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Enhancing strength and durability of concrete: a comparative analysis of metakaolin and fly ash replacement

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Abstract
The construction industry continually seeks sustainable practices to mitigate environmental impacts, on reducing the reliance on ordinary Portland cement (OPC). This study investigates the potential of metakaolin (MK) and fly ash (FA) as partial replacements for OPC in concrete formulations, aiming to enhance performance and sustainability. MK and FA were incorporated on a gravimetric basis at levels of 11%, 12%, 13%, 14%, and 15% for MK, and 21%, 22%, 23%, 24%, and 25% for FA. The fresh concrete mixes workability is evaluated using the slump cone test, ensuring practical applicability in real-world construction scenarios. To assess the mechanical properties of the cured concrete, a series of tests were conducted, including compressive strength (CS), split tensile strength (STS), flexural strength (FS), and modulus of elasticity (MoE). The results demonstrated that concrete with MK substitution exhibited enhanced mechanical properties, with significant improvements in CS (14.06%), STS (17.64%), and FS (14.82%) compared to the control mix. Although FA replacements also enhanced strength properties, the improvements were slightly lower, with increases of 8.72% in CS, 13.54% in STS, and 9.77% in FS. These findings suggest that MK is a more effective replacement material for achieving higher strength characteristics in concrete. The study provides valuable insights for researchers and engineers in optimizing concrete formulations, thereby enhancing sustainability and performance in construction projects.

Keywords
Sustainable concrete, Metakaolin, Fly ash, Mechanical properties, Ordinary Portland cement.

1.Introduction
The construction industry, a fundamental pillar of global infrastructure development, plays a critical role in shaping modern society. However, this sector is also a significant contributor to environmental degradation, primarily due to the extensive use of ordinary Portland (OP) in concrete production. Ordinary Portland cement (OPC) manufacturing is associated with high energy consumption and substantial carbon dioxide emissions, prompting the need for more sustainable alternatives. Metakaolin (MK) significantly improves concrete properties, enhancing construction performance and durability. It optimizes blended cements, offering insights for better cement compositions [1–3]. Using thermally activated kaolin (TAK) in blends further improves concrete performance [4]. Neural networks are used to predict concrete workability, allowing targeted adjustments for optimal mixture characteristics [5–7]. MK also enhances corrosion and chloride-penetration resistance, contributing to more resilient building materials [8–10]. Increasing fly ash (FA) concentration raises drying shrinkage but reduces and delays crack formation [11–13]. In self-consolidating concrete, FA and natural pozzolans offer sustainable alternatives [14]. Alkali-activated FA/slag mortars provide valuable insights into binding mechanisms for sustainable construction [15]. Recent research has increasingly focused on incorporating supplementary cementitious materials (SCMs) like MK and FA as partial replacements for OPC. These SCMs are industrial byproducts, and

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their use in concrete not only reduces the environmental impact but also has the potential to enhance the material properties of concrete. MK, a pozzolanic material derived from the thermal activation of kaolin, and FA, a byproduct of coal combustion in power plants, have shown promise in improving concrete's durability and mechanical properties. While numerous studies have explored the concrete benefits of MK and FA, challenges remain. Some research has focused primarily on the compressive strength (CS)of these modified concretes, often overlooking other critical mechanical properties like tensile strength, CS, and modulus of elasticity (MoE) [6–10]. Additionally, there is a need for a more comprehensive understanding of the microstructural changes that occur when MK and FA are introduced into the concrete matrix [7–14]. The interactions between these SCMs and the other concrete components at various replacement levels have not been fully elucidated, leaving a gap in knowledge regarding the optimal usage of these materials. This study employs a combined methodology, incorporating both experimental analysis and microstructural examination to gain a deeper understanding of the material's behavior (*Figure 1*).

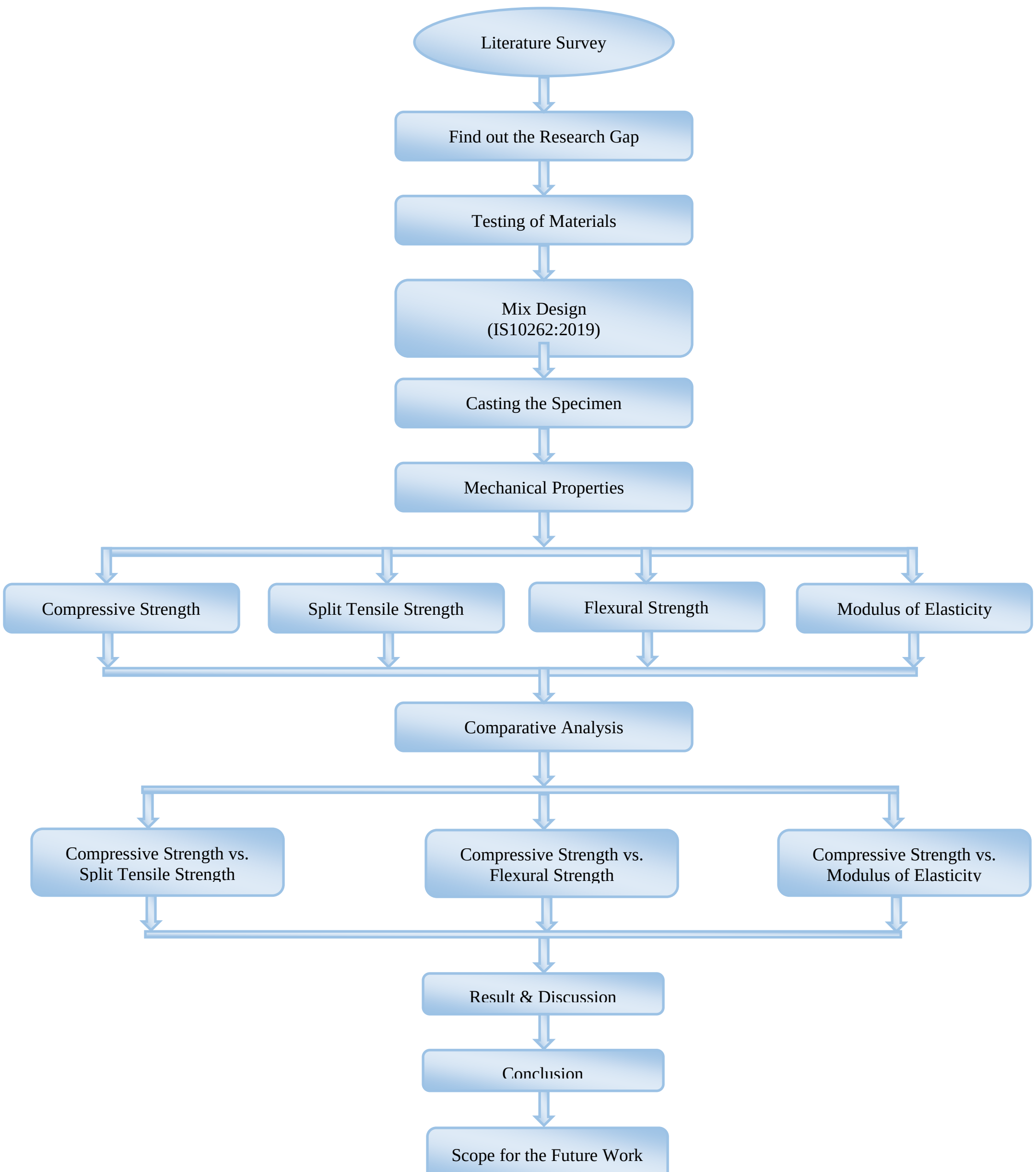

Figure 1 Research methodology

The construction industry faces environmental challenges due to the production of OPC, prompting the exploration of sustainable alternatives like MK and FA as partial replacements [16–19]. While MK enhances concrete's CS, durability, and fire resistance, its higher water demand and increased brittleness present challenges to workability [20]. FA improves workability, reduces cracking, and enhances long-term performance, but its composition variability can lead to inconsistent results. This study addresses these challenges by optimizing the replacement levels of MK and FA, offering solutions to mitigate workability and material consistency issues. Refined mix designs were proposed in this research to balance the benefits of MK and FA while ensuring consistent and enhanced performance in concrete production.

