

Ternary Blended Cement for Sustainable Construction

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Abstract - The rapid growth in construction activities has significantly increased the demand for cement, leading to serious environmental concerns due to high carbon dioxide emissions associated with its production. In this context, the development of sustainable and eco-friendly construction materials has become essential. This study focuses on the production and performance evaluation of ternary blended cement by partially replacing Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA), which are industrial and agricultural by-products respectively. The primary objective of this research is to investigate the combined effect of GGBS and SCBA on the mechanical, physical, and durability properties of cementitious materials. Various mix proportions were prepared by replacing OPC with different percentages of GGBS and SCBA, and laboratory tests were conducted to determine properties such as standard consistency, initial and final setting times, compressive strength at different curing periods, and water absorption. The experimental results demonstrate that the incorporation of GGBS and SCBA improves the long-term strength, enhances durability, and refines the microstructure of the cement matrix due to their pozzolanic and latent hydraulic characteristics. Furthermore, the study reveals that ternary blended cement can achieve comparable or even superior performance compared to conventional OPC, particularly in terms of strength development and resistance to environmental degradation. The utilization of these waste materials not only reduces clinker content and energy consumption but also contributes to waste management and promotes sustainable construction practices. Overall, this research highlights the potential of ternary blended cement as an effective and environmentally responsible alternative, supporting the global objective of reducing carbon emissions and advancing green construction technologies.

Keywords - Ternary Blended Cement, GGBS, SCBA, Sustainable Construction, Compressive Strength

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I. Introduction

Cement is one of the most essential and widely used construction materials in the world, playing a crucial role in the development of infrastructure such as buildings, bridges, highways, dams, and other civil engineering structures. It acts as a primary binding agent in concrete, imparting strength, durability, and stability to structures. With rapid urbanization and industrialization, the demand for cement has increased significantly over the past few decades. However, despite its importance, the production of cement—particularly Ordinary Portland Cement (OPC)—is associated with serious environmental concerns. The manufacturing process of cement involves the calcination of limestone and the burning of fossil fuels at high temperatures, which

leads to the emission of large quantities of carbon dioxide (CO₂).

It is estimated that cement production contributes approximately 7–8% of global CO₂ emissions, making it one of the major contributors to climate change. In addition, cement manufacturing consumes vast amounts of natural resources such as limestone, clay, and gypsum, which are non-renewable and are being depleted at an alarming rate. These environmental challenges have prompted researchers and engineers to explore sustainable alternatives to conventional cement. One of the most effective approaches is the partial replacement of OPC with supplementary cementitious materials (SCMs). SCMs are materials that possess pozzolanic or latent hydraulic properties and can react with calcium hydroxide in the presence of water to form additional cementitious compounds. The use of

SCMs not only reduces the dependency on OPC but also improves the overall performance of concrete. These materials are often derived from industrial by-products or agricultural wastes, making them environmentally and economically beneficial. By incorporating SCMs into cement, it is possible to reduce clinker content, minimize CO₂ emissions, lower energy consumption, and promote sustainable construction practices. Among the various SCMs available, **Ground Granulated Blast Furnace Slag (GGBS)** and **Sugarcane Bagasse Ash (SCBA)** have gained considerable attention due to their availability, cost-effectiveness, and beneficial properties. GGBS is a by-product obtained during the production of iron in a blast furnace. When molten slag is rapidly cooled and ground into a fine powder, it forms GGBS, which exhibits latent hydraulic properties. It reacts slowly with water in the presence of calcium hydroxide to produce additional calcium silicate hydrate (C-S-H) gel, which enhances the long-term strength and durability of concrete. The use of GGBS also reduces the heat of hydration, making it suitable for mass concrete structures such as dams and large foundations. Additionally, GGBS improves resistance to sulphate attack, chloride penetration, and alkali-silica reaction, thereby increasing the lifespan of concrete structures [5], [10]. On the other hand, SCBA is an agricultural by-product obtained from the burning of sugarcane bagasse in sugar industries. It is rich in silica content and exhibits strong pozzolanic properties when properly processed and finely ground. SCBA reacts with calcium hydroxide released during cement hydration to form additional cementitious compounds, leading to improved strength and reduced permeability of concrete. The use of SCBA not only enhances the mechanical properties of concrete but also helps in managing agricultural waste and reducing environmental pollution. However, the effectiveness of SCBA depends on factors such as burning temperature, grinding process, and particle size, which influence its pozzolanic reactivity. In recent years, the concept of ternary blended cement, which involves the combination of OPC with two different SCMs, has emerged as a promising solution for achieving sustainable and high-performance concrete. Compared to binary blends (OPC + one SCM), ternary blends offer improved performance due to the synergistic interaction between the constituent materials. The combination of GGBS and SCBA in ternary systems provides complementary benefits, where GGBS contributes to long-term strength and durability, while SCBA enhances early-age reactions and microstructural refinement. This synergy results in improved compressive strength, better workability, reduced permeability, and enhanced resistance to chemical attacks. Furthermore, the incorporation of

