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Optimizing concrete performance through metakaolin and flyash incorporation: a critical appraisal of regression modeling and design code applicability

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ABSTRACT

An investigation into the use of metakaolin (MK) and fly ash (FA) as partial cement replacements in concrete was conducted to enhance the sustainability of the construction industry. The MK and FA were incorporated into the concrete mix design by weight, replacing a portion of the portland cement content. The replacement percentages varied in two sets: 5%, 7.5%, 10%, 12.5%, and 15% for MK; and 5%, 10%, 15%, 20%, and 25% for FA. Workability of the fresh concrete was evaluated using the slump cone test to identify the optimal replacement level. Subsequently, the mechanical properties of the hardened concrete were investigated using compressive strength (CS), split tensile strength (STS), flexural strength (FS), modulus of elasticity (MoE). The results revealed that incorporating MK improved the mechanical properties: CS increased by 12.06%, STS by 16.84%, and FS by 15.42% compared to the control mix. In comparison, FA substitution resulted in a slightly lower increase: CS by 9.72%, STS by 12.84%, and FS by 8.57%. The study concluded that MK exhibited a superior performance in enhancing the strength properties of concrete compared to FA. Additionally, linear regression analysis was employed to establish correlations between the experimentally determined strength properties and the mix design parameters. This analysis demonstrated a strong correlation between the predicted and experimental values, making it a valuable tool for future concrete mix design optimization.

Keywords: metakaolin; flyash; compressive strength; split tensile strength; flexural strength; linear regression analysis.

1. INTRODUCTION

Concrete serves as the cornerstone material in the global construction industry, its development and use intricately linked to the industry's growth. However, a significant environmental concern lies in the CO2 emissions associated with cement production, a key constituent of concrete. These emissions contribute to rising air pollution levels. In response to this challenge, researchers and engineers have continuously sought methods to improve the characteristics of concrete, prioritizing enhanced durability, sustainability, and cost-efficiency. A promising strategy gaining traction involves the integration of supplementary cementitious materials (SCMs) such as metakaolin (MK) and fly ash (FA) into concrete formulations. This approach, coupled with the utilization of chemical admixtures from Sika, presents an opportunity to achieve significant advancements in concrete properties. This study meticulously analyzes the effects of MK, FA, and Sika admixtures on various performance aspects of concrete.

The use of MK in concrete, providing a comprehensive overview of its applications and contributions to optimizing concrete properties for enhanced performance in construction [1]. It investigates the properties of MK blended cements, offering insights into the performance and characteristics of these blends, crucial for optimizing cement formulations in construction materials [2]. It investigate the properties of blended cements incorporating thermally activated kaolin, offering valuable insights into optimizing cement mixtures for enhanced performance in construction materials [3]. It presents a novel approach for optimizing concrete mixtures containing MK and FA. It utilizes neural networks to predict the workability of the concrete, allowing for targeted adjustments to achieve desired workability in construction projects [4]. Researchers are investigating the potential of metakaolin (MK) to improve the corrosion resistance of cement mortars, paving the way for

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more durable construction materials [5]. Long-term tests are being conducted to assess the chloride-penetration resistance of concrete containing high-reactivity MK. These tests will provide valuable insights into the material's overall durability and its ability to withstand chloride-induced deterioration in real-world construction applications [6]. The study reviews the influence of MK in concrete mixtures, offering insights into its effects on concrete properties for potential improvements in construction materials [7]. The CS and chloride resistance of MK concrete, offering insights into its potential for durable construction and resistance to chloride-induced deterioration [8]. Replacing cement with ground granulated blast furnace slag (GGBS) and metakaolin (MK) offers a sustainable solution for concrete production. This study investigates the impact of these materials on the microstructure of concrete, aiming to improve its overall performance and sustainability in construction projects [9]. Impact of MK on hydration in mixtures of MK and lime/cement at room temperature (20°C), providing valuable insights into the material's behavior and reaction rates, contributing to the understanding of cement systems in construction [10]. The strength properties of metakaolin-admixed concrete, contributing valuable insights into the material's structural characteristics and potential improvements for concrete strength [11]. The influence of MK surface area on the properties of cement-based materials, shedding light on how variations impact performance and contributing insights for optimizing material formulations in construction [12]. Metakaolin (MK) is under scrutiny for its potential in concrete. Studies are examining its microstructure through pore size distribution analysis in MK paste, providing valuable insights for cement and concrete research [13]. Additionally, research is exploring how MK, combined with fly ash (FA), can influence concrete strength, paving the way for optimized and high-performing concrete mixtures [14]. Furthermore, the impact of MK as a cement replacement on mortar durability is being investigated, particularly its resistance to magnesium sulfate solutions that simulate harsh environments. This knowledge is crucial for ensuring the long-term performance of MK-based concrete in construction applications [15]. The fracture properties of geopolymer concrete, incorporating MK, FA, and rice husk ash, providing valuable insights into the material's structural characteristics and potential applications [16]. The performance of MK concrete at elevated temperatures, providing insights into the material's behavior under heat exposure and contributing to the understanding of its suitability for fire-resistant construction applications [17]. Several studies are investigating the potential of metakaolin (MK) in construction materials. One study by [18] explores MK as a supplementary cementitious material (SCM) in concrete, examining its influence on both strength and durability. Another study focuses on MK-based geopolymers, analyzing how curing temperature affects the development of the hardened structure [19]. Understanding this is crucial for optimizing geopolymer production and achieving superior material properties. Finally, research is exploring the combined effect of MK and fly ash (FA) on concrete composites [20]. This study examines how these materials influence both strength and efflorescence (the formation of white deposits on the concrete surface). This knowledge is valuable for optimizing concrete mixtures to achieve enhanced performance and minimize efflorescence issues. The study investigates the synergistic effects of recycled aggregate and GGBS/metakaolin on the physicochemical properties of geopolymer concrete, providing valuable insights into sustainable construction materials [21]. The spalling behavior of MK-FA-based geopolymer concrete when exposed to elevated temperatures, providing insights into the material's fire resistance and structural performance [22].