This research addresses gaps in the literature by assessing the mechanical properties, including CS, split tensile strength (STS), flexural strength (FS), and MoE, along with the microstructural characteristics of concrete incorporating MK and FA as partial replacements for OPC. The study aims to determine the optimal replacement levels that improve performance while advancing sustainability in construction practices.

This research advances the understanding of concrete formulations by MK and FA's mechanical and microstructural effects. It provides valuable insights into enhancing the sustainability and durability of concrete while introducing predictive modeling to evaluate workability and performance, offering a novel and practical approach to optimizing concrete mixtures.

Section 1 provides an introduction to the research topic, objectives, and contributions. Section 2 presents a review of existing studies on MK and FA in concrete, highlighting research gaps. The subsequent sections detail the experimental methods (Section 3), results (Section 4), and their interpretation (Section 5), culminating in a summary of key findings and future directions in Section 6.

2.Literature review

The construction industry is vital for global development, but conventional concrete (CC) production methods have a significant environmental impact. This research investigates the potential of MK and FA as partial replacements for OPC in concrete formulations. These SCMs are byproducts from industrial processes, and their incorporation offers a more sustainable approach to concrete production.

The impact of MK's surface area on the qualities of cement-based materials is investigated, offering crucial information for improving material mixtures in the construction industry.MK paste microstructure analysis in cement and concrete research, the pore size distribution of MK paste provides information about the material's microstructure and advances knowledge of MK's general characteristics. Optimizing concrete with MK and FA explores how using FA and MK together can be controlled to optimize the strength of concrete mixtures, ultimately leading to enhanced performance in construction projects. The ability of geopolymer concrete including MK, FA, and rice husk ash to crack to evaluate the material's structural behaviour and possible uses. The performance of MK concrete at elevated temperatures is analyzed to understand its behavior under heat exposure and suitability for fire-resistant construction.MK as SCM examines the influence of MK as a SCM on the strength and durability of concrete [21]. The influence of the temperature at which it cures on the complex structure's formation in MK-based geopolymers, aiming to optimize production for enhanced material properties [22]. Combined effects of MK and FA on the strength and efflorescence of cement-based composites are studied, aiming for improved performance and reduced efflorescence [23]. Synergistic effects in geopolymer concrete effects of recycled aggregate, ground granulated blast-furnace slag (GGBS), and MK on the physicochemical properties of geopolymer concrete for sustainable construction applications [24]. A sustainable method for producing concrete and disposing of waste is demonstrated by the use of olive residual biomass FA in self-compacted concrete [25, 26]. The mechanical strength and longevity of mortars are improved when FA and nano-MK are combined [27]. Pumice powder and FA in concrete improve mechanical properties and microstructure, encouraging effectiveness and environmental responsibility [28]. To reach appropriate combinations and preserve strong mechanical properties, concrete with a very high Class F FA concentration can show promise for high performance and sustainability [29]. FA demonstrates potential for improved performance and sustainability in concrete. FA-based geopolymer concrete with binary and ternary mixes shows enhanced durability and desired microstructures [30]. Recycled aggregate combined with FA promotes sustainable construction practices by improving concrete sustainability [31].

Furthermore, the addition of FA positively impacts the strength and hydration properties of blended cements, suggesting potential for further advancements [32]. The inclusion of carbon dioxide powder modifies the air void properties in FA concrete, influencing its durability and overall performance [33]. Research on concrete containing elevated temperatures of FA and MK offers valuable insights into fire resistance [34]. Additionally, lightweight FA-based geopolymer mortar achieves high FS by incorporating recycled fiber cement, presenting a high-performing and environmentally friendly alternative [35]. This section explores various aspects of FA in cementitious materials. Studies examine the impact of limestone particle size on the heat of hydration in Portland high-calcium FA cement [36]. Moreover, research investigates the influence of FA on the overall properties of cement-based materials, providing insights into its performance benefits [37]. Also, using recycled asphaltic concrete aggregate with a high percentage of calcium FA geopolymer concrete encourages decreases in waste and ecologically friendly construction methods [38]. Furthermore, investigated are the effects of the curing circumstances on the evolution of FA-based geopolymers, offering valuable information for optimizing these materials [39]. Early-age mechanical properties of FA concrete, including strength in one direction only and MoE, are investigated to understand its behavior during the setting and curing process [40]. The potential of MK-FA geopolymers as fire-resistant construction materials is highlighted by their development for use in fire-resistant applications [41]. The literature review examines the use of MK and FA as partial replacements for OPC in concrete, focusing on their environmental and performance benefits. MK improves CS, durability, and fire resistance, while FA enhances workability, reduces cracking, and contributes to long-term performance. Combining MK and FA shows potential for optimizing concrete strength and reducing efflorescence. Studies also explore their impact on microstructure, chloride resistance, and fire resistance, along with their role in geopolymer concrete. Overall, the research highlights MK and FA as sustainable alternatives, emphasizing the need for optimized mix designs to improve concrete's mechanical and environmental properties.

3.Methods

3.1Materials

Concrete mixtures were prepared using MK, low-calcium pulverized fuel ash, and OPC. *Table 1* provides a thorough description of these materials' physical characteristics and chemical composition.

Table 1 Composition of OPC, FA and MK

	OPC	**FA**	**MK**
Chemical composition (%)			
SiO_2	19.6	57	53.2
Al_2O_3	7.3	28	43.9
Fe_2O_3	3.3	5.3	0.38
CaO	63.1	3	0.02
MgO	2.5	5.2	0.05
Na_2O	0.1	-	0.17
K_2O	1.1	-	0.1
SO_3	2.1	0.7	-
LoI	3	3.9	-
Physical properties			
Specific gravity	3.16	2.3	2.62
Specific surface (m^2/kg)	312	412	12680
Initial setting time (Min)	125	-	-
Final setting time (Min)	240	-	-

Figure 2 presents the scanning electron microscope (SEM) microstructures of MK and FA. These microstructural images can offer valuable insights into how these materials influence the mechanical properties of concrete, particularly its strength and durability.

The SEM image of MK shows a plate-like, irregular structure with rough surfaces. This morphology is indicative of its highly reactive nature. The plate-like particles of MK create a dense and compact matrix when incorporated into concrete. This densification of the microstructure improves the concrete's CS. The pozzolanic reaction between MK and calcium hydroxide (CH) produces additional Calcium Silicate Hydrate (C-S-H), which fills pores and reduces porosity. This enhanced durability, making the concrete becomes less permeable to water and aggressive agents. The SEM image of FA reveals spherical particles, some of which are hollow (cenospheres) or contain smaller particles (plerospheres). These smooth spheres contribute to improved workability of the concrete mix. The spherical nature of FA particles reduces the water demand in the concrete mix, enhancing workability without compromising strength. The pozzolanic reaction of FA with CH is slower than MK, but over time it contributes to the development of strength. The spherical particles refine the pore structure, increasing long-term strength and durability. FA reduces the water demand in the concrete mix due to its smooth, spherical particles, thereby enhancing workability without compromising strength.