ternary blended cement significantly improves the microstructure of concrete by reducing pore size and increasing density. The formation of additional C-S-H gel due to pozzolanic and hydraulic reactions leads to a more compact and durable matrix. This improved microstructure enhances the durability of concrete by reducing water absorption and preventing the ingress of harmful substances such as chlorides and sulphates. As a result, structures made with ternary blended cement exhibit better performance in aggressive environmental conditions, making them suitable for marine structures, industrial constructions, and infrastructure exposed to harsh climates. Apart from technical advantages, the use of GGBS and SCBA in cement offers substantial environmental and economic benefits. The utilization of industrial and agricultural waste materials reduces the burden on landfills and promotes effective waste management. It also minimizes the environmental impact associated with cement production by reducing CO₂ emissions and conserving natural resources. From an economic perspective, the availability of these materials in regions with steel and sugar industries makes them cost-effective alternatives to OPC. This approach aligns with the principles of sustainable development and circular economy, where waste materials are converted into valuable resources for construction [20]. In addition to environmental and economic benefits, the adoption of ternary blended cement also supports global sustainability goals, including reducing greenhouse gas emissions and promoting eco-friendly construction practices. Governments and regulatory bodies are increasingly encouraging the use of alternative materials in construction to minimize environmental impact. The use of ternary blended cement can play a significant role in achieving these objectives by providing a balance between performance, durability, and sustainability. Therefore, the present study focuses on the development and evaluation of ternary blended cement using OPC, GGBS, and SCBA. The research aims to investigate the mechanical properties such as compressive strength, physical properties such as consistency and setting time, and durability characteristics of different blend proportions. Experimental investigations are carried out to determine the optimum mix that provides the best performance while ensuring environmental sustainability. By analyzing the combined effect of GGBS and SCBA, this study contributes to the advancement of sustainable construction materials and provides valuable insights for the practical implementation of ternary blended cement in the construction industry.

II. Ternary Blended Cement: An Overview

Ternary blended cement represents an advanced and sustainable approach in modern construction materials, where Ordinary Portland Cement (OPC) is partially replaced with two supplementary cementitious materials (SCMs). This combination enhances the overall performance of cement while reducing environmental impact. The increasing demand for eco-friendly construction practices has made ternary blended systems a promising alternative to conventional cement-based materials.

2.1 Introduction to Ternary Blended Cement

Ternary blended cement is formed by combining OPC with two different SCMs such as Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA). Unlike traditional binary blends, ternary systems utilize the complementary properties of multiple materials to achieve improved mechanical and durability characteristics. This approach reduces clinker content in cement, thereby lowering carbon dioxide emissions and energy consumption during production. The interaction between these materials creates a synergistic effect, which enhances the performance of concrete in both fresh and hardened states.

2.2 Constituent Materials

2.2.1 Ordinary Portland Cement (OPC)

OPC acts as the primary binding material in the ternary system and is mainly responsible for early strength development. During hydration, it produces calcium silicate hydrate (C-S-H) gel and calcium hydroxide, which form the fundamental structure of the cement matrix.