During free drying, shrinkage increases with higher fly ash content, but crack width decreases and crack formation is delayed [23]. High-volume natural pozzolan and FA have been shown to be effective in self-consolidating concrete mixtures, offering sustainable construction material alternatives [24]. The binding mechanism and properties of alkali-activated FA/slag mortars provide valuable insights into their utilization in sustainable construction [25]. FA activated with alkaline solutions exhibits rheological properties beneficial for soil improvement techniques like jet grouting [26]. Studies on using olive residue biomass FA in self-compacting concrete demonstrate a sustainable approach for concrete production while addressing agricultural waste management [27]. Investigations into incorporating ground FA in concrete components (paste, mortar, and concrete) provide valuable insights for optimizing the performance of each element [28]. Combining FA with nano-metakaolin can improve the mechanical strength and durability of mortars, offering a potentially superior material [29]. Experimental use of pumice powder and FA in concrete results in improved mechanical properties and favorable microstructural characteristics, highlighting potential for sustainability and efficiency [30]. Concrete with very high volumes of Class F FA can exhibit suitable mix proportions and maintain good mechanical properties, demonstrating the potential for sustainability and high performance [31]. Binary and ternary blends in FA-based geopolymer concrete show improved strength and desirable microstructural properties [32]. The combined use of recycled aggregate and FA enhances concrete sustainability, offering insights for eco-friendly construction practices [33]. The use of FA positively impacts the strength and hydration properties of blended cements, indicating possible improvements [34]. The air void properties of FA-containing concrete are altered by the addition of powdered activated carbon, which affects the longevity and performance of the concrete [35]. Concrete containing FA and MK at elevated temperatures offers insights into fire resistance [36]. High flexural strength can be achieved in lightweight FA geopolymer mortar by incorporating waste fiber cement, providing a sustainable and high-performance alternative [37].

The heat of hydration in Portland high-calcium FA cement containing limestone powder is studied, focusing on the impact of limestone particle size during the curing process [38]. The influence of FA on the evolution of properties in cement-based materials sheds light on its impact on construction material performance [39]. The beneficial utilization of recycled asphaltic concrete aggregate in high calcium FA geopolymer concrete contributes to sustainable construction practices and waste reduction [40]. The influence of initial water content and curing moisture conditions on the development of FA-based geopolymers at both heat and ambient temperatures offers valuable insights for optimizing geopolymer materials [41]. Data on the uniaxial tensile strength and tensile Young's modulus of FA concrete at early ages help understand the material's behavior during the initial stages of concrete setting and curing [42]. The creation of geopolymers based on MK and FA designed for fire resistance applications showcases their potential as fire-resistant building materials [43]. The structural response of concrete containing fly ash and metakaolin when exposed to fire, contributing to the development of more resilient and fire-resistant concrete mixes [44]. Utilizing waste materials of e-plastic waste and fly ash into concrete to improve concrete properties while promoting environmental sustainability [45]. The role of nano materials in improving concrete durability, paving the way for the development of more resilient concrete structures. Their findings shed light on the potential benefits of incorporating nano materials in concrete mixes to enhance structural integrity and longevity [46, 47–52].

This study delves deep into the effects of incorporating metakaolin (MK), fly ash (FA), and a superplasticizer (Sika) on the properties of concrete. Researchers are adopting a rigorous approach that combines both experimental analysis and microstructural examination to gain a comprehensive understanding of the material's behavior. High-quality ingredients form the foundation of this investigation, with ordinary Portland cement (OPC) 53 grade, M-sand, and 20mm coarse aggregates meticulously chosen to ensure consistency and reliability. The core of the study revolves around understanding how varying proportions of MK and FA influence the overall performance of the concrete. Intriguingly, all concrete mixes incorporate a constant 0.5% concentration of Sika superplasticizer. This allows researchers to isolate the specific effects of MK and FA variations, while ensuring consistent workability across all test specimens. Furthermore, the investigation extends beyond traditional strength testing to encompass crucial durability metrics. By analyzing water absorption and density, the researchers can assess the concrete's resistance to degradation and its long-term suitability for structural applications. Ultimately, this combined approach provides valuable insights into the potential of MK, FA, and Sika for optimizing concrete performance and sustainability in the construction industry.