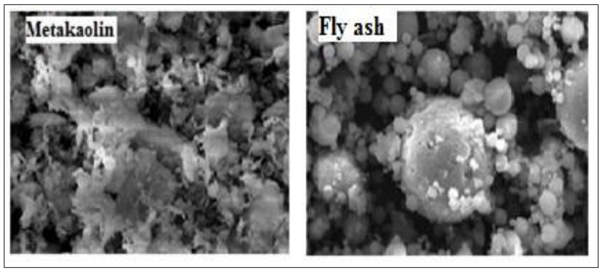

Figure 2 SEM image of admixtures

For the fine aggregate (FA) component, M-sand was chosen. The coarse aggregate (CA) fraction consisted of crushed granite. The FA particles were characterized by a specific gravity of 2.58, an inhalation value of 0.85% during a 24-hour period, and a fineness modulus of 2.6. A specific gravity of 2.60 and the rate of water absorption of 0.7% during a 24-hour period were observed in the CA granules. To ensure both proper workability and adequate strength in the final concrete product, superplasticizer (sika) was introduced. Specifically, a condensate of sulphonated naphthalene formaldehyde was added into the mixes in precisely measured quantities to achieve a desired slump of at least 88 millimeters.

3.2Mix proportions

This study looked at 11 distinct mix proportions, encompassing a control mix as a baseline for comparison. The specific composition details of each mix are presented in *Table 2*. It's important to note that MK and FA functioned as pozzolans within the concrete mixture, indicating they partially replaced ordinary OPC– except in the case of the CC mix. The incorporation of MK and FA varied across the different mixes, with replacement levels ranging from 21% to 25%. FA, another pozzolanic material, was also introduced as a cement substitute, but at lower replacement levels between 11% and 15%. *Figure 3* illustrates the manufacturing process for creating the concrete specimens.

Table 2 Mix proportions (per m^3)

Mix ID	OPC (kg)	MK (kg)	FA (kg)	Water (kg)	FA (kg)	CA (kg)
CC	442	0	0	198	702	1013
MK11	393	49	0	198	702	1013
MK12	389	53	0	198	702	1013
MK13	384	58	0	198	702	1013
MK14	380	62	0	198	702	1013
MK15	376	66	0	198	702	1013
FA21	349	0	93	198	702	1013
FA22	345	0	97	198	702	1013
FA23	340	0	102	198	702	1013
FA24	336	0	106	198	702	1013
FA25	332	0	110	19	702	1013

Figure 3 Manufacturing process of concrete mix

The concrete ingredients were mixed using a laboratory pan mixer. The dry materials (OPC, MK, FA, and coarse aggregate) were initially loaded into the mixer. These materials were mixed for 2 minutes to ensure an even distribution of the components. After the dry mixing, approximately 75% of the total water was gradually added while the mixer. Simultaneously, the superplasticizer was introduced to enhance the workability of the mix. The mixture was allowed to mix for an additional 1 minute. The remaining 25% of the water was then added, and mixing continued for another 2 minutes to achieve a uniform consistency. The mixed concrete was then visually inspected to ensure homogeneity, and a slump test was performed to verify that the desired slump. The entire mixing process was carefully timed and monitored to ensure consistency across all mixes. *Figure 3* provides a visual representation of the overall manufacturing process for the concrete mix.

After mixing, the concrete was poured into standard molds to create the test specimens. Cube molds of dimensions 150 mm × 150 mm × 150 mm were used to cast the concrete specimens for CS testing. Cylindrical molds of dimensions 150 mm in diameter and 300 mm in height were employed for testing STS and MoE. Additionally, Prism molds of dimensions 100 mm × 100 mm × 500 mm were utilized for preparing specimens for the FS test. The concrete was compacted using a vibration method to remove any air pockets and ensure the concrete was dense and well-compacted. This was done using a vibrating table for a duration of 15 to 30 seconds per specimen, depending on the mix's workability. For each mix, three specimens were cast for CS, STS, and MoE, resulting in nine specimens per mix. Three prism specimens were cast for each blend to determine the FS.

3.3Curing conditions

Following a 24-hour curing period in their molds, the concrete specimens were carefully de-molded and submerged in a water tank maintained at a constant temperature of 27 degrees Celsius [42–44]. The specimens were immersed in the water tank for designated curing durations of 7, 14, and 28 days. After this initial curing stage, they were then transferred to a controlled environment with a constant humidity of 65% and a temperature of 27 degrees Celsius for further testing. This extended curing process helps to simulate real-world conditions and ensures the concrete specimens have ample time to develop their full strength and other performance characteristics.

3.4Testing procedures for mechanical properties

The mechanical properties of the concrete specimens were assessed the American Society for Testing and Materials (ASTM) C39 standards. CS tests were conducted on 150 mm × 150 mm × 150 mm cubes using a compression testing machine (CTM) with a 2000 kN capacity, applying a load at 0.25 MPa/s until failure. STS and MoE were performed on 150 mm diameter × 300 mm height cylinders, in accordance with ASTM C496. The loading rates for these tests were 1.2 MPa/min until splitting and gradual loading up to 40% of the ultimate load, respectively, with a compressometer used to measure the MoE in accordance with ASTM C469. FS was evaluated on 100 mm × 100 mm × 500 mm prisms using a flexural testing machine with a 100 kN capacity, applying a load at 0.05 MPa/s until fracture (ASTM C78).

To ensure the quality and consistency of the concrete mixes, materials were sourced from reputable suppliers and checked for uniformity, while all equipment used for mixing, measuring, and testing was regularly calibrated. Standardized mixing procedures were followed, and periodic quality control checks were performed, including slump tests [45, 46]. Environmental conditions were carefully controlled throughout the testing process, with temperature maintained at a constant 20°C and relative humidity at 60%. Three specimens per mix were tested for each mechanical property, and average values were recorded for analysis.

4.Results

4.1Concrete properties (Fresh strata)

Slump is a standard metric employed in the construction industry to gauge the workability of concrete mixtures. The slump test was conducted following the procedure outlined in ASTM C143. A standard slump cone was cleaned, dampened, and placed on a non-absorbent, flat surface. The cone was held firmly in place during the test. The freshly mixed concrete was placed into the slump cone in three layers, each approximately one-third the height of the cone. Each layer was compacted with 25 tamping rod strokes, ensuring uniform distribution throughout the cone. After filling, the cone was carefully lifted vertically, allowing the concrete to slump under its weight. The vertical distance between the top of the cone and the top of the slumped concrete was measured immediately after the cone was lifted. This distance represents the slump value. For each batch, the slump test was conducted three times to ensure consistency. The three slump values were recorded, and the average of these values was calculated to represent the workability of the mix. The results were recorded in a tabular format, and the average value was used to compare the workability of different mixes. These averaged values are depicted in *Figure 4.*

The control mix exhibits a slump value of 83 millimeters (mm), as indicated on the graph. This value is a benchmark for comparison with other concrete mixes containing SCMs like MK and FA. The slump values for concrete mixes containing MK as a partial replacement for OPC vary between 84 mm and 90 mm. This range is comparable to the slump value observed for the control mix, suggesting that the incorporation of MK within the investigated range did not exert a significant influence on the workability of the concrete mix.

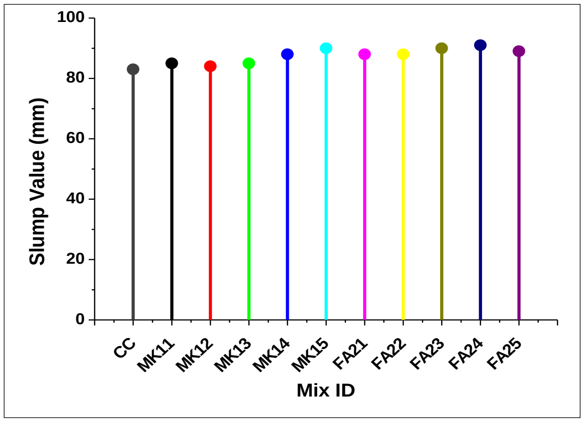

Figure 4 Slump values of concrete mixes

The slump values for concrete mixes containing FA as a partial replacement for OPC range from 88 mm to 91 mm. This range aligns with the values measured for the control mix and the MK mixes, further indicating that the partial substitution of OPC with FA at the replacement levels explored in this study did not substantially alter the workability of the concrete mix.

