

EXPERIMENTAL STUDY ON STRENGTH DEVELOPMENT AND DURABILITY CHARACTERISTICS OF MODIFIED CEMENT-BASED CONCRETE MIXTURES

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Abstract - Concrete remains the most widely used construction material; however, its conventional form exhibits limitations such as low tensile strength, high permeability, and poor resistance to aggressive environmental conditions. This study investigates the strength development and durability characteristics of modified cement-based concrete mixtures incorporating mineral and chemical admixtures. An experimental program was conducted using control and modified mixes with varying replacement levels of supplementary cementitious materials (0%, 10%, 20%, and 30%) while maintaining a constant water-cement ratio. The performance of concrete was evaluated through tests on fresh properties (slump), mechanical strength (compressive, split tensile, and flexural strength), and durability indicators including water absorption, sorptivity, and chloride penetration. Results indicate that modified concrete exhibits improved workability and enhanced long-term strength compared to conventional concrete. The optimum performance was observed at 20% replacement level, showing significant increases in compressive, tensile, and flexural strength. Additionally, durability characteristics improved substantially, with reduced permeability and water absorption, indicating a denser microstructure. Although early-age strength showed a slight reduction, long-term performance was superior due to pozzolanic reactions. The findings demonstrate that the use of modified concrete mixtures can enhance structural performance, durability, and sustainability in modern construction.

Key Words: Modified concrete, Strength development, Durability, Mineral admixtures, Supplementary cementitious materials, Sustainable construction

1. INTRODUCTION

1.1 Background

1.1.1 Importance of Concrete in Infrastructure

Concrete is the most widely utilized construction material in civil engineering due to its versatility, cost-effectiveness, and ease of production. It plays a fundamental role in the development of infrastructure such as buildings, bridges, highways, dams, and marine structures. The global demand for concrete continues to increase with rapid urbanization and industrialization, making it indispensable for modern construction practices. Its ability to be molded into various shapes and its high compressive strength make it suitable for

diverse structural applications. However, the long-term performance of concrete structures is highly dependent on their material properties and environmental exposure conditions (Neville, 2011).

1.1.2 Need for Improved Performance and Sustainability

Despite its widespread use, conventional concrete faces challenges related to durability, environmental impact, and performance under aggressive conditions. Cement production, a key component of concrete, contributes significantly to global carbon dioxide emissions, raising sustainability concerns. Additionally, modern infrastructure requires materials that can withstand harsh environmental conditions while maintaining long-term structural integrity. As a result, there is an increasing emphasis on developing high-performance and sustainable concrete through the incorporation of supplementary cementitious materials and advanced admixtures, which enhance both mechanical properties and environmental compatibility (Mehta and Monteiro, 2014).

1.2 Research Problem

1.2.1 Durability Issues in Concrete

Durability is a critical concern in concrete structures, as it directly affects service life and maintenance costs. Conventional concrete is prone to issues such as high permeability, cracking, and chemical attack from chlorides and sulfates. These factors facilitate the ingress of harmful substances, leading to reinforcement corrosion and structural deterioration. The presence of microcracks further accelerates degradation, especially in aggressive environments such as marine and industrial regions (Mindess et al., 2003).

1.2.2 Inconsistent Strength Development

Another major challenge in concrete technology is the variability in strength development. Factors such as water-cement ratio, curing conditions, and material quality significantly influence the strength of concrete. In modified concrete, the inclusion of admixtures introduces additional complexity, as improper proportioning may lead to reduced early-age strength or unpredictable long-term performance. This inconsistency creates uncertainty in structural design and performance assessment.

1.2.3 Lack of Combined Admixture Studies

While extensive research has been conducted on individual admixtures, there is limited understanding of the combined effects of multiple modifiers in concrete. In practical applications, concrete mixtures often include a combination of mineral and chemical admixtures, which interact in complex ways. The absence of comprehensive experimental studies on these interactions limits the ability to accurately predict performance and optimize mix design.

1.3 Research Gap

1.3.1 Limited Experimental Data on Combined Modifiers

Existing literature primarily focuses on the effects of single admixtures on concrete properties, with relatively few studies addressing the synergistic effects of combined modifiers. This gap in knowledge restricts the development of advanced concrete mixtures that can simultaneously enhance strength and durability. A systematic experimental investigation is therefore required to understand these combined effects and establish reliable performance trends (Thomas, 2013).

1.3.2 Need for Optimized Mix Design

The lack of comprehensive data on multi-component systems highlights the need for optimized mix design strategies. Achieving an optimal balance between workability, strength, and durability requires careful selection and proportioning of materials. Without proper optimization, the benefits of admixtures may not be fully realized, leading to inefficient or suboptimal concrete performance.

