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# INNOVATIVE BLENDS OF GGBFS, METAKAOLIN, AND ALCCOFINE FOR ENHANCED MECHANICAL PROPERTIES IN GREEN CONCRETE

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**Abstract**

This research aims to improve the sustainability and mechanical properties of concrete by using partial replacement of cement with Ground Granulated Blast Furnace Slag (GGBFS), Alccofine (AL), and Metakaolin (MK). The study compares the effects of different proportions of GGBFS (0-50%), Alccofine (0-20%), and Metakaolin (0-15%) on the compressive, tensile, and flexural strength and at curing ages of 7$^{th}$, 28$^{th}$, 56$^{th}$, and 90$^{th}$ days. The effective proportions of the replacements were determined to be 30% GGBFS, 15 % Alccofine, and 10% Metakaolin in ratios, which considerably improved the structural characteristics of conventional concrete. A ternary blend of these optimal levels was subsequently studied to determine its synergistic effect on the mechanical properties and microstructure. The ternary blend of these optimal levels demonstrated a 67.1% increase in compressive strength at 28 days and a 51.2% increase at 90 days compared to the control mix. Scanning Electron Microscopy (SEM) analysis suggested that increased pozzolanic activities, an increase in densities of the microstructure, and packing densities of the particles were the key factors for the improved performance. The results highlight that through the application of supplemental cementitious materials (SCMs), there exist promising opportunities in attaining high performance at the same time as a low environmental footprint that could help in concrete innovation for more sustainable solutions.

**Keywords:**

Alccofine, GGBFS, Metakaolin, Sustainable Concrete, supplementary cementitious constituents

## 1 INTRODUCTION

In large part to the construction industry's substantial contribution to global carbon dioxide ($CO_2$) emissions, there is a pressing needs for sustainable techniques to reduce their negative effects on the environment. The usage of SCMs, which improve resource economy and durability while concurrently lowering Carbon footprint of construction, is a crucial component of sustainability in the building industry [W. Cardoso 2022]. Adopting SCMs - especially those made from industrial by products - represents a critical first step toward more environmentally friendly building techniques, since these materials lower total $CO_2$ emissions as well as cement consumption [B. S. Thomas 2021]. In response, the industry has looked for substitutes or additional materials to clinker, which lessens the environmental impact. With surfactants, stabilizing agents, or polymeric ligands is a prevalent technique using blast furnace slag - an industrial by product - into cementitious materials is one method that shows promise. By doing this, concrete performs better and the environmental impact is reduced [R. S. Prabhu 2022].

GGBFS, Alccofine, and Metakaolin have been shown to be very successful in enhancing the mechanical qualities of concrete while lowering its carbon footprint, out of all the SCMs investigated for sustainable concrete manufacturing. Utilizing almost 60% of all raw minerals on Earth, the building industry has been using these mineral admixtures more and more to change the characteristics of concrete and encourage sustainability [F. Hussain 2020], [A. Mani 2023].

There are several environmental advantages to using SCMs in concrete mixtures, including as lowering raw material consumption and preventing waste from building up in landfills. Examples of these are fly ash, GGBFS, and alccofine. Particularly fly ash and GGBFS are prized for their pozzolanic reactivity, which improves the performance of concrete. [B. L. N. S. Srinath 2021].

It has been shown that using GGBFS in place of certain cement can effectively reduce $CO_2$ emissions during the manufacturing of concrete. Studies reveal that concrete that has up to 40% of its cement replaced by GGBFS performs better than control concrete in some areas. Higher replacement levels, however, might result in a loss of strength, mainly because GGBFS has a slower hydration process that prolongs the setting times [H. Vanoutrive 2022]. Furthermore, studies on sustainability have demonstrated that using industrial by products like steel slag and GGBFS in place of cement can drastically lower the energy used and greenhouse gas emissions during the manufacturing of concrete [P. He, S. Drissi 2023], [X. Xiong et al 2023].

