unique findings that demonstrate their potential to achieve significantly higher compressive strengths compared to conventional designs. Compressive strength tests conducted at 3, 7, and 28 days revealed that strategically optimized concrete mixes incorporating ultra-fine mineral materials exhibit superior performance compared to conventional 100% cement-based mixes. The findings underscore the potential of ultra-fine minerals to significantly enhance both the mechanical properties and the sustainability of high-performance concrete (HPC), while maintaining its structural integrity.

**Keywords**: Ultra-High-Performance Concrete (UHPC), Ultra-Fine Mineral Materials, Cement Replacement, Mechanical Properties of Concrete, Compressive strength, Cube Test Analysis.

1. **Introduction**

Ultra-High-Performance Concrete (UHPC) has emerged as a transformative innovation in the field of concrete technology, offering exceptional mechanical properties and durability that far surpass those of conventional concrete. The superior performance of UHPC is attributed to its highly refined microstructure, achieved through the incorporation of advanced binders and innovative additives that enhance its strength and resilience. This advancement has opened new possibilities for structural applications where performance, longevity, and sustainability are critical.

One of the pressing challenges in modern construction is the reduction of cement usage without compromising the mechanical properties and durability of concrete. Cement production is energy-intensive and contributes significantly to global carbon emissions, making sustainable alternatives imperative. To address this challenge, this research explores the use of ultra-fine mineral materials as partial substitutes for cement in high-performance concrete (HPC).

Ultra-fine mineral materials, such as silica fume and ultra-fine fly ash, have garnered attention for their ability to refine the concrete microstructure, enhance the hydration process, and improve overall performance. By partially replacing cement with these supplementary materials, it is possible to not only reduce the environmental impact but also achieve higher compressive strength and improved durability.

In this study, two sets of cube tests were conducted to evaluate the compressive strength of concrete with varying cement content. In Case 1, a conventional mix was used with 100% cement (530 kg), serving as the control group. In Case 2, the cement content was reduced to 85% (450 kg), with 15% of the cement replaced by alternative ultra-fine mineral materials (80 kg). Compressive strength tests were performed on the specimens after 28 days of curing to assess the effect of cement reduction and the incorporation of alternative materials on the concrete's strength.

This research investigates the compressive strength development of concrete mixes incorporating ultra-fine minerals, with tests conducted at 3, 7, and 28-day curing intervals. Standardized cube tests were performed to evaluate the mechanical properties, while additional analyses assessed the durability and structural integrity of the optimized mixes. The findings highlight the potential of ultra-fine materials to redefine high-performance concrete applications by achieving equivalent or superior strength compared to 100% cement-based mixes, thereby promoting sustainability in construction practices.

This paper aims to present a comprehensive evaluation of the role of ultra-fine mineral materials in enhancing the strength, durability, and sustainability of high-performance concrete, providing a pathway for the development of eco-friendly and high-strength structural solutions.

1. **Experimental Study**

**2.1 Material**

The materials utilized in this study include Ordinary Portland Cement (OPC 53 conforming to BIS IS 12269:2013), UltraFine™ mineral additive, Ground Granulated Blast Furnace Slag (GGBS), natural sand (fine and coarse), Admixture, and water.

* **Ordinary Portland Cement (OPC 53):** Conforming to BIS IS 12269:2013, OPC 53 is a high-strength cement used as the primary binder in concrete mixes.
* **UltraFine™ Mineral Additive:** Known for its high pozzolanic activity and superior fineness, UltraFine™ was utilized as a partial replacement for cement. It was selected to improve the packing density and mechanical performance of the concrete while maintaining sustainability by reducing the overall cement content.
* **Ground Granulated Blast Furnace Slag (GGBS):** GGBS is a byproduct of steel manufacturing, known for its pozzolanic properties. It was used as a supplementary cementitious material to enhance durability and reduce the carbon footprint of the concrete mix.
* **Natural Sand (Fine and Coarse):** Classified into fine and coarse grades, natural sand was used as aggregates in the mix. These sands adhered to the required grading limits and were chosen to ensure adequate workability and strength development of the concrete mixes.
* **Admixture:** Admixture was used to enhance the workability and performance of the concrete mixes.
* **Water:** Water was used to hydrate the cement and facilitate the chemical reactions necessary for setting and hardening.

**2.2 Design Mix**

The primary objective of these mix designs is to enhance the concrete's structural performance by improving its strength, durability, and longevity. This is achieved using alternative materials like UltraFine™ mineral additives and Ground Granulated Blast-Furnace Slag (GGBS), which help reduce the reliance on traditional cement. The optimized mix design aims to provide a high-performance concrete solution that meets the demands of modern engineering applications.

 **Case 1 (Conventional Mix)** uses only Ordinary Portland Cement (OPC) with no additional mineral additives or GGBS, resulting in a lower density and potentially lower durability when compared to the optimized mix.

 **Case 2 (Optimized Mix)** includes UltraFine™ mineral additive and GGBS, which improve the concrete's durability and contribute to environmental sustainability by reducing cement usage. This mix also demonstrates a higher density, which might positively influence strength and durability characteristics.