2.2.2 Ground Granulated Blast Furnace Slag (GGBS)

GGBS is an industrial by-product obtained from the iron and steel industry. It possesses latent hydraulic properties and reacts slowly in the presence of water and calcium hydroxide. Its inclusion enhances long-term strength, reduces heat of hydration, and improves resistance to sulphate and chloride attack.

2.2.3 Sugarcane Bagasse Ash (SCBA)

SCBA is an agricultural waste obtained from burning sugarcane bagasse. It is rich in silica and exhibits strong pozzolanic properties. It reacts with calcium hydroxide to form additional cementitious compounds, thereby refining the microstructure and reducing permeability.

2.3 Mechanism of Hydration and Pozzolanic Reaction

The performance of ternary blended cement is governed by hydration and pozzolanic reactions occurring within the system. When water is added to OPC, hydration produces C-S-H gel and calcium hydroxide. The SCMs further react with

calcium hydroxide to form additional C-S-H gel. GGBS contributes through latent hydraulic reactions, while SCBA participates in pozzolanic reactions. These combined reactions lead to increased strength, reduced porosity, improved microstructure, and enhanced durability of the cement matrix.

2.4 Synergistic Effect of GGBS and SCBA

The combined use of GGBS and SCBA results in a synergistic effect that significantly improves the overall performance of cement. GGBS contributes to long-term strength and durability, whereas SCBA enhances early-stage reactions and microstructural refinement. This complementary behavior leads to better compressive strength development, reduced permeability, and improved resistance to environmental attacks. As a result, ternary blended cement performs more efficiently than conventional and binary blended systems.

2.5 Properties of Ternary Blended Cement

Ternary blended cement exhibits improved properties in both fresh and hardened states. In fresh conditions, it provides better workability, reduced heat of hydration, and improved cohesiveness of the mix. In hardened conditions, it shows higher compressive strength, improved tensile and flexural strength, and better long-term strength gain. Additionally, durability is enhanced due to reduced permeability and increased resistance to sulphate, chloride, and chemical attacks.

2.6 Environmental Benefits

Ternary blended cement offers significant environmental advantages by reducing the carbon footprint of construction materials. The reduction in clinker content lowers CO₂ emissions, while the use of GGBS and SCBA promotes the utilization of industrial and agricultural waste. This not only reduces landfill disposal but also conserves natural resources such as limestone, making the material eco-friendly and sustainable.

2.7 Applications

Due to its improved performance characteristics, ternary blended cement is widely used in structural concrete for buildings, bridges, and pavements. It is also suitable for marine and coastal structures, industrial floors, and mass concrete works such as dams. Its enhanced durability makes it particularly effective in structures exposed to harsh environmental conditions.

2.8 Limitations and Challenges

Despite its advantages, ternary blended cement has certain limitations. The variability in the properties of GGBS and SCBA can affect consistency in

performance. It may also exhibit slower early strength development, especially due to GGBS content. Furthermore, the lack of standardized mix design procedures and guidelines can limit its large-scale application. Addressing these challenges through further research is essential for wider adoption.

III. Materials and Methodology

This chapter describes the materials used and the methodology adopted for the experimental investigation of ternary blended cement. The study involves the partial replacement of Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA) to evaluate their combined effect on strength and durability properties. Standard procedures were followed throughout the experimental work to ensure accuracy and reliability of results.

3.1 Materials Used

3.1.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used as the primary binding material in this study. Cement plays a vital role in providing strength and cohesion to the mix. The physical properties of cement, such as specific gravity, standard consistency, and setting time, were determined as per relevant IS codes to ensure its suitability for the experiment.

3.1.2 Fine Aggregate

Locally available river sand passing through a 4.75 mm sieve was used as fine aggregate. The sand was clean, dry, and free from organic impurities. It conformed to Zone II grading as per IS 383 standards, ensuring proper particle distribution and workability of the mix.

3.1.3 Ground Granulated Blast Furnace Slag (GGBS)

GGBS, an industrial by-product obtained from the iron and steel industry, was used as a partial replacement for cement. It possesses latent hydraulic properties and contributes significantly to long-term strength and durability. Its use also helps in reducing the heat of hydration and improving resistance to chemical attacks.