The best Alccofine replacement level, according to research, is between 8% and 12%. This results in notable increases in the strength and longevity of concrete. Alccofine has been demonstrated to decrease porosity and boost resistance to harsh conditions at a 15% replacement level, prolonging the life of concrete structures [K. Prasad Yadav and A. K. Samanta 2023].

Another SCM that has major advantages in the manufacturing of concrete is metakaolin, despite not being an industrial by-product. Metakaolin, which is made by a controlled thermal process from kaolin clay, improves the microstructure of concrete by generating more calcium silicate hydrate (C-S-H) and consuming calcium hydroxide that is generated during cement hydration. Over the past 20 years, metakaolin has become more and more popular exactly as a form of cement substitute because of its capacity to improvising [E. Güneyisi 2014].

The ultimate purpose of this research is to address the growing need for high-efficiency and Friendly to the environment for construction materials by offering vital information for creating inventive and sustainable concrete blends. It specifically looks into the combined benefits of ternary mixes that contain Metakaolin, GGBFS, and Alccofine. Using an extensive experimental approach, the study measures the compressive, tensile, and flexural strengths of concrete specimens that have proven to be cured for varying periods. It also does a thorough microstructure examination of the specimens.

## 2 MATERIALS AND METHODS

2.1 Materials and Properties

Ordinary Portland Cement (OPC) of grade 53, obtained from UltraTech, was used for this study in accordance with IS 12269-2013 [IS 12269 2013]. Tab. 1 provide specifics on the physical and chemical properties of the mineral additives, which include GGBFS, Alccofine, and Metakaolin. The fine combined utilized had a fineness modulus of 2.88 and a specific gravity of 2.68. With a maximum particle size of 4.75 mm, it is natural river sand that satisfies Zone II requirements. The crushed angular particles with a specific gravity of 2.7 that were kept on a 4.75 mm filter after going through a 20 mm sieve made up the coarse aggregate, which was chosen in accordance with IS 383-2016 [IS 383 2016].

*Tab. 1: Physical and Chemical properties of OPC, GGBS, Alccofine 1203, and Metakaolin.*

| Component | Cement | GGBFS | Alccofine | Metakaolin |
|---|---|---|---|---|
| Physical properties | | | | |
| Specific gravity | 3.10 | 2.53 | 2.90 | 2.45 |
| Specific surface area (m2/kg) | 340 | 600 | 1200 | 4330 |
| Chemical composition | | | | |
| CaO | 66.67 | 32.79 | 32.20 | 0.09 |
| SiO2 | 18.91 | 30.34 | 35.30 | 52 |
| Fe2O3 | 4.94 | 2.83 | 1.20 | 0.60 |
| Al2O3 | 4.51 | 14.11 | 21.40 | 46 |
| SO3 | 2.5 | - | 0.13 | - |
| MgO | 0.87 | 7.73 | 6.20 | 0.03 |
| K2O | 0.43 | - | - | 0.03 |
| Na2O | 0.12 | - | - | 0.10 |

**Note:** The chemical properties listed are sourced from the manufacturer's datasheets provided by Astrra Chemicals Pvt. Ltd., Chennai.

**2.2 Mix Proportioning**

In accordance with IS 10262-2019 [IS 1026 2019], concrete mix proportions were created for M20 grade concrete. A total of 450 kg/m³ of powder was evaluated at different replacement levels for GGBFS (10%, 20%, 30%, 40%, and 50%), Alccofine (5%, 10%, 15%, and 20%), and Metakaolin (5%, 10%, and 15%). The remaining ingredients in the mix remained unchanged. Tab. 2 displays the various mix proportions that were assessed. Tests for the compaction factor and slump showed better workability when mineral admixtures were used optimally. At $7^{th}$, $28^{th}$, $56^{th}$, and $90^{th}$ days after curing, the compressive strength, split tensile strength, and flexural strength of a total of 14 concrete mixtures were examined. For each age group, each mix was examined in duplicate, yielding 12 samples for each test type. This resulted in 168 samples overall for every strength test, for a total of 504 samples for all tests.