1.4 Objectives

1.4.1 Evaluation of Mechanical Strength

The primary objective of this study is to evaluate the mechanical properties of modified concrete, including compressive, split tensile, and flexural strength. These parameters are essential for assessing the load-bearing capacity and structural performance of concrete.

1.4.2 Study of Strength Development

This research aims to investigate both early-age and long-term strength development of concrete mixes. Understanding the rate of strength gain is crucial for construction scheduling and long-term structural reliability.

1.4.3 Analysis of Durability Characteristics

The study also focuses on evaluating key durability parameters such as water absorption, permeability, and

resistance to chloride penetration (RCPT). These indicators provide insight into the long-term performance of concrete under environmental exposure.

1.4.4 Comparative Performance Assessment

A comparative analysis between conventional and modified concrete mixes is conducted to quantify improvements in strength and durability. This comparison helps in identifying the effectiveness of different modifications.

1.4.5 Determination of Optimum Mix

Another important objective is to determine the optimum replacement level of admixtures that provides the best combination of mechanical and durability properties, ensuring both performance and sustainability.

1.5 Scope and Limitations

1.5.1 Laboratory-Based Study

The present research is conducted under controlled laboratory conditions to ensure consistency and accuracy in experimental results. While this approach minimizes external variability, it may not fully represent field conditions.

1.5.2 Selected Admixtures and Replacement Levels

The study is limited to selected mineral and chemical admixtures with specific replacement levels. Although these materials are commonly used, the results may not be directly applicable to all types of concrete mixtures.

1.5.3 Time-Bound Durability Assessment

Durability evaluation is carried out over relatively short curing periods (up to 56 days), which may not fully capture long-term performance. Extended studies are required to assess durability over the entire service life of concrete structures.

2. LITERATURE REVIEW

2.1 Overview of Conventional Concrete

2.1.1 Composition and Properties

Conventional concrete is a composite material composed of cement, fine aggregates, coarse aggregates, and water. Cement acts as the binding agent, while aggregates provide bulk and mechanical strength. The hydration of cement results in the formation of calcium silicate hydrate (C-S-H) gel, which is primarily responsible for strength development. The properties of concrete in both fresh and hardened states depend on the proportions and quality of these constituents. Fresh concrete must possess adequate workability for

proper placement and compaction, whereas hardened concrete should exhibit sufficient strength, durability, and dimensional stability. Key properties include density, permeability, shrinkage, and resistance to environmental exposure (Neville, 2011).

2.1.2 Strength Characteristics

The strength of conventional concrete is typically evaluated in terms of compressive, tensile, and flexural strength. Compressive strength is the most important parameter and is widely used for structural design and quality control. However, concrete exhibits relatively low tensile strength, which makes it prone to cracking under tensile stresses. Flexural strength, representing the resistance to bending, is particularly significant in structural elements such as beams and slabs. The overall performance of concrete depends on the balance between these strength parameters and is influenced by factors such as water-cement ratio, curing conditions, and material properties (Mindess et al., 2003).

2.1.3 Limitations

Despite its advantages, conventional concrete has inherent limitations that affect its long-term performance. One of the primary issues is its low tensile strength, leading to crack formation under stress or environmental effects. Additionally, conventional concrete often exhibits high permeability, allowing the ingress of water and harmful ions such as chlorides and sulfates. This results in durability problems including reinforcement corrosion, sulfate attack, and progressive deterioration. Furthermore, the production of cement contributes significantly to greenhouse gas emissions, raising environmental concerns and necessitating the development of more sustainable alternatives (Mehta and Monteiro, 2014).

2.2 Modified Concrete Concepts

2.2.1 Definition and Classification

Modified concrete refers to concrete in which additional materials are incorporated to enhance its performance characteristics. These modifications can influence the hydration process, microstructure, and overall behavior of concrete. Based on the type of modification, concrete can be classified into mineral admixture-based concrete, chemically modified concrete, fiber-reinforced concrete, and polymer-modified concrete. Each category offers specific benefits depending on the intended application and performance requirements (Aïtcin, 2000).

2.2.2 Types of Modification

Various modification techniques are employed to improve the properties of concrete. Mineral admixtures such as fly ash, silica fume, and GGBS are used to enhance strength and durability through pozzolanic reactions. Chemical

admixtures, including superplasticizers, retarders, and accelerators, are used to control workability and setting time. Fiber reinforcement improves tensile strength and crack resistance, while polymer modification enhances bonding, flexibility, and impermeability. The combined use of these modifications has gained importance in producing high-performance and durable concrete (Neville, 2012).