4.2CS Test

CS is a vital characteristic of concrete, defining its ability to bear loads and resist deterioration. It signifies the maximum force a concrete sample can endure before showing signs of cracking, breaking, or failing [38, 39]. CS is essentially the highest pressure that a concrete sample can withstand without being harmed. This characteristic greatly affects the cube specimens' performance and longevity in terms of design, manufacture, and use. The measurement of CS is typically expressed in MPa.

Samples of concrete are usually tested every 7, 14, and 28 days. The IS:516-1959 standards contain comprehensive instructions for performing CS tests that guarantee accurate and consistent assessments of concrete strength in accordance with industry standards. The results (*Figure 5*) show that different impacts on CS are obtained when FA and MK are partially substituted for cement.

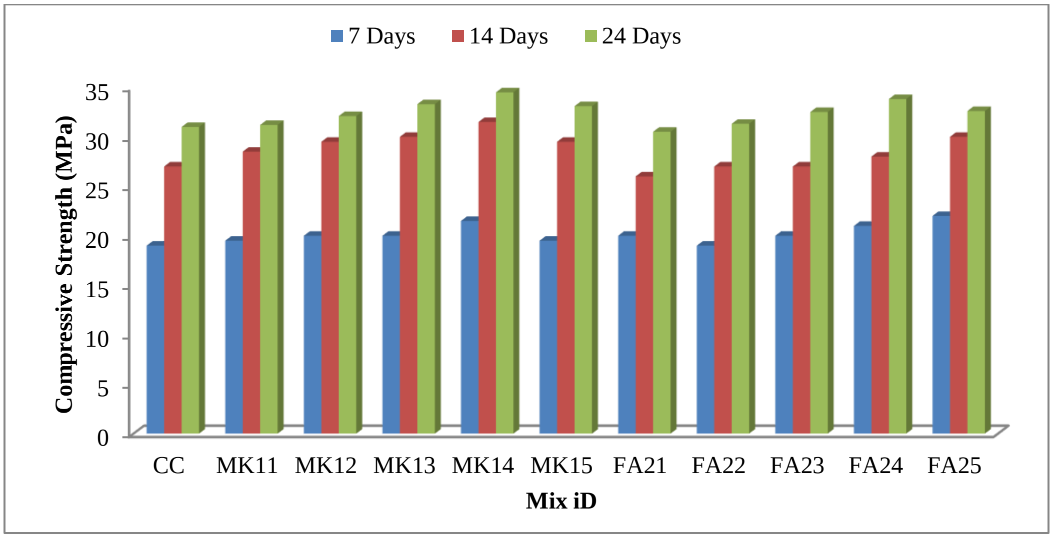

Figure 5 CS value of the cube samples

At 7 days, the mix identified as MK12 exhibits the highest CS at 20 MPa, followed by FA21, MK11, and FA23, each registering 20 MPa. A marginal increase in CS is observed at 14 days for all mixtures. MK14 demonstrates the highest CS at 14 days, recording 31.5 MPa, closely trailed by MK12 and MK15 at 29.5 MPa each. This trend persists at 28 days, with MK14 showing the highest CS at 34.5 MPa, followed by MK12 at 32.1 MPa. Based on the data presented in the *Figure 5*, the MK blends consistently outperform the FA blends in terms of CS. MK12 consistently ranks among the top performers across all three testing intervals (7, 14, and 28 days), obtaining in 28 days a CS of 32.1 MPa. Among the FA blends, FA20 demonstrates the highest CS at 7 and 14 days, reaching 20 MPa and 26 MPa, respectively. However, by day 28, it is outperformed by FA25, which records a CS of 32.61 MPa.

4.3STS test

The STS of a concrete cylinder is a measure of its ability to resist tensile forces. This test involves applying a tensile force to a cylindrical concrete sample until it breaks. Several key factors influence the STS of the concrete, such as the type of material, manufacturing method, size, form, and duration of the curing time of the specimen. Together, these elements establish the concrete's tensile stress tolerance, demonstrating its durability and strength under various load scenarios.

The mixes are identified as CC, MK11, MK12, MK13, MK14, MK15, FA21, FA22, FA23, FA24, and FA25. The table displays the tensile strength at 7 days, 14 days, and 28 days, measured in megapascals (MPa).

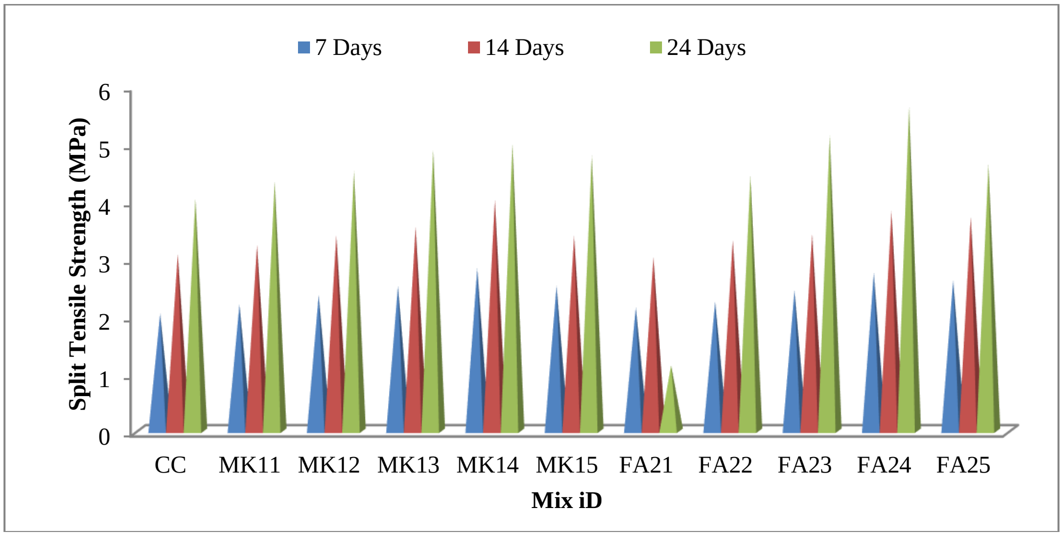

Figure 6 STS value of cylindrical specimens

It is observed (*Figure 6*) that the tensile strength of all the mixes increases over time. For instance, mix CC shows a tensile strength of 2.04 MPa at 7 days, which rises to 4.04 MPa at 28 days. This enhancement in tensile strength is likely attributed to the cement's hydration process. Hydration is a chemical reaction between the cement and water that makes the cement harder and more muscular.

Furthermore, the different mixes exhibit varying tensile strengths. Mix FA24, for example, demonstrates a tensile strength of 5.64 MPa at 28 days, surpassing the tensile strength of mix CC, which is 4.04 MPa at the same age. Compared to all mix MK14 and FA24 mix was optimum value (higher value) of other mix proportions.

4.4FS Test

In concrete specimens (prisms), FS describes the specimen's ability to bear bending loads without breaking or cracking. This quality is essential for concrete, especially for components that support weight, such beams. Maintaining the strength and visual appeal of concrete over an extended period of time depends critically on the material's capacity to withstand flexural stress. Standardized testing, commonly expressed in N/mm², is used to evaluate the FS of concrete. The concrete's resistance to applied loads and bending stresses is determined by this testing process, which guarantees that the material is suitable for various building applications that call for strong and resilient materials. *Figure 7*, shows the FS of the all mixes. It explains the flexural variation of the all mix.

Compared to the CC, the MK14 concrete exhibited higher FS, while the FA24 mix also demonstrated an improvement in FS compared to other concrete mixes. Over 14 days, all mixes showed a gradual increase in strength. After 28 days of curing, the FS values for all mixes increased compared to the CC. Notably, the FS values of MK14 and FA24 were higher than those of the other mixes, including CC. This increase in FS is likely attributed to the enhanced hydration of the cement, as previously described.