*Tab. 2: Mix proportions and properties of concrete with varying percentages of GGBFS, alccofine, and metakaolin.*

| Mix Name | Cement (C) Kg/m³ | GGBFS Kg/m³ | AL Kg/m³ | MK Kg/m³ | W Kg/m³ | FA Kg/m³ | CA Kg/m³ | Slump value (mm) | Compaction factor |
|---|---|---|---|---|---|---|---|---|---|
| Control | 450 | - | - | - | 179 | 719 | 1099 | 103 | 0.95 |
| GGBFS-10 | 405 | 45 | - | - | 179 | 719 | 1099 | 100 | 0.90 |
| GGBFS-20 | 360 | 90 | - | - | 179 | 719 | 1099 | 97 | 0.90 |
| GGBFS-30 | 315 | 135 | - | - | 179 | 719 | 1099 | 92 | 0.89 |
| GGBFS-40 | 270 | 180 | - | - | 179 | 719 | 1099 | 89 | 0.88 |
| GGBFS-50 | 225 | 225 | - | - | 179 | 719 | 1099 | 85 | 0.85 |
| AL-5 | 427.5 | - | 22.5 | - | 179 | 719 | 1099 | 99 | 0.90 |
| AL-10 | 405 | - | 45 | - | 179 | 719 | 1099 | 96 | 0.90 |
| AL-15 | 382.5 | - | 67.5 | - | 179 | 719 | 1099 | 93 | 0.89 |
| AL-20 | 360 | - | 90 | - | 179 | 719 | 1099 | 89 | 0.88 |
| MK-5 | 427.5 | - | - | 22.5 | 179 | 719 | 1099 | 97 | 0.90 |
| MK-10 | 405 | - | - | 45 | 179 | 719 | 1099 | 92 | 0.89 |
| MK-15 | 382.5 | - | - | 67.5 | 179 | 719 | 1099 | 90 | 0.87 |
| Ternary blend | | | | | | | | | |
| GGBFS-30, AL-15, MK-10 | 225 | 135 | 45 | 45 | 179 | 719 | 1099 | 93 | 0.89 |

### 2.3 Test methods for the properties of the concrete

#### 2.3.1 Compressive strength

To calculate compressive strength, 150 mm cubes were used, which were cast and cured for 7th, 28th, 56th, and 90th days. Testing was conducted as per IS 516 1959) [IS 516 1959] utilizing a 2000 kN digital compression testing apparatus

#### 2.3.2 Split Tensile Strength

A split tensile strength was recorded using cylindrical specimens measuring 150 millimeters in diameter and 300 millimeters in height after the 7th, 28th, 56th, and 90th days of curing. The examination was carried out in compliance with IS:5816 [IS 5816 1999]. To test the specimens, a 2000 kN maximum capacity compression testing apparatus with a 1.5 MPa/min loading rate was deployed.

#### 2.3.2 Flexural strength

Beam specimens having dimensions of 500 mm in length, 100 mm in width, and 100 mm in depth were used to evaluate flexural strength. As to IS: 516: 2020 (2020), testing was conducted with different curing conditions (7th, 28th, 56th, and 90th days). To find the flexural strength, a Universal Testing Machine (UTM) was employed with a loading rate of 180 kg/min.

#### 2.3.4 Microstructural Analysis

To investigate the microstructural properties, Scanning Electron Microscopy (SEM) was performed on selected samples at 28th day of curing. The analysis included control concrete and samples with optimal levels of GGBFS (30%), Alccofine (15%), and Metakaolin (10%). A ternary mix with these proportions was also examined to evaluate the synergistic effects on concrete's microstructure.

## 3 RESULTS AND DISCUSSION

This experimental research examination was to assess the affect over mechanical properties and structural characteristics of concrete, comprising its compressive strength, split tensile strength, and flexural strength, of partially replacing cement with GGBFS, MK, and AL. The most efficient dosages of each cement substitute were determined for this study, and their combined effects were evaluated at the best dose levels (7th, 28th, 56th, and 90th days).