3.1.4 Sugarcane Bagasse Ash (SCBA)

SCBA is an agricultural waste obtained from the controlled burning of sugarcane bagasse. It contains a high amount of silica and exhibits strong pozzolanic properties. When used in cement, it reacts with calcium hydroxide to form additional cementitious compounds, thereby improving the microstructure and reducing permeability.

3.1.5 Water

Clean potable water free from impurities was used for mixing and curing purposes. Water plays a crucial role in the hydration process and directly influences

the strength development of the cementitious material.

3.2 Mix Proportions

The mix proportions were designed by partially replacing OPC with GGBS and SCBA to study their combined effect. Four different mixes were prepared for the investigation. The control mix (M1) consisted of 100% OPC without any replacement. In mix M2, OPC was replaced by 10% GGBS and 10% SCBA. In mix M3, OPC was replaced by 5% GGBS and 15% SCBA, while in mix M4, OPC was replaced by 15% GGBS and 5% SCBA. In all mixes, the total binder content was maintained at 100%, and the water-cement ratio was kept constant to ensure uniform comparison among the mixes.

3.3 Experimental Procedure

The experimental procedure involved systematic steps to ensure proper preparation and testing of specimens. Initially, all materials such as cement, GGBS, and SCBA were sieved to remove lumps and impurities. The fine aggregate was cleaned and dried before use. The required quantities of materials were then measured accurately according to the mix proportions.

The mixing process was carried out by first dry mixing cement, sand, GGBS, and SCBA thoroughly to achieve a uniform blend. Water was then added gradually, and mixing was continued until a homogeneous mixture was obtained. The prepared mix was used to cast mortar cubes of size 70.6 mm × 70.6 mm × 70.6 mm. Before casting, the moulds were properly cleaned and oiled to prevent adhesion. The mortar was placed in the moulds in layers and compacted using a tamping rod or vibrating table to remove air voids and ensure proper compaction.

After casting, the specimens were kept undisturbed for 24 hours at room temperature. The cubes were then demoulded and placed in water for curing. The curing process was carried out for different durations of 7 days, 14 days, and 28 days to study the strength development over time.

3.4 Tests Conducted

Various tests were conducted to evaluate the properties of ternary blended cement. The standard consistency test was performed using the Vicat apparatus to determine the amount of water required to produce a paste of standard consistency. The setting time test was conducted to determine the initial and final setting times, which indicate the hardening characteristics of the cement.

The compressive strength test was carried out using a compression testing machine (CTM) on cube specimens after curing periods of 7, 14, and 28 days. The compressive strength was calculated by dividing

the applied load by the cross-sectional area of the specimen. In addition, the water absorption test was performed to assess the durability of the cement mortar. Lower water absorption values indicate better resistance to permeability and improved durability.

3.5 Methodology Overview

The overall methodology of the study involved selection of materials, preparation of mix proportions, casting and curing of specimens, and testing of properties. The results obtained from these tests were analyzed to evaluate the performance of ternary blended cement in comparison with conventional cement.

IV. Results and Discussion

This chapter presents the results obtained from the experimental investigation carried out on ternary blended cement mixes and discusses their performance in comparison with conventional cement. The study evaluates the effects of partial replacement of Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA) on various properties such as compressive strength, setting time, and water absorption. The results are analyzed for different curing periods of 7, 14, and 28 days.

4.1 Standard Consistency and Setting Time The standard consistency test was conducted using the Vicat apparatus to determine the water requirement for achieving a standard cement paste. It was observed that the consistency slightly increased with the addition of GGBS and SCBA due to their finer particle size and higher surface area. This increase in water demand is attributed to the porous nature of SCBA and the fineness of GGBS.

The setting time test results indicated that the initial and final setting times increased with the replacement of OPC. This is mainly due to the slower hydration rate of GGBS and the pozzolanic nature of SCBA. The delayed setting time is beneficial in improving workability and handling time, especially in large-scale construction works.