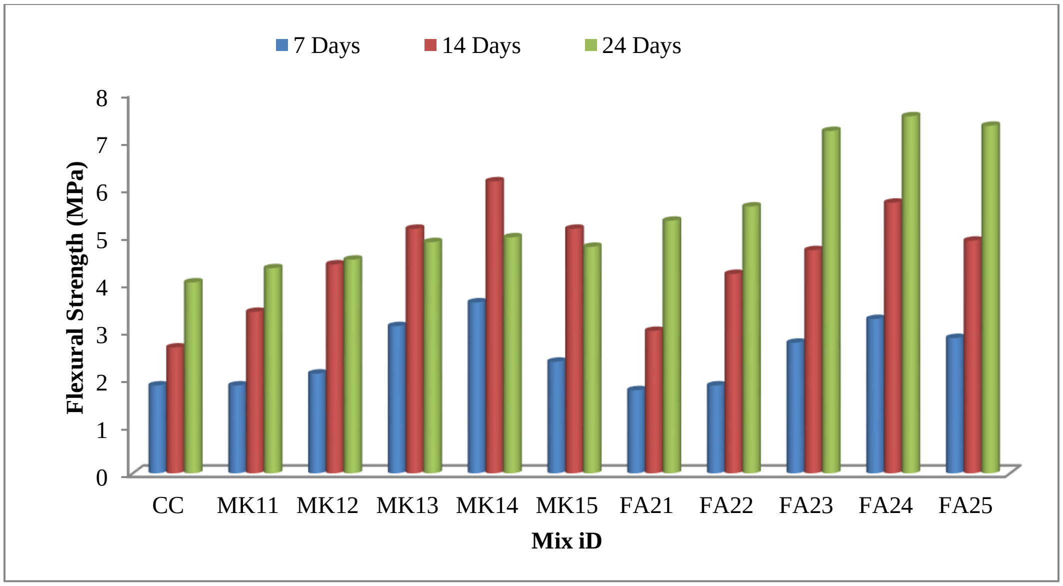

Figure 7 FS value of prism specimens

4.5MoE

The MoE was determined using cylinder specimens with a diameter of 15 mm and a length of 300 mm, and it was computed for both R-sand and M-sand mixtures. The experiment was conducted in accordance with IS 516:1959 [47], with a compressometer and extensometers attached to the cylinder, which was placed on the CTM. Normal-strength concrete, which is typical for many building projects, has an elasticity modulus that ranges from 27.27 gigapascal (GPa) to 32.34 GPa. The structural design is directly impacted by this variance in stiffness. Stiffer concrete becomes essential for tall buildings or strongly laden structures because of its decreased deflection under stress. It is noteworthy that a slightly larger increase (19.25%) in the MoE corresponds with the observed rise in CS (14.14%), suggesting a positive correlation between the two properties. In simpler terms, concrete mixes with higher CS generally tend to have higher elastic moduli. This is explained by the impact of elements that affect both strength and stiffness, such as premium components and appropriate curing.

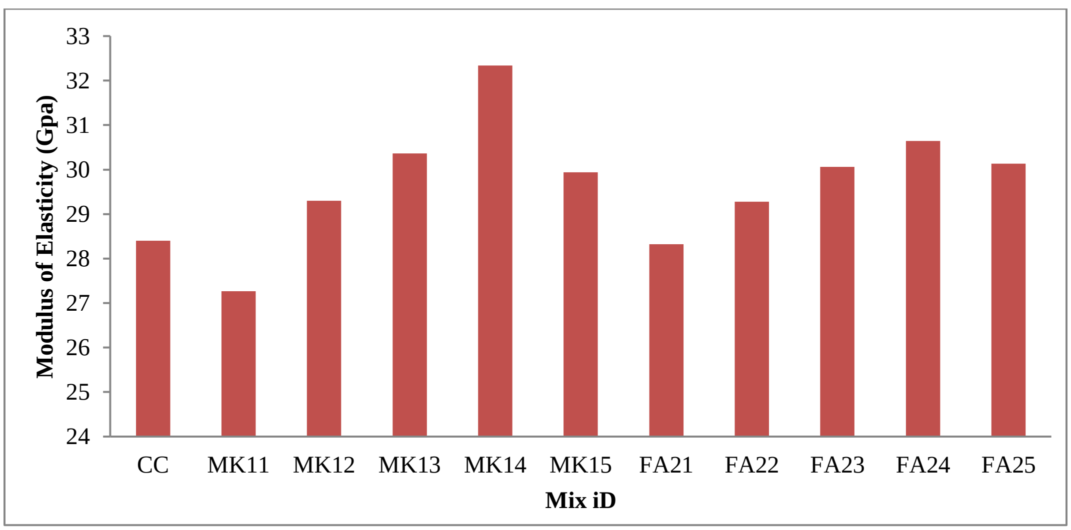

Figure 8 MoE of concrete

Mix MK14 (32.34 GPa) has the highest MoE, indicating it is the stiffest among all listed mixes. MK11 (27.27 GPa) has the lowest MoE among the listed mixes. CC (28.40 GPa) is moderately stiff compared to the other mixes (*Figure 8*). The MK modified mixes generally show a higher MoE compared to the CC mix. MK14 stands out as the stiffest, while MK11 is the least stiff among the MK modified mixes. The FA modified mixes also generally show a higher Moe compared to the CC mix. FA24 has the highest MoE among the FA modified mixes, making it one of the stiffest mixes overall. The MK modified mixes tend to be stiffer than both the CC and FA modified mixes [48, 49]. The highest MoE in the MK modified mixes (MK14 at 32.34 GPa) is higher than the highest in the FA modified mixes (FA24 at 30.64 GPa). The results indicate that the MK14 mix is the stiffest, and the MK11 mix is the least stiff among the listed mixes. The MK-modified mixes generally exhibit greater stiffness compared to both the CC and the FA-modified mixes.

4.6Water absorption

The water absorption test is performed on concrete to determine their ability to absorb water. The test involves immersing the concrete specimen in water for a specified period of time and measuring the increase in weight due to water absorption.