### 3.1 Compressive Strength

The following graph, Fig. 1. depicts the compressive strength of concrete produced with cement substitutes. There was an rise in the strength of mixtures at different time spans and at maximum replacement of cement by GGBFS up to 30 percent. Pozzolanic nature of GGBFS is involved in extending concrete's longevity and service life, hence it provides extra formation of calcium silicate hydrate (C S H) gel [L. Nishanth 2023]. Also inclusion of alccofine up to 15% increases the compressive strength. Alccofines high reactivity and the part it played in the synthesis of the C S H gel [S. Elavarasan 2023]. When metakaolin was used as a material or replaced 10% of cement content it can be attributed to metakaolin's activity and its effectiveness, in optimizing pore structure [B. Harish 2021].

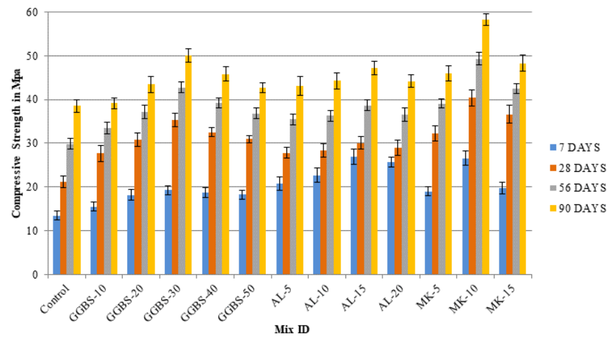


*Fig. 1: Compressive Strength of the various concrete mixtures studied.*

The findings for the ternary blend comprising GGBFS (30%), alccofine (15%), and metakaolin (10%) are shown in Fig. 2. This blend performed better than the standard concrete mixture and individual cement replacements. At 7th, 28th, 56th, and 90th days, the compressive strengths were, in that order, 21.73 MPa, 32.54 MPa, 40.16 MPa, and 47.78 MPa. The increased compressive strength was a result of the three additional cementitious ingredients working in concert to improve packing density, pozzolanic reactivity, and production of additional C-S-H gel [N. Bheel 2024].

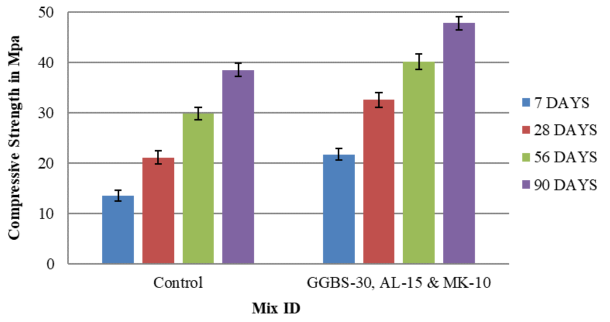


*Fig. 2: Compressive strength results for the ternary blend.*

### 3.2 Split tensile Strength

The split tensile strength development of concrete with various cement replacement materials is shown in Fig. 3. The addition of GGBFS up to 30% demonstrated a progressive increase in split tensile strength in comparison to the control mixture, which was consistent with the compressive strength results. With split tensile strengths at 7th, 28th, 56th, and 90th days, respectively, it was discovered that 30% was the prefect dosage of GGBFS. Pozzolanic activity of GGBFS is comparatively low and different to the hydration of ordinary Portland cement. This attribute leads to a further rise in the strength after some time, which has a slow rate of reaction [Y.-X. Zou 2024]. The application of alccofine up to 15% also demonstrated improved split tensile strength; 15% was the ideal dosage, yielding split tensile strengths at 7th, 28th, 56th, and 90th days, in that order. The higher split tensile strength was a result of the enhanced microstructure and ITZ between the cement paste and the aggregates [S. S. Vivek 2023]. Out of all the cement replacement materials, metakaolin demonstrated the highest split tensile strength at 7th, 28th, 56th, and 90th days when employed as a 10% replacement for cement.The enhanced split tensile strength of concrete was a result of metakaolin's pozzolanic behavior and its capacity to fine-tune the pore structure of the material [Y. R. Alharbi 2021].