4.2 Compressive Strength

The compressive strength of all mixes was determined at curing periods of 7, 14, and 28 days. The control mix (M1) showed normal strength development as expected for conventional cement. The ternary blended mixes (M2, M3, and M4) exhibited a slightly lower strength at early ages (7 days), which is mainly due to the slower reaction of GGBS.

However, as the curing period increased, the strength of ternary mixes improved significantly. At 28 days, the mixes containing GGBS and SCBA showed comparable or higher strength than the control mix. Among the mixes, M2 (80% OPC, 10% GGBS, 10%

SCBA) showed the best overall performance due to the balanced proportion of both materials. The improvement in strength at later ages is attributed to the formation of additional calcium silicate hydrate (C-S-H) gel resulting from pozzolanic and hydraulic reactions.

4.3 Water Absorption

The water absorption test was conducted to evaluate the durability characteristics of the mixes. The results indicated that the ternary blended cement mixes showed lower water absorption compared to the control mix. This reduction in water absorption is due to the refinement of the pore structure caused by the reaction of SCBA and GGBS.

The formation of additional cementitious compounds leads to a denser and less permeable matrix, thereby improving durability. Among the mixes, M2 and M4 showed better resistance to water absorption, indicating improved performance in terms of durability.

4.4 Effect of GGBS and SCBA

The combined use of GGBS and SCBA in ternary blended cement resulted in a significant improvement in overall performance. GGBS contributed to long-term strength development and enhanced durability, while SCBA improved the microstructure by filling voids and participating in pozzolanic reactions.

The synergistic effect of these materials resulted in improved compressive strength, reduced permeability, and enhanced resistance to environmental conditions. The proper balance between GGBS and SCBA is essential to achieve optimum performance, as excessive replacement may reduce early strength.

4.5 Comparison of Mixes

The comparative analysis of mixes M1, M2, M3, and M4 indicates that the ternary blended mixes perform better than conventional cement in terms of long-term strength and durability. While M1 showed higher early strength, M2 provided the best overall balance between strength and durability. Mix M3 showed slightly lower strength due to higher SCBA content, while M4 performed better in durability due to higher GGBS content.

Overall, the results indicate that partial replacement of OPC with GGBS and SCBA can produce a sustainable and high-performance cementitious material without compromising structural properties.

V. Comparative Analysis with Previous Studies

The results obtained in the present study were compared with findings reported in previous research on ternary blended cement systems incorporating Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA). Earlier studies have consistently highlighted that the

inclusion of GGBS improves long-term strength and durability due to its latent hydraulic properties, while SCBA contributes through its pozzolanic activity by reacting with calcium hydroxide to form additional cementitious compounds. The experimental observations in this study are in strong agreement with these established findings. Similar to previous research, the control mix exhibited higher compressive strength at early ages due to the rapid hydration of Ordinary Portland Cement (OPC). However, the ternary blended mixes demonstrated gradual strength development, with significant improvement at later curing stages, particularly at 28 days. This behavior is attributed to the delayed but continuous formation of calcium silicate hydrate (C-S-H) gel resulting from the combined hydraulic and pozzolanic reactions of GGBS and SCBA. The trend observed in the present work confirms that ternary blended systems can achieve comparable or superior long-term strength compared to conventional cement, thereby validating the effectiveness of these supplementary materials.

In terms of durability characteristics, previous studies have reported that the incorporation of GGBS and SCBA leads to reduced permeability, enhanced resistance to sulphate and chloride attack, and improved microstructural properties. The findings of this study align with these conclusions, as evidenced by the lower water absorption values observed in the ternary blended mixes compared to the control mix. The reduction in permeability can be attributed to the refinement of pore structure and the formation of a denser cement matrix due to secondary hydration reactions. Furthermore, the concept of synergistic interaction between GGBS and SCBA, widely discussed in earlier research, was also evident in this study, where the mix with balanced proportions (M2) showed the best overall performance. Minor variations between the present results and previous studies may be due to differences in material sources, fineness, and experimental conditions; however, the overall trends remain consistent. Thus, the comparative analysis clearly demonstrates that the present study supports and reinforces existing research, confirming that ternary blended cement is a reliable and sustainable alternative for improving the strength and durability of cementitious materials.