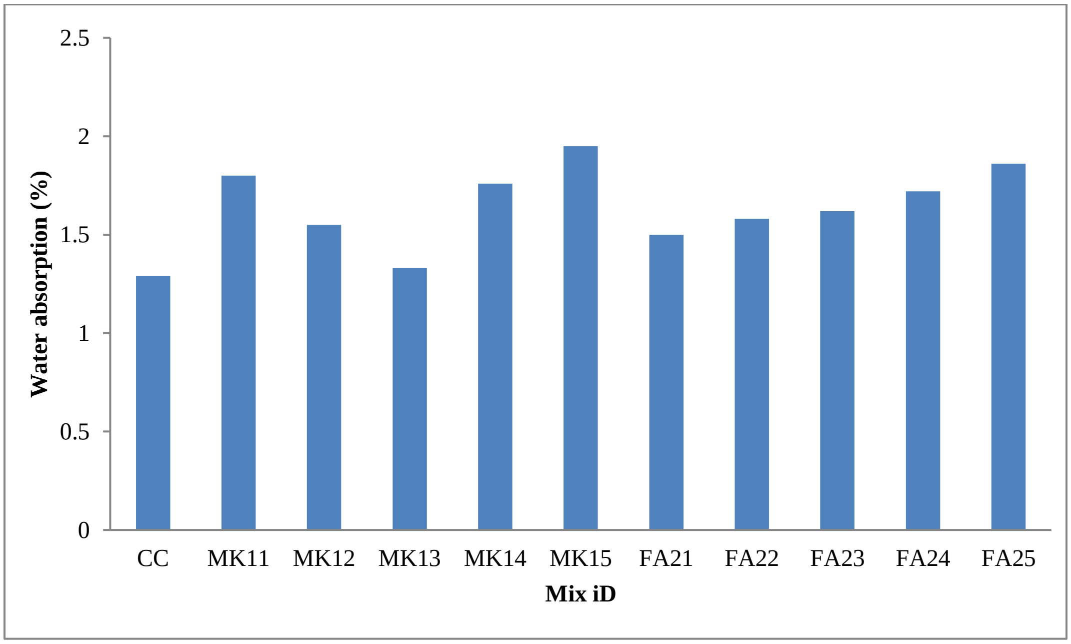

Figure 9 Result of water absorption of concrete for all mix

Figure 9 illustrates that, in most instances, the values increase compared to the baseline CC material. MK15 (1.95%) is the most significant percentage increase, followed closely by MK14 (1.76%). This indicates that the incorporation of MK, particularly at higher percentages, has a positive impact on enhancing concrete properties. The cylinder specimen reflects the percentage changes in these property for the various materials. Similar to the cube specimen property, an overall positive trend is observed; with the highest percentage change occurring for MK15 (1.95%) and MK11 (1.80%). These outcomes align with the potential improvement in concrete performance attributed to the use of MK. The prism property also exhibits changes with the different materials, with a comparable pattern observed, showcasing higher percentage changes for MK14 (1.76%) and MK15 (1.95%). It shows that, in most cases, the values increase compared to the baseline CC material. The highest percentage increase is observed for FA24 (1.72%), followed by FA15 (1.62%). This suggests that the introduction of fine FA especially at higher percentages tends to enhance the concrete property. The cylinder specimen indicates the percentage changes in this property for the different materials. Similar to the cube specimen property, an overall positive trend is observed, with the highest percentage change occurring for FA24 (1.72%) and FA15 (1.621%). These findings align with the potential improvement in concrete's performance when using fine FA. The prism property changes with the different materials.

4.7Density

The dry density of concrete can vary depending on several factors, including the mix design, the proportions of the components (cement, aggregates, water, additives), and the compaction level. In general, the dry density of normal concrete typically falls within a range of 2200 kg/m³ (kilograms per cubic meter) to 2500 kg/m³ [36].

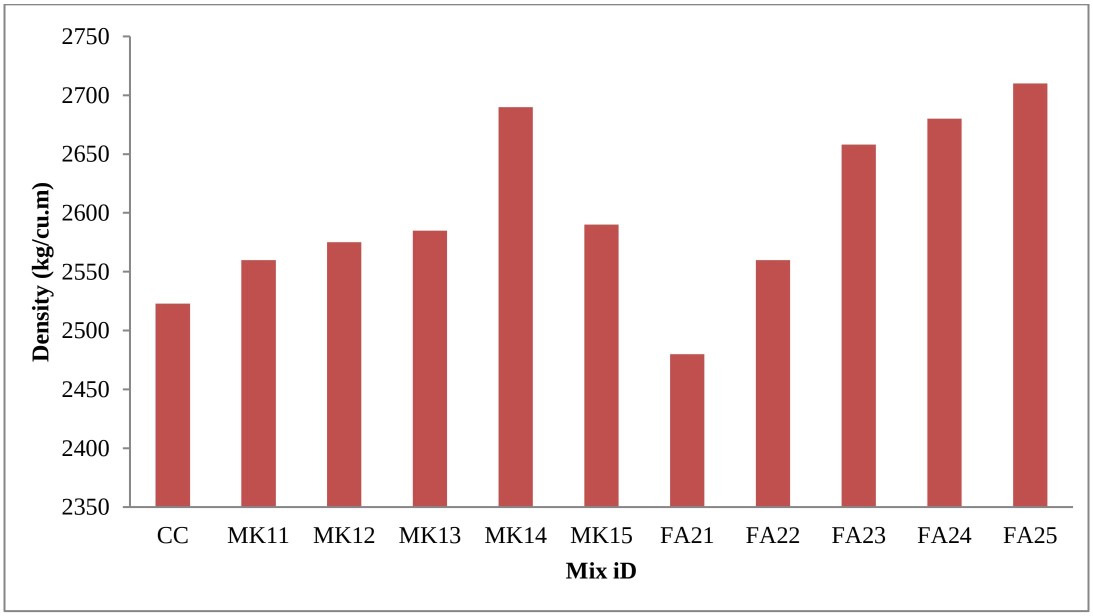

Figure 10 Result of density of concrete for all mix

The maximum density is noted in the MK14 mixture, registering a density of 2690 kg/m³ (*Figure 10*). Parallel to cube density, the cylinder density experiences an increment with the higher proportion of MK in the mixture. The MK14 mixture attains the highest density among cylinders, reaching 7350 kg/m³. A similar trend is observed in prism density, with values ascending as the MK content increases [28]. The highest density is observed in the FA25 mixture, with a density of 2710 kg/m³. Similar to cube density, the cylinder density also increases as the proportion of FA in the mixture increases [29]. The highest density is recorded for the FA24 mixture, which has a 7350 kg/m³ density. The prism density exhibits a comparable trend, with increasing values as the FA content rises.

5.Discussion

This research investigated the influence of MK and FA as partial replacements for OPC on the mechanical properties and durability of concrete. The results provide valuable insights for optimizing concrete formulations towards improved performance and sustainability. MK blends demonstrated a clear advantage over FA blends in terms of CS at all curing ages (7, 14, and 28 days). Notably, mix MK14 achieved the highest CS at all stages, reaching 34.5 MPa at 28 days. This suggests that MK promotes the formation of a denser and stronger microstructure within the concrete matrix, leading to superior load-bearing capacity. While FA blends like FA25 exhibited appreciable CS at 28 days (32.61 MPa), they did not match the performance of MK blends. Similar to the trend observed in CS, both MK14 and FA24 mixes exhibited higher STS and FS compared to the CC and other mixes at all curing ages. This indicates that incorporating MK or FA, particularly MK14 and FA24 formulations, can enhance concrete's resistance to tensile and flexural stresses, vital for structures subjected to bending or twisting forces.

The research revealed a positive correlation between CS and MoE, implying that stiffer concrete with higher CS typically exhibits a higher MoE. This relationship was evident as mix MK14, which had the highest CS, boasted the greatest stiffness (32.34 GPa) as measured by MoE. The incorporation of both MK and FA resulted in lower water absorption compared to the control mix, indicating improved resistance to water penetration and potentially enhanced durability. This is likely due to the pozzolanic reaction between SCMs and CH, leading to a denser microstructure with fewer pores for water ingress [50]. MK15 displayed the most significant reduction in water absorption for all specimen types, highlighting the potential of MK for improving concrete's defence against water-related degradation. Furthermore, the density of concrete specimens increased with the incorporation of both MK and FA. MK14 had the highest density for all specimen types, while FA25 exhibited the highest density among FA mixes. Increased density is often associated with improved strength and durability, which aligns with the observations for CS and water absorption.

The findings of this research suggest that MK offers a more pronounced improvement in most mechanical properties and durability compared to FA when used as a partial replacement for OPC in concrete. MK blends like MK14 demonstrated superior performance in CS, STS, FS, MoE, and water absorption. However, the study also revealed that both MK and FA can contribute to enhancing the performance and sustainability of concrete production. FA can be a viable option for applications where achieving the highest possible strength is not the primary concern, but benefits like workability and environmental sustainability are still important.

This investigation used a rigorous experimental design to evaluate the effects of incorporating MK and FA as partial replacements for OPC on concrete performance, covering fresh properties, mechanical strengths (CS, STS and FS), MoE, water absorption, and density. The results showed that MK and FA minimally impacted workability, consistent with other studies. MK consistently demonstrated superior CS compared to FA, with Mix MK14 showing the highest strength at all curing ages, aligning with previous research highlighting MK's effectiveness. STS and FS increased with curing time, with FA24 and MK14 achieving the highest strengths, matching trends observed in the literature. The MoE ranged from 27.27 GPa to 32.34 GPa, with MK14 showing the highest value, reflecting increased stiffness, consistent with other studies. Water absorption increased for most MK and FA mixes compared to the control mix, suggesting potential effects on durability. MK14 also had the highest density, with a general increase in density associated with higher FA content, similar to prior findings. Existing predictive models are limited in estimating STS and FS for MK and FA mixes, a discrepancy noted in previous research. These findings highlight MK's potential for enhancing concrete properties and suggest that future research should focus on the long-term durability of MK and FA concrete under various conditions and optimize mix designs to balance performance with workability and cost.