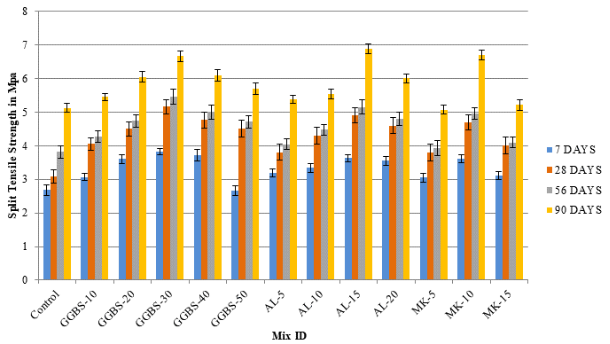


*Fig. 3: Split tensile strength of the various concrete mixtures studied.*

The split tensile strength findings for the ternary mix including metakaolin (10%), alccofine (15%), and GGBFS (30%) are shown in Fig. 4. At earlier ages (7th and 28th day), the split tensile strength was less than the individual optimal dosages; however, at later ages (56th and 90th days), with values of 4.33 MPa and 5.53 MPa, respectively, it exceeded the control combination. Through better microstructure and the interfacial transition zone, the three additional cementitious materials worked in concert to improve split tensile strength [Q. Peng 2018].

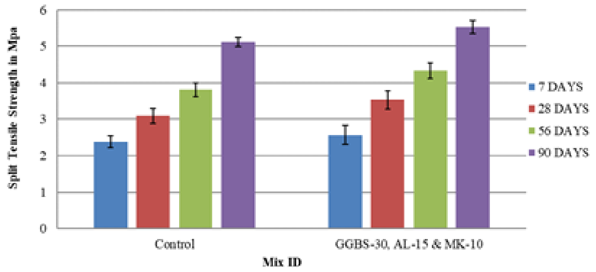


*Fig .4: Split tensile strength results for the ternary blend.*

### 3.3 Flexural Strength

The evolution of concrete's flexural strength with various cement replacement materials is depicted in Fig. 5. When compared to the conventional concrete mixture, incorporating GGBFS up to 30% led to a consistent improvement in flexural strength. It was discovered that 30% was the ideal dosage of GGBFS at 7$^{th}$, 28$^{th}$, 56$^{th}$, and 90$^{th}$ days, respectively [S. Rawat 2024]. Out of all the cement replacement materials, metakaolin demonstrated the highest Flexural strength at 7$^{th}$, 28$^{th}$, 56$^{th}$, and 90$^{th}$ days when employed as a 10% replacement for cement. The metakaolin-modified concrete has better mechanical properties than normal concrete on account of the interrelationship between the conventional pozzolanic reaction, improved microstructure, and decreased porosity. These factors put together lead to the achievement of superior flexural strength in the composite at the mentioned curing intervals [C. Zhong 2024]. Flexural strength was also improved by using alccofine up to 15%; the ideal dosage was 15% at 7$^{th}$, 28$^{th}$, 56$^{th}$, and 90$^{th}$ days, respectively. The higher flexural strength was a result of the enhanced microstructure and ITZ between the cement paste and the aggregates [R. R. Kundanati 2020].

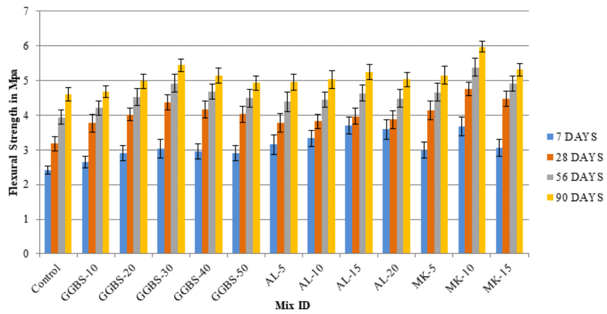


*Fig .5: Flexural strength of the various concrete mixtures studied.*

The ternary mix of GGBFS (30%), alccofine (15%), and metakaolin (10%) exhibits findings for flexural strength in Fig. 6. In comparison to the traditional concrete mixture and individual cement replacements, the ternary blend demonstrated improved flexural strength across all age groups. Flexural strengths were 2.70 MPa, 4.51 MPa, 4.84 MPa, and 5.75 MPa at 7th, 28th, 56th, and 90th days, in that order. The increased flexural strength was a result of the three additional cementitious materials working in concert to improve the microstructure, packing density, and interfacial transition zone [ L. Nishanth 2022].