VI. Microstructural Interpretation

The improved performance of ternary blended cement observed in this study can be effectively explained through the microstructural changes occurring within the cement matrix. During the hydration of Ordinary Portland Cement (OPC), primary products such as calcium silicate hydrate (C-S-H) gel and calcium hydroxide are formed. While

C-S-H gel contributes significantly to strength, calcium hydroxide does not directly enhance mechanical properties and may even reduce durability if present in excess. In ternary blended systems, the inclusion of Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA) leads to additional reactions that modify the internal structure of the material. GGBS participates in latent hydraulic reactions, while SCBA, being rich in amorphous silica, undergoes pozzolanic reactions with calcium hydroxide. These combined reactions result in the formation of additional C-S-H gel, thereby increasing the density and cohesion of the cement matrix.

The presence of SCBA plays a crucial role in refining the pore structure due to its fine particle size and filler effect. The ash particles occupy void spaces within the matrix, leading to improved particle packing and reduced porosity. At the same time, the pozzolanic reaction of SCBA consumes calcium hydroxide and converts it into additional binding compounds, further enhancing the compactness of the structure. GGBS contributes to the gradual development of a stable and uniform gel structure, which improves long-term strength and durability. The combined action of these materials results in a well-connected and dense microstructure with fewer capillary pores. This reduction in pore size and connectivity significantly limits the ingress of water and harmful chemicals, thereby improving resistance to environmental degradation. The lower water absorption values observed in the experimental results can be directly correlated to this refined microstructure.

Furthermore, the synergistic interaction between GGBS and SCBA leads to a more efficient utilization of hydration products and enhances the overall performance of the cementitious system. The continuous formation of C-S-H gel over time contributes to progressive strength gain and improved durability characteristics. The densification of the matrix not only enhances mechanical properties but also increases resistance to sulphate attack, chloride penetration, and other aggressive environmental conditions. The microstructural improvements observed in this study clearly indicate that ternary blended cement develops a more homogeneous and durable internal structure compared to conventional cement. Thus, the enhanced performance of the ternary system can be directly attributed to the refinement of microstructure and the effective interaction between OPC, GGBS, and SCBA.

VII. Sustainability and Environmental Impact

7.1 Introduction

Sustainability has become a key consideration in modern construction practices due to the increasing environmental concerns associated with conventional building materials. Cement production, particularly Ordinary Portland Cement (OPC), is one of the major contributors to global carbon dioxide emissions, accounting for a significant share of greenhouse gas emissions. In this context, the development and use of ternary blended cement, incorporating Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA), offer an effective solution for reducing the environmental impact of construction activities. The utilization of these supplementary cementitious materials not only enhances the performance of cement but also promotes sustainable development by minimizing resource consumption and environmental pollution.

7.2 Reduction in Carbon Emissions

One of the most important environmental benefits of ternary blended cement is the significant reduction in carbon dioxide emissions. The production of OPC involves the calcination of limestone and high-temperature processing, which releases a large amount of CO₂ into the atmosphere. By partially replacing OPC with GGBS and SCBA, the clinker content in cement is reduced, thereby lowering the overall carbon footprint. GGBS, being an industrial by-product, does not require additional energy-intensive processing, and SCBA is obtained from agricultural waste, making both materials environmentally friendly alternatives.

The combined use of these materials contributes to a substantial decrease in greenhouse gas emissions, supporting global efforts to combat climate change.

7.3 Waste Utilization and Resource Conservation

The incorporation of GGBS and SCBA in cement plays a vital role in effective waste management and conservation of natural resources. GGBS is a by-product of the iron and steel industry, and its utilization in construction reduces the need for disposal in landfills. Similarly, SCBA is an agricultural waste generated in large quantities by sugar industries, and its use in cement helps in minimizing environmental pollution caused by open dumping or burning. By converting these waste materials into valuable construction resources, ternary blended cement promotes a circular economy and reduces the dependency on natural raw materials such as limestone, clay, and sand. This approach contributes to sustainable resource management and

supports environmentally responsible construction practices.