Incorporating MK and FA as partial replacements for OPC in concrete production offers substantial environmental benefits. These include significant reductions in CO_2 emissions, conservation of natural resources, energy savings, and enhanced durability of concrete structures. By reusing industrial by-products like FA, the approach also addresses waste management issues, contributing to a more sustainable construction industry. However, considerations such as the availability of materials and the energy required for MK production must be taken into account to maximize these environmental benefits.

The effects of using MK and FA as partial substitutes for OPC on the workability, mechanical strengths (CS, STS, FS), MoE, water absorption, and density of concrete were thoroughly assessed in this study. In line with earlier studies, MK continuously beat FA, with mix MK14 showing the maximum strength at all curing ages. Over time, STS and FS rose, with MK14 and FA24 attaining the greatest levels. Additionally, the greatest MoE (32.34 GPa) was shown by MK14, showing greater stiffness. By lowering water absorption in comparison to the control mix, MK and FA improved water penetration resistance and possible durability. The enhanced performance of MK and FA blends, especially in MK14 and FA25 mixtures, was further supported by their increased density.

Significant environmental advantages come from employing MK and FA as OPC substitutes, including as reduced CO_2 emissions, resource conservation, and efficient waste management through the reuse of industrial byproducts like FA. These advantages, along with enhanced durability and mechanical qualities, demonstrate MK and FA's promise for environmentally friendly building. However, to maximize cost-effectiveness and environmental impact, the energy requirements for MK manufacturing and material availability must be taken into account. Future studies should examine long-term durability in a range of environmental settings and optimise mix designs to strike a balance between cost, workability, and performance.

5.1CS and STS relationship

The presented research compared the findings of the current study on STS with results obtained in previous research works. Three specific formulas were used for comparison in the previous studies: $f_{sp} = 0.55x(f_{ck})^{0.5}$ [42], $f_{sp} = 0.301x(0.8xf_{ck})^{0.65}$ [43], and $fsp= 0.19x(f_{ck})^{0.75}$ [44] (*Table 3*). This comparison primarily aimed to analyze the discrepancies between the experimentally measured STS values (*Table 4*) and the values predicted using the aforementioned formulas.

Table 3 Formulas were used to estimate the STS of concrete containing MK and FA

Concrete type	STS (f_{sp})
Plain cement concrete	$f_{sp} = 0.55x(f_{ck})^{0.5}$ [42]
	$f_{sp} = 0.301x(0.8xf_{ck})^{0.65}$ [43]
	$f_{sp}= 0.19x(f_{ck})^{0.75}$ [44]

Table 4 Code practice formulas, and the experimental STS of concrete utilizing MK and FA comparison

Mix ID	Experimental values (MPa)		Predicted STS (MPa)		
	f_{ck}	f_{sp}	[42]	[43]	[44]
CC	31.00	4.04	3.06	2.42	2.49
MK11	31.20	4.34	3.07	2.43	2.50
MK12	32.10	4.52	3.11	2.48	2.02
MK13	33.30	4.89	3.17	2.54	2.56
MK14	34.50	4.99	3.23	2.60	2.70
MK15	33.10	4.79	3.16	2.53	2.62
CC	31.00	4.04	3.06	2.42	2.49
FA21	30.51	4.14	3.03	2.40	2.46
FA22	31.32	4.44	3.07	2.44	2.51
FA23	32.51	5.14	3.13	2.50	2.58
FA24	33.82	5.64	3.19	2.56	2.66
FA25	32.61	4.64	3.14	2.51	2.59

f_{ck}- Compressive strength; f_{sp}– Split tensile strength

An interesting observation was that the experimental value (4.99 MPa) for the mix ID MK 14 surpassed the predicted values obtained from all three equations. Similarly, the FA 24 mix also exhibited an experimental STS value that was higher than all the predicted values. In fact, for every mix investigated, including the CC, the experimentally measured STS values were consistently more significant than the values predicted using the formulas from past research. Among the three formulas, $f_{sp} = 0.55x(f_{ck})^{0.5}$ [42] yielded the highest predicted values compared to the other two formulas. The correlation between the experimental STS values and the predicted values from all three literature-derived formulas was further explored through *Figure 11*. Notably, *Figure 11* delves deeper into the 10% disparity observed between the predicted STS values and the experimentally obtained values.

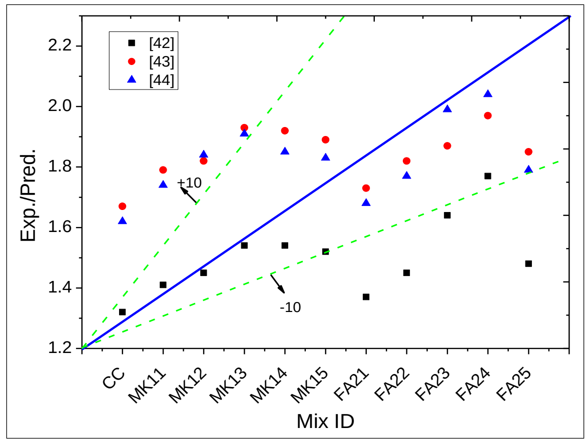

Figure 11 Ratio comparison of the experimental and predicted value of STS

5.2CS and FS relationship

The researchers behind this study conducted a comparison between their own findings on FS of concrete and the results documented in previous research papers. Established formulas, likely presented in *Table 5*, were used as the basis for this evaluation. The primary objective was to analyze the discrepancies between the experimentally measured FS values (shown in *Table 6*) and the values predicted using these formulas from previous research.

Table 5 Formulas were used to estimate the FS of concrete containing MK and FA

Concrete type	FS (f_b)
Plain cement concrete	$f_b = 0.62x(f_{ck})^{0.5}$[42]
	$f_b = 0.81x(f_{ck})^{0.5}$[45]
	$f_b = 0.70x(f_{ck})^{0.5}$[46]

Table 6 Code practice formulas, and the experimental FS of concrete utilizing MK and FA comparison

Mix ID	Experimental values (MPa)		Predicted FS (MPa)		
	f_{ck}	f_b	[42]	[45]	[46]
CC	31.00	4.02	3.45	4.50	3.89
MK11	31.20	4.32	3.46	4.52	3.90
MK12	32.10	4.5	3.51	4.58	3.96
MK13	33.30	4.87	3.57	4.67	4.03
MK14	34.50	4.97	3.64	4.75	4.11
MK15	33.10	4.77	3.56	4.66	4.02
CC	31.00	4.02	3.45	4.50	3.89
FA21	30.51	5.32	3.42	4.47	3.86
FA22	31.32	5.62	3.46	4.53	3.91
FA23	32.51	7.21	3.53	4.61	3.99
FA24	33.82	7.52	3.60	4.71	4.07
FA25	32.61	7.32	3.54	4.62	3.99

f_{ck}- Compressive strength; f_b-Flexural strength

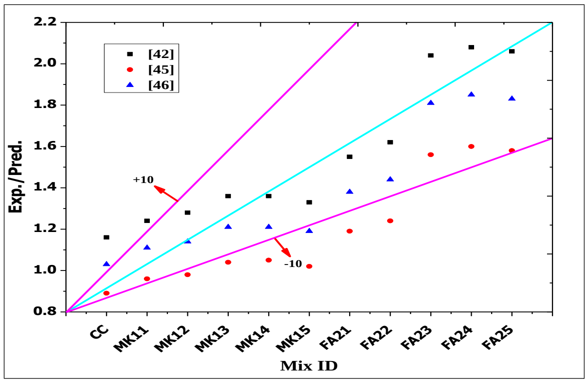

Figure 12 Ratio comparison of the experimental and predicted value of FS

The experimental FS value for the concrete mix labelled MK-14 (4.97 MPa) significantly outperformed the predictions generated by all three equations. This trend continued with the FA-24 mix, where the experimentally measured FS value (7.52 MPa) was even further above all the predicted values. Interestingly, this phenomenon applied to every concrete mix tested, including the CC. It's worth noting that among the three formulas, $f_b = 0.81x(f_{ck})^{0.5}$ [45] yielded the highest predicted values compared to the other two. To gain a deeper understanding of the relationship between the experimental FS results and the predictions from past literature, the researchers utilized *Figure 12*. Notably, *Figure 12* focuses explicitly on the 10% disparity observed between the predicted FS values and the experimentally obtained values.