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| --- | --- | --- |
| **Material** | **Case 1: Conventional Mix (kg/m³)** | **Case 2: Optimized Mix (kg/m³)** |
| **Cement (OPC 53)** | 530 | 450 |
| **UltraFine™ Mineral Additive** | 0 | 80 |
| **GGBS** | 275 | 275 |
| **Natural Sand (Fine)** | 678 | 678 |
| **Natural Sand (Coarse)** | 935 | 935 |
| **Admixture** | 8.85 | 8.85 |
| **Water** | 125 | 125 |

Table 1: Case 1 & Case 2 mix proportions

1. **Result And Discussion**

**3.1 Compressive Strength**

The compressive strength comparison between Case 1 (Conventional Concrete Mix) and Case 2 (Optimized Concrete Mix) provides valuable insights into the performance of the two mix designs over time. The following data presents the compressive strength results at three key stages: 3 days, 7days, and 28 days. These stages are crucial for assessing the early-age strength development and the long-term durability of the concrete. By analysing the compressive strength at these intervals, the study highlights the impact of the inclusion of UltraFine™ mineral additive in Case 2, which aims to improve the overall performance of the concrete.

**3.1.1 Conventional Concrete Mix: Compressive Strength**

The compressive strength of the Conventional Concrete Mix (Case 1) was tested at 3 , 7, 28 days. The results show the typical strength development with increasing curing time, providing a baseline for comparison with the optimized mix.

|  |  |  |  |
| --- | --- | --- | --- |
| **Cube Name** | **Age of Cube** | **Compressive Strength (MPa)** | |
| **AN-1** | **3 Days** | 39.4 | 40.26 |
| 40.27 |
| 41.1 |
| **AN-2** | **7 Days** | 44.31 | 46.54 |
| 48.73 |
| 46.58 |
| **AN-3** | **28 Days** | 58.4 | 55.39 |
| 53.51 |
| 54.27 |

Table 2: Case 1 Compression Strength

**3.1.2 Optimized Concrete Mix: Compressive Strength**

The compressive strength of the Optimized Concrete Mix (Case 2) was tested at 3 , 7, 28 days. The results show the typical strength development with increasing curing time, providing a baseline for comparison with the optimized mix.

|  |  |  |  |
| --- | --- | --- | --- |
| **Cube Name** | **Age of Cube** | **Compressive Strength (MPa)** | |
| **AnN-1** | **3 Days** | 57.73 | 57.23 |
| 57.64 |
| 56.31 |
| **AnN-2** | **7 Days** | 72.5 | 73.98 |
| 74 |
| 75.45 |
| **AnN-3** | **28 Days** | 86.64 | 85.61 |
| 87.39 |
| 82.81 |

Table 3: Case 2 Compression Strength

**3.2 Comparison Analysis**

The comparison between the compressive strength results of Case 1 and Case 2 reveals significant differences at all stages of testing. At 3 days, Case 2 achieves a compressive strength of **57.23 MPa**, which is **16.97 MPa** higher than the **40.26 MPa** observed in Case 1, indicating significantly better early strength development. At 7 days, the strength in Case 2 increases to **73.98 MPa**, surpassing Case 1’s **46.54 MPa** by **27.44 MPa**, demonstrating a greater strength gain over this period. By 28 days, Case 2 reaches a final strength of **85.64 MPa**, which is **30.25 MPa** higher than the **55.39 MPa** recorded for Case 1, showcasing its superior long-term performance. These results suggest that the mix used in Case 2 exhibits better hydration, curing, and overall optimization compared to Case 1.

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| --- | --- | --- | --- | --- |
| **Age of Cube** | **Case 1 (MPa)** | **Case 2 (MPa)** | **Difference (MPa)** | **Technical Observation** |
| **3 Days** | 40.26 | 57.23 | 16.97 | Case 2 shows significantly higher early strength development compared to Case 1. |
| **7 Days** | 46.54 | 73.98 | 27.44 | Case 2 demonstrates a greater increase in compressive strength over the 7-day period. |
| **28 Days** | 55.39 | 85.64 | 30.25 | Case 2 surpasses Case 1 by a substantial margin, showing superior long-term strength. |

Table 4: Case 1 & 2 Compression Strength Comparison Analysis

1. **Conclusion**

From the experimental analysis of compressive strength cube tests for two cases involving different concrete mixes, the following conclusions can be drawn:

1. **Superior Strength Development in Ultra-Fine Material Mix (Case 2):**  
   The mix incorporating ultra-fine materials (Case 2) exhibited significantly higher compressive strength across all curing periods compared to the standard mix (Case 1). At 3 days, Case 2 achieved **57.23 MPa**, surpassing Case 1 by **16.97 MPa**. At 7 days, the strength gain in Case 2 reached **73.98 MPa**, which is **27.44 MPa** higher than Case 1. By 28 days, Case 2 recorded a compressive strength of **85.64 MPa**, exceeding Case 1 by **30.25 MPa**.
2. **Early Strength Gain:**  
   The higher strength at 3 days in Case 2 indicates that the use of ultra-fine materials accelerates the hydration process. This is particularly advantageous for projects requiring early load-bearing capacity or fast-track construction.
3. **Long-Term Performance:**  
   The substantial strength difference at 28 days demonstrates the superior long-term performance of the ultra-fine material mix. This suggests a denser microstructure and better bonding within the cementitious matrix.
4. **Practical Implications:**
   * **Case 1:** Suitable for general construction applications where standard performance is acceptable.
   * **Case 2:** Ideal for high-strength and high-performance applications such as Ultra-High Performance Concrete (UHPC), precast elements, or structures requiring high durability and load-bearing capacity.
5. **Research Insights:**  
   The experimental results underline the potential of ultra-fine materials in optimizing concrete performance. However, further research is recommended to:
   * Optimize the proportion of ultra-fine material replacement for cost-efficiency and maximum performance.
   * Investigate other mechanical properties, such as tensile strength and flexural performance, for a comprehensive evaluation.

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