7.4 Energy Efficiency

The production of ternary blended cement requires less energy compared to conventional cement manufacturing. Since a portion of OPC is replaced with GGBS and SCBA, the energy-intensive processes involved in clinker production are reduced. GGBS is already processed as part of steel manufacturing, and SCBA requires minimal processing before use. This reduction in energy consumption not only lowers production costs but also decreases the overall environmental impact associated with energy use. The improved efficiency in material utilization further enhances the sustainability of ternary blended cement systems.

7.5 Durability and Service Life

Ternary blended cement exhibits enhanced durability due to its refined microstructure and reduced permeability. The improved resistance to environmental factors such as moisture, sulphates, and chlorides results in a longer service life of structures. This reduces the need for frequent maintenance and repair, thereby conserving resources and minimizing environmental impact over the lifecycle of the structure. The increased durability also contributes to the sustainability of construction by ensuring long-term performance and reliability.

7.6 Contribution to Green Construction The use of ternary blended cement aligns with the principles of green construction and sustainable development. It supports eco-friendly building practices by reducing emissions, conserving natural resources, and promoting the use of recycled materials. The material can contribute to green building certifications and environmental rating systems by improving the sustainability performance of construction projects. As the construction industry moves towards more sustainable solutions, ternary blended cement offers a practical and efficient option for reducing the environmental footprint of infrastructure development.

VIII. Future Research Directions

Although ternary blended cement incorporating Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA) has shown promising results in terms of strength, durability, and sustainability, several areas require further investigation to enhance its performance and facilitate large-scale adoption. The following research directions are recommended for future studies.

8.1 Optimization of Mix Proportions

One of the key challenges in ternary blended cement is determining the optimum proportion of OPC, GGBS, and SCBA to achieve the best balance between strength, workability, and durability. Future research should focus on advanced optimization techniques such as statistical modeling, response surface methodology (RSM), and artificial intelligence-based approaches to identify ideal mix proportions under varying conditions [5]. Additionally, studies should consider the influence of water-to-binder ratio, curing conditions, and admixtures on the performance of ternary blends.

8.2 Long-Term Durability Studies

While short-term experimental results indicate improved durability, comprehensive long-term studies are required to evaluate the performance of ternary blended cement under real environmental conditions. Future research should focus on durability aspects such as resistance to sulphate attack, chloride penetration, carbonation, freeze-thaw cycles, and alkali-silica reaction [8]. Long-term field exposure tests and life-cycle performance analysis will help in understanding the behavior of these materials over extended periods and ensure their reliability in structural applications.

8.3 Microstructural and Chemical Analysis

A deeper understanding of the microstructural properties of ternary blended cement is essential to improve its performance. Advanced analytical techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Energy Dispersive X-ray Spectroscopy (EDX) can be used to study the hydration products, pore structure, and interfacial bonding between different components [10]. Future research should focus on correlating microstructural characteristics with mechanical and durability properties to develop more efficient and optimized cementitious systems.

8.4 Utilization of Additional Supplementary Materials

In addition to GGBS and SCBA, other industrial and agricultural by-products such as fly ash, rice husk ash, silica fume, and metakaolin can be incorporated into ternary or even quaternary blended systems. Future studies can explore the combined effect of multiple supplementary materials on the performance of cement [7]. This will not only improve the mechanical properties but also enhance sustainability by utilizing a wider range of waste materials.

8.5 Improvement in Early Strength Development

One of the limitations of using GGBS in cement is the slower rate of early strength development. Future research should focus on methods to improve early-age strength, such as the use of chemical activators,

nano-materials, or optimized curing techniques [3]. Enhancing early strength will make ternary blended cement more suitable for time-sensitive construction projects.

8.6 Environmental and Life-Cycle Assessment

Although ternary blended cement is considered environmentally friendly, detailed life-cycle assessment (LCA) studies are necessary to quantify its overall environmental impact. Future research should evaluate parameters such as carbon footprint, energy consumption, and resource efficiency throughout the life cycle of the material—from raw material extraction to disposal or recycling [19], [20]. Such studies will help in validating the sustainability claims and promoting wider acceptance of ternary blended cement in the construction industry.