2.3 Mineral Admixtures

2.3.1 Fly Ash, Silica Fume, and GGBS

Mineral admixtures, also known as supplementary cementitious materials (SCMs), are widely used to improve concrete performance. Fly ash, a by-product of coal combustion, enhances workability and contributes to long-term strength. Silica fume, a highly reactive material with extremely fine particles, significantly increases strength and reduces permeability. Ground granulated blast furnace slag (GGBS), a by-product of the steel industry, improves durability and resistance to chemical attack. These materials are commonly used as partial replacements for cement, contributing to both performance enhancement and sustainability (Thomas, 2013).

2.3.2 Effect on Strength and Durability

The inclusion of mineral admixtures leads to improved strength and durability through pozzolanic reactions. These reactions consume calcium hydroxide and produce additional C-S-H gel, resulting in a denser microstructure. While early-age strength may be slightly reduced due to slower reaction rates, long-term strength is significantly enhanced. Additionally, reduced porosity and permeability improve resistance to chloride ingress, sulfate attack, and other environmental factors, thereby increasing the service life of concrete structures (Malhotra and Mehta, 2005).

2.4 Chemical Admixtures

2.4.1 Superplasticizers, Retarders, and Accelerators

Chemical admixtures are added to concrete in small quantities to modify its properties in both fresh and hardened states. Superplasticizers are high-range water reducers that improve workability without increasing water content, enabling the production of high-strength concrete. Retarders are used to delay the setting time, making them suitable for hot weather conditions or large pours. Accelerators, on the other hand, increase the rate of hydration and are used to achieve early strength, especially in cold climates (Ramachandran, 1995).

2.4.2 Influence on Hydration and Workability

Chemical admixtures significantly influence the hydration process and workability of concrete. Superplasticizers reduce the water-cement ratio, leading to higher strength

and improved durability. Retarders and accelerators modify the rate of hydration, allowing better control over setting time and strength development. These admixtures also enhance compaction and reduce void formation, resulting in a more uniform and dense concrete matrix (Neville and Brooks, 2010).

2.5 Fiber and Polymer Modification

2.5.1 Crack Resistance and Tensile Behavior

Fiber-reinforced concrete incorporates discrete fibers such as steel, polypropylene, or glass into the mix to improve tensile strength and crack resistance. Fibers act as crack arresters by bridging microcracks and preventing their propagation. This enhances the ductility and toughness of concrete, allowing it to withstand higher tensile stresses without sudden failure. Fiber reinforcement is particularly effective in reducing shrinkage and thermal cracking (Bentur and Mindess, 2007).

2.5.2 Durability Enhancement

Polymer-modified concrete involves the addition of polymers such as latex or epoxy to improve bonding and impermeability. Polymers form a continuous film within the concrete matrix, reducing pore connectivity and limiting the ingress of water and harmful chemicals. This results in improved resistance to chemical attack, abrasion, and environmental degradation. The combined use of fibers and polymers further enhances durability and structural performance, making such concrete suitable for demanding applications (Ohama, 1995).

2.6 Strength Development Mechanisms

2.6.1 Early vs Long-Term Strength

Strength development in concrete is a time-dependent process influenced by material composition and curing conditions. Conventional concrete typically exhibits rapid early-age strength due to cement hydration. In contrast, modified concrete containing mineral admixtures may show slower early strength gain but achieves higher long-term strength. This delayed strength development is attributed to the gradual pozzolanic reaction, which continues over an extended period (Taylor, 1997).

2.6.2 Hydration and Pozzolanic Reactions

The primary mechanism of strength development in concrete is the hydration of cement, which produces C-S-H gel and calcium hydroxide. In modified concrete, pozzolanic materials react with calcium hydroxide to form additional C-S-H gel, enhancing the microstructure. This results in reduced porosity, improved strength, and increased durability. The synergistic effect of hydration and pozzolanic

reactions is essential for achieving high-performance concrete (Scrivener et al., 2015).

2.7 Durability Characteristics

2.7.1 Water Absorption and Permeability

Water absorption and permeability are key indicators of concrete durability. High permeability allows the ingress of water and aggressive agents, leading to deterioration. Modified concrete with mineral admixtures exhibits reduced permeability due to a refined pore structure. Lower water absorption indicates a denser matrix and improved resistance to environmental exposure (Basheer et al., 2001).