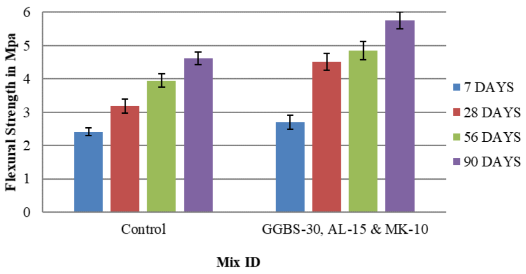


*Fig.6: Flexural strength results for the ternary blend.*

### 3.4 Microstructural Evaluation

The durability and mechanical capabilities of concrete are substantially governed by its microstructure. Understanding the micro structural properties of cementitious materials by SEM study helps to clarify how SCMs affect the concrete matrix.

Concrete samples (from 28th day) were collected from test specimens created in the laboratory, which were initially prepared for strength tests. After conducting compressive strength testing SEM analysis was performed on the same samples as reported for cementitious products [Y. Su et al 2023]. Sample pieces (10 mm x 10 mm x 5 mm) at that point, it dried in an oven at 60°C for 24 hours to remove any residual moisture before SEM analysis. This analysis was done using a ThermoFisher Scientific Apreo 2S HiVac FESEM with an acceleration voltage of 15 kV was employed for capturing high-resolution images.

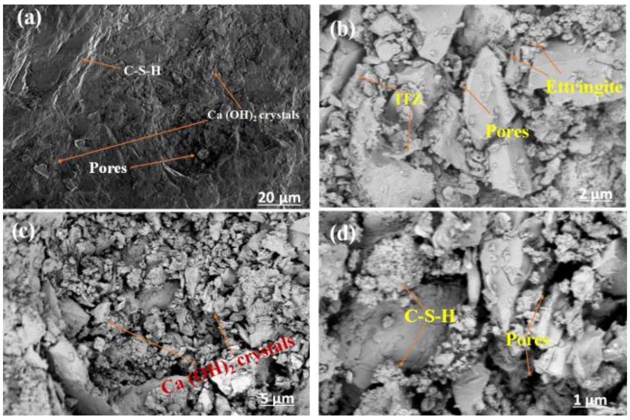


*Fig .7: SEM images of control concrete specimens at 28 days.*

Fig. 7. (a-d) presents SEM images of control concrete specimens at 28$^{th}$ days, highlighting key microstructural features that influence the material's durability and mechanical properties. The control concrete exhibits a typical microstructure (Fig. 7a) with prominent calcium hydroxide (Ca(OH)) crystals (Fig. 7a,c,d), fibrous calcium silicate hydrate (C-S-H), ettringite formations, and interfacial transition zones (ITZ) as shown in Fig. 7b-d. From Fig. 7 data also displays a significant presence of pores which can adversely affect the mechanical properties and durability by providing pathways for deleterious substances. [V. Anish 2024], [S. S. Bangaru 2022].

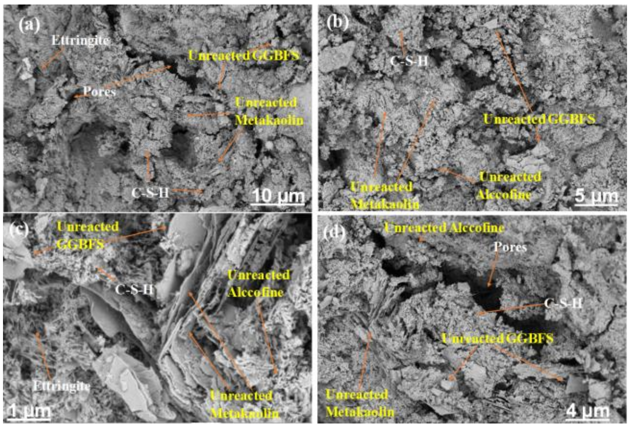


*Fig. 8: SEM images of the ternary blend of mineral admixtures (GGBFS, metakaolin, and alccofine) at 28 days.*