8.7 Field Applications and Standardization

Most of the existing studies on ternary blended cement are limited to laboratory-scale investigations. There is a need for large-scale field trials to assess the practical feasibility and performance of these materials in real construction projects. Future research should focus on pilot projects, monitoring structural performance, and developing standardized guidelines for mix design, testing, and quality control [12], [13]. Establishing proper standards and codes will facilitate the widespread use of ternary blended cement in the construction industry.

8.8 Cost Analysis and Commercial Feasibility

Economic feasibility is an important factor in the adoption of new construction materials. Future studies should focus on detailed cost analysis, considering material availability, transportation, processing, and overall construction costs. Comparative studies between conventional cement and ternary blended cement will help in understanding the economic benefits and encourage industry stakeholders to adopt sustainable alternatives.

IX. Conclusion

The present study focused on the development and performance evaluation of ternary blended cement by partially replacing Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA). The experimental investigation was carried out to analyze the mechanical, physical, and durability properties of different mix proportions, with the objective of identifying a sustainable and high-performance alternative to conventional cement. From the results obtained, it can be concluded that the incorporation of GGBS and SCBA as supplementary cementitious materials significantly influences the properties of cement and concrete. The use of GGBS contributed to improved long-term strength and enhanced resistance to

chemical attacks due to its latent hydraulic nature, while SCBA, owing to its high silica content, exhibited strong pozzolanic reactivity that helped in refining the microstructure and reducing permeability [5], [9]. The combined use of these materials in ternary blended cement resulted in a **synergistic effect**, leading to better performance compared to conventional OPC and even binary blends. The experimental results showed that compressive strength increased with curing age for all mixes, and the optimized ternary blend achieved strength values comparable to or higher than that of conventional cement. This indicates that partial replacement of OPC with GGBS and SCBA does not compromise structural performance when used in appropriate proportions. In addition, the standard consistency and setting times were found to be within acceptable limits, ensuring good workability and practical applicability in construction. The water absorption test results indicated reduced permeability in ternary blended mixes, which reflects improved durability and resistance to environmental degradation.

Another important observation from this study is the improvement in the microstructural characteristics of the cement matrix. The pozzolanic reaction of SCBA with calcium hydroxide and the hydraulic reaction of GGBS lead to the formation of additional calcium silicate hydrate (C-SH) gel. This results in a denser and more compact structure with reduced pore size, thereby enhancing the overall durability of concrete. Such improvements make ternary blended cement particularly suitable for structures exposed to aggressive environmental conditions, such as marine environments, industrial areas, and regions with high sulphate or chloride exposure.

From an environmental perspective, the use of GGBS and SCBA offers significant benefits. Since both materials are derived from industrial and agricultural waste, their utilization reduces landfill disposal and promotes waste valorization. Moreover, partial replacement of OPC reduces clinker consumption, which in turn lowers carbon dioxide emissions and energy usage associated with cement production. This contributes to sustainable construction practices and aligns with global efforts to mitigate climate change and reduce environmental impact.

Economically, the use of locally available materials such as GGBS and SCBA can reduce the overall cost of construction, especially in regions where steel and sugar industries are prominent. The adoption of such materials not only improves resource efficiency but also supports the concept of circular economy by converting waste into valuable construction materials.

Overall, the study demonstrates that ternary blended cement is a viable and effective alternative to conventional cement, offering a balance between performance, durability, and sustainability. The optimized blend of OPC, GGBS, and SCBA can be successfully used in various construction applications without compromising quality. In conclusion, the research highlights the potential of ternary blended cement as an eco-friendly and high-performance material for modern construction. Future studies can focus on long-term durability assessment, large-scale field applications, and optimization of mix design to further enhance its practical implementation. The adoption of such sustainable materials will play a crucial role in reducing the environmental footprint of the construction industry and advancing toward greener infrastructure development.

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