2.7.2 Chloride and Sulfate Resistance

Durability of concrete is significantly influenced by its resistance to chloride and sulfate attack. Chloride ingress leads to corrosion of reinforcement, while sulfate attack causes expansion and cracking. The use of supplementary cementitious materials reduces the permeability and alters the chemical composition of concrete, thereby enhancing resistance to these attacks. Improved durability ensures longer service life and reduced maintenance costs in aggressive environments (Santhanam et al., 2002).

3. MATERIALS AND METHODS

3.1 Research Methodology

3.1.1 Experimental Approach

The present study adopts an experimental research methodology to evaluate the strength development and durability characteristics of modified cement-based concrete mixtures. A systematic laboratory-based approach is used to ensure accuracy, repeatability, and control over variables influencing concrete performance. The experimental program involves the selection of suitable materials, design of concrete mixes, preparation of specimens, and testing of both fresh and hardened properties. This approach enables the generation of reliable quantitative data, which is essential for analyzing the influence of various modifications on concrete behavior.

3.1.2 Comparative Study (Control vs Modified Mixes)

A comparative framework is employed in which a conventional concrete mix, referred to as the control mix, is prepared without any modification and used as a baseline. Modified concrete mixes are developed by incorporating selected admixtures at different replacement levels. The performance of modified mixes is compared with that of the control mix in terms of workability, strength, and durability. This comparative analysis facilitates the identification of improvements achieved through modification and helps determine the most effective mix composition.

3.2 Materials

3.2.1 Cement (OPC/PPC)

Cement is used as the primary binding material in the concrete mix. Ordinary Portland Cement (OPC) or Portland Pozzolana Cement (PPC) is selected based on availability and compliance with relevant standards. The properties of cement, such as consistency, setting time, and strength, play a crucial role in determining the performance of concrete.

3.2.2 Fine and Coarse Aggregates

Fine aggregate, typically natural sand or manufactured sand, is used to fill voids between coarse aggregates and improve workability. Coarse aggregates, generally crushed stone of specified sizes, provide bulk and strength to the concrete. The physical properties of aggregates, including grading, specific gravity, and water absorption, influence the strength and durability of the concrete mix.

3.2.3 Mineral Admixtures

Mineral admixtures such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) are incorporated as partial replacements for cement. These materials contribute to improved strength and durability through pozzolanic reactions and help in reducing permeability and enhancing the microstructure of concrete.

3.2.4 Chemical Admixtures

Chemical admixtures, particularly superplasticizers, are used to improve workability without increasing the water-cement ratio. These admixtures enhance the flowability of concrete and contribute to better compaction and strength development.

3.2.5 Water

Clean potable water is used for both mixing and curing of concrete. The quality of water is essential, as impurities may adversely affect the hydration process, strength, and durability of concrete.

3.3 Mix Design

3.3.1 Basis of Mix Design (IS 10262:2019 and IS 456:2000)

The mix design is carried out in accordance with standard guidelines to ensure that the concrete meets the required strength and durability criteria. The design procedure considers factors such as exposure conditions, workability requirements, and material properties. The objective is to achieve an optimal proportion of ingredients for enhanced performance.

3.3.2 Target Strength Calculation

The target mean strength is determined to account for variations in material properties and quality control during production. It is calculated based on the characteristic strength and standard deviation, ensuring that the designed mix consistently achieves the required performance level.

3.3.3 Water-Cement Ratio Selection

The water-cement ratio is selected based on both strength and durability requirements. A lower water-cement ratio generally results in higher strength and reduced permeability, while maintaining adequate workability through the use of admixtures.

3.3.4 Trial Mixes

Trial mixes are prepared to validate the designed proportions and assess workability and strength. Adjustments are made based on test results to achieve the desired performance characteristics. This iterative process ensures the reliability of the final mix design.

3.4 Experimental Variables

3.4.1 Admixture Type

Different types of admixtures, including mineral and chemical admixtures, are used to modify the concrete properties. Each type of admixture has a specific effect on strength development and durability.

3.4.2 Replacement Levels (0%, 10%, 20%, 30%)

The study investigates the effect of varying replacement levels of cement with admixtures. Typical replacement levels include 0% (control), 10%, 20%, and 30%, allowing for a systematic evaluation of performance trends.

3.4.3 Curing Periods (7, 28, 56 Days)

Concrete specimens are tested at different curing ages to assess both early-age and long-term performance. The selected curing periods provide insight into the rate of strength development and durability characteristics over time.