The ternary blend of mineral admixtures (GGBFS, metakaolin, and alccofine) and its possible effect on concrete microstructure was also evidenced by the SEM images (Fig. 8.). Heterogeneous admixtures resulted in varied distribution in terms of shapes and sizes (Fig. 8a-d) which would be beneficial as it contributes to the filling and refinement of the microstructure. The diverse particle sizes allow for a more compact arrangement (Fig. 8b,c), reducing porosity and improving the overall density of the concrete.

Further, The images (Fig. 8b,d) indicate that the surface texture of the GGBFS particles is relatively smoother compared to the textured surfaces of alccofine and metakaolin. The textured particles of alccofine and metakaolin enhance the interfacial bonding within the concrete matrix, leading to better mechanical interlocking and adhesion. This stronger bonding is crucial for improving the concrete's structural integrity and resistance to mechanical stresses.

One more significant observation from the SEM images is the good inter-particle contact, which results in a denser microstructure (Fig. 8c). The fine particles of metakaolin and alccofine effectively filled the spaces between the larger GGBFS particles and other concrete constituents. This effective packing reduces voids, minimizes porosity, and leads to a more compact and robust concrete matrix.

Thus SEM analysis demonstrate a synergistic the impact of GGBFS, metakaolin, and alccofine, resulting in a densely packed microstructure with enhanced C-S-H formation. This combination enhances the strength and durability of the concrete by leveraging the distinct properties of each admixture: the pozzolanic activity of GGBFS, the latent hydraulic properties of metakaolin, and the finer nature of alccofine. Together, these properties significantly contribute to the strength development and resistance to chemical attacks, making the concrete more durable in various environmental conditions.

The combined use of these mineral admixtures in the ternary blend not only improves the mechanical properties of the conventional concrete, such as compressive strength and tensile strength but also enhances its durability against chemical attacks. The improved microstructure, with reduced porosity and increased C-S-H formation, indicates a concrete matrix that is less permeable to aggressive agents, thereby offering enhanced longevity and reduced maintenance requirements. The results of this study collectively underscore the beneficial impact of using a ternary blend of GGBFS, metakaolin, and alccofine in concrete [M. Kamath 2021], [A. Sepulcre Aguilar 2013].

## 4 CONCLUSIONS

The current research study explored the effects and impact of incorporating GGBFS, metakaolin, and alccofine on the structural characteristics of conventional concrete. Furthermore, investigations intended to determine the optimal dosage of these SCMs as partial cement replacements, both individually and in a ternary blend. Mechanical properties, including compressive, split tensile, and flexural strengths, were assessed at various curing ages (7th, 28th, 56th, and 90th days).

Results indicated that individually, 30 % GGBFS, 15 % alccofine, and 10 % metakaolin significantly improved the concrete's mechanical properties compared to the control mix. For instance, at 28th and 90th day, compressive strength increased by 67.1 % and 30 % for GGBFS, 42.4 % and 22.7 % for Alccofine, and 65.4 % and 51.2 % for metakaolin. Similar trends were observed in split tensile and flexural strengths. Furthermore, the ternary blend (30 % GGBFS, 15 % alccofine, and 10 % metakaolin) outperformed individual SCMs, with noteworthy strength gains at 28th and 90th days across all mechanical properties.

The enhancements in mechanical properties are credited to the pozzolanic reactivity of the SCMs, which led to improved pore structure, increased packing density, and additional C-S-H gel formation, as showed by SEM analysis. The synergistic effects of the ternary blend demonstrated superior performance compared to the individual SCMs, emphasizing the combined chemical and physical contributions. Additionally, the use of SCMs promotes sustainability by reducing cement content and lowering greenhouse gas emissions, aligning with sustainable development goals in the construction industry and its sectors.

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