5.3CS and MoE relationship

The analysis is based on experimental data concerning the MoE and CS derived from concrete specimens that incorporate MK and FA. This study expected to compare the results obtained with past research by using outdated literature formulas, as presented in *Table 7*. The primary focus of this comparison involved comparing the experimental values with the predicted MoE values, which are detailed in *Table 8.*

Upon examining the results, it was observed that in the MK14 mix, the experimental MoE value was 32.34 GPa, which surpassed the predicted values from the three equations. Similarly, in the FA 24 mix, the experimental MoE value stood at 30.64 GPa, higher than all the predicted values. Notably, all the expected values derived from the outdated formulas were lower than the experimental values for all mixes, including CC.

Table 7 Formulas were used to estimate the MoE of concrete containing MK and FA

Concrete type	MoE (E_c)
Plain cement concrete	$E_C = 4700x(f_{ck})^{0.5}$ [42]
	$E_C = 5000x(f_{ck})^{0.5}$ [46]

Table 8 Code practice formulas, and the experimental MoE of concrete utilising MK and FA comparison

Mix ID	Experimental values (MPa)		Predicted MoE (GPa)	
	f_{ck}	E_C	[42]	[46]
CC	31.00	28.40	26.16	27.83
MK11	31.20	27.27	26.25	27.92
MK12	32.10	29.30	26.62	28.32
MK13	33.30	30.36	27.12	28.85
MK14	34.50	32.34	27.60	29.36
MK15	33.10	29.94	27.04	28.76
CC	31.00	28.40	26.16	27.83
FA21	30.51	28.32	25.96	27.61
FA22	31.32	29.28	26.30	27.98
FA23	32.51	30.06	26.79	28.50
FA24	33.82	30.64	27.33	29.07
FA25	32.61	30.13	26.83	28.55

f_{ck}- Compressive strength; Ec– Modulus of elasticity

Among the various formulas, the equation $E_C = 5000x(f_{ck})^{0.5}$ [46] yielded a predicted value that was higher than the other formulas. The correlation between the experimental values of FS and the predicted values from all three literature-derived formulas is elucidated in *Figure 13*. It specifically highlights the 10% deviation observed between the predicted FS and the experimental values. The established relationships between the MoE and characteristic CS in concrete mixes containing MK and FA can be of significant value for a variety of engineering applications. It is possible to use these equations in conjunction with structural analysis models to predict the behaviour of concrete structures that include these SCMs.

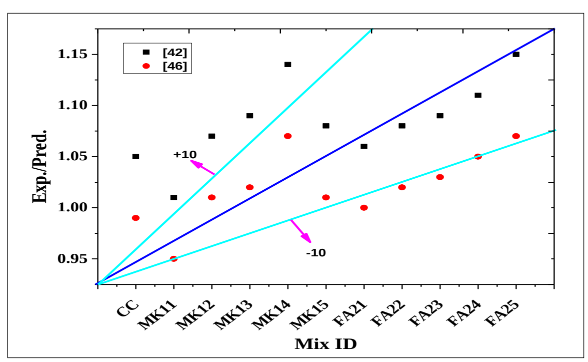

Figure 13 Ratio comparison of the experimental and predicted value of MoE

A complete list of abbreviations is listed in *Appendix I*.

6.Conclusion and future work

This investigation employed a rigorous experimental design to evaluate the influence of incorporating MK and FA as partial replacements for OPC on the performance of concrete. A comprehensive assessment encompassed fresh properties, mechanical strengths (CS, STS, FS), MoE, water absorption, and density.

- The findings demonstrated that within the designated ranges, MK and FA incorporation minimally impacted the workability of concrete mixtures. Notably, concrete mixes containing MK exhibited consistently higher CS at all curing ages (7, 14, and 28 days) than those containing FA. Mix MK14 displayed the highest CS across all test ages.
- For both STS and FS, a positive correlation with curing time was observed for all mixes. At 28 days, mixes FA24 and MK14 achieved the highest STSs, while MK14 and FA24 displayed the greatest FSs compared to the CC.
- TheMoEvalues indicated normal-strength concrete behavior (27.27 GPa to 32.34 GPa). Mix MK14 demonstrated the maximum modulus, indicating enhanced stiffness compared with the standard mix and mixes treated with FA.
- Water absorption tests revealed an increase in most MK and FA concrete mixes compared to the control mix. This suggests a potential influence of MK and FA content, particularly at higher replacement levels, on the water absorption characteristics of concrete.
- The dry density of the concrete mixes varied with the mix design and component proportions. Mix MK14 demonstrated the highest density among all mixes, followed by a general trend of increasing density with higher FA content.
- Existing formulas were found to be limited in predicting STS, FS, and MoE for MK and FA concrete mixes. While MK content offered a reliable predictor for CS, established models underestimated the actual STS and FS.

The promising results achieved with MK, particularly at higher replacement levels, highlight the need for further investigation in the following areas:

- Assess the durability of MK and FA concrete mixes under various exposure conditions, including freeze-thaw cycles, aggressive chemical environments, and chloride exposure, to ensure their reliability in diverse applications.
- Develop optimized mix designs for MK and FA concrete blends to achieve the desired mechanical properties while maintaining workability and cost-effectiveness. This may involve the use of SCMs, chemical admixtures, and advanced optimization techniques.
- Monitor the long-term performance of these concrete mixes, with a focus on carbonation and shrinkage behavior, to confirm the sustained effectiveness of MK and FA under varying environmental conditions.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

The data supporting this study were obtained from experimental investigations on concrete specimens with metakaolin and fly ash replacements. While the data are not publicly available, they may be provided by the corresponding author upon reasonable request.

Author's contribution statement

Saravanan M M: Conceptualization, methodology, software, validation, investigation, resources, data curation, writing-original draft preparation. **Ananthakumar Ayyadurai, Viswanathan G and Sasikumar P:** Supervision, investigation, resources, and review the article.

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Appendix I

S. No.	Abbreviation	Description
1	ASTM	American Society for Testing and Materials
2	CA	Coarse Aggregate
3	CC	Conventional Concrete
4	CH	Calcium Hydroxide
5	CS	Compressive Strength
6	C-S-H	Calcium Silicate Hydrate
7	CTM	Compression Testing Machine
8	GPa	Gigapascal
9	GGBS	Ground Granulated Blast-Furnace Slag
10	FA	Fly Ash
11	FA	Fine Aggregate
12	FS	Flexural Strength
13	MK	Metakaolin
14	MPa	Megapascals
15	mm	Millimeter
16	MoE	Modulus of Elasticity
17	OP	Ordinary Portland
18	OPC	Ordinary Portland Cement
19	SCMs	Supplementary Cementitious Materials
20	SEM	Scanning Electron Microscope
21	STS	Split Tensile Strength
22	TAK	Thermally Activated Kaolin