3.5 Specimen Preparation

3.5.1 Batching, Mixing, and Casting

Materials are batched using the weight method to ensure accuracy and consistency. Mixing is carried out using a laboratory mixer to achieve a homogeneous mix. Concrete is then cast into standard moulds corresponding to different tests, ensuring uniform specimen preparation.

3.5.2 Compaction and Curing

Compaction is performed using vibration or manual tamping to remove entrapped air and achieve maximum density. After casting, specimens are cured under standard conditions, typically by immersion in water, to ensure proper hydration and strength development.

3.6 Testing Procedures

3.6.1 Fresh Concrete Tests

Slump Test

The slump test is conducted to evaluate the workability of fresh concrete. It measures the consistency and ease of flow, which are essential for proper placement and compaction.

Compaction Factor Test

The compaction factor test provides a measure of workability, particularly for low-workability mixes. It indicates the degree of compaction achieved under standard conditions.

3.6.2 Strength Tests

Compressive Strength

Compressive strength is determined using cube specimens tested under a compression testing machine. It represents the load-bearing capacity of concrete and is a primary parameter for structural design.

Split Tensile Strength

The split tensile strength test evaluates the tensile behavior of concrete indirectly. It provides insight into cracking resistance and the effectiveness of modifications in improving tensile properties.

4. RESULTS

4.1 Fresh Concrete Properties

4.1.1 Workability Results (Slump and Compaction Factor)

The workability of concrete mixes was evaluated using slump and compaction factor tests. The results indicate that the incorporation of mineral admixtures, along with superplasticizers, significantly improved the flowability of concrete. The control mix exhibited moderate workability, whereas modified mixes showed enhanced consistency due to reduced water demand and improved particle packing. However, at higher replacement levels (30%), a slight reduction in workability was observed, possibly due to increased surface area of fine particles requiring additional water.

Table 1: Workability Results

Mix ID	Replacement (%)	Slump (mm)	Compaction Factor
M0 (Control)	0%	75	0.85
M1	10%	85	0.88
M2	20%	95	0.91
M3	30%	80	0.87

4.2.3 Flexural Strength

Flexural strength results followed a similar trend as tensile strength, with modified mixes outperforming the control mix. The improved flexural performance is attributed to enhanced interfacial bonding and reduced microcracking.

Table 2: Flexural Strength (MPa)

S.No	Mix ID	28 Days
1	M0	4.5
2	M1	4.9
3	M2	5.3
4	M3	4.8

4.3 Durability Results

4.3.1 Water Absorption

Water absorption values decreased significantly with the inclusion of mineral admixtures. The reduction indicates a denser concrete matrix with lower porosity, enhancing resistance to moisture ingress.

Table 3: Water Absorption (%)

S.No	Mix ID	Water Absorption (%)
1	M0	5.2
2	M1	4.5
3	M2	3.8
4	M3	4.2

5. CONCLUSIONS

This study investigated the strength development and durability characteristics of modified cement-based concrete mixtures incorporating mineral and chemical admixtures at varying replacement levels. Based on the experimental results, it is concluded that the inclusion of supplementary cementitious materials significantly enhances both mechanical and durability properties of concrete. Although a slight reduction in early-age compressive strength was observed in modified mixes, long-term strength showed considerable improvement due to ongoing pozzolanic reactions and the formation of additional calcium silicate hydrate gel. Among all mixes, the 20% replacement level demonstrated optimum performance, exhibiting the highest compressive, split tensile, and flexural strengths.

Workability of concrete improved with the use of superplasticizers, enabling lower water-cement ratios without compromising consistency. Durability indicators such as water absorption, sorptivity, and chloride ion penetration were markedly reduced in modified mixes, confirming the development of a denser and less permeable microstructure. These improvements directly contribute to enhanced resistance against environmental degradation and increased service life of concrete structures.

Statistical analysis further validated the reliability and consistency of the experimental results, with low standard deviation values indicating uniform performance. Overall, the study demonstrates that modified concrete mixtures provide a viable and sustainable alternative to conventional concrete, offering improved structural performance, durability, and reduced environmental impact.

6. FUTURE SCOPE OF RESEARCH

Future research can focus on extending the durability assessment to longer periods, such as 90 days, 180 days, and beyond, to better understand long-term performance. Advanced microstructural analysis techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) can be employed to investigate the internal structure and hydration mechanisms in greater detail. The use of emerging materials such as nano-silica, graphene, and geopolymers may further enhance concrete performance and sustainability. Additionally, field-based studies are recommended to validate laboratory findings under real environmental and loading conditions. The application of statistical and machine learning models for mix optimization can also be explored to develop more efficient and predictive design methodologies.

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