1.1. Research significance

This research holds significance for the construction industry in promoting sustainable practices and improving concrete performance. By exploring the use of MK and FA as partial replacements for Portland cement, the study contributes to the development of more environmentally friendly concrete. Portland cement production is a significant source of greenhouse gases, so reducing its use lowers the environmental impact of concrete production. The investigation demonstrates that incorporating MK, particularly at the optimal replacement level, significantly enhances the mechanical properties of concrete. This translates to stronger and more durable concrete structures, potentially leading to longer lifespans and reduced maintenance costs. The study provides valuable insights by comparing the effectiveness of MK and FA. While both materials improve concrete performance, MK shows a clearer advantage in enhancing compressive, split tensile, and flexural strengths. This information can guide engineers in selecting the most suitable supplementary cementitious material (SCM) for their specific project requirements. The successful use of linear regression analysis to correlate strength properties with mix design parameters offers a valuable tool for future concrete mix design. This approach allows engineers to predict the performance of concrete mixes more accurately, leading to more efficient and optimized concrete formulations.

2. MATERIALS AND MIXPROPORTIONS

2.1. Materials

Concrete mixes were formulated using OPC, low-calcium pulverized FA, and MK. Table 1 details the chemical composition and physical properties of these binding materials. Scanning electron microscope (SEM) images of MK and FA are presented in Figure 1.

The fine aggregate consisted of M-sand, and crushed granite served as the coarse aggregate. Specific gravities for both were around 2.6, with fine aggregate having a 24-hour absorption of 0.7% and a fineness modulus of 2.4. The coarse aggregate particles exhibited a specific gravity of 2.62 and a 24-hour water absorption of 0.6%. A superplasticizer, likely a sulphonated naphthalene formaldehyde condensate (such as Sika), was incorporated to achieve a target slump of 85 millimeters or greater, ensuring good workability and maintaining concrete strength.

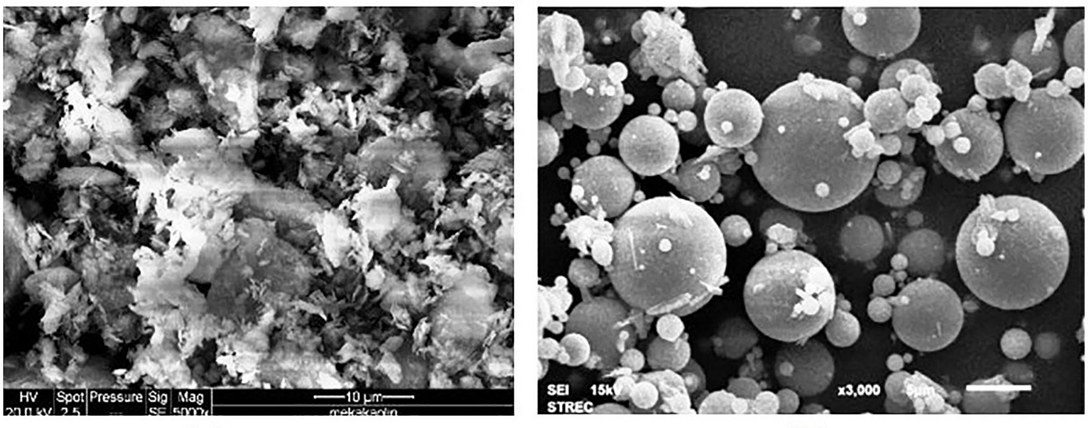
2.2. Mix proportions

This study examined eleven concrete mix designs, including a conventional mix (refer to Table 2 for details on mix proportions).The concrete mix while MK and FA are pozzolans which were used as cement replacement except conventional concrete. MK and FA was used in replacement level of 5%, 7.5%, 10%, 12.5%, and 15% (MK5, MK7.5, MK10, MK12.5, and MK15) The FA content was varied in replacement levels of 5%, 10%, 15%, 20% and 25%, designated as FA5, FA10, FA15, FA20 and FA25, respectively. Figure 2 delves the manufacturing process of concrete.

OPC has a lower percentage (19.6%) of silicon dioxide compared to FA (57%). Silica is a major component of pozzolans, a material that reacts with calcium hydroxide (a hydration product of Portland cement) to form additional cementitious compounds, improving strength and durability. The alumina content is also lower in OPC (7.3%) compared to FA (28%). Alumina, along with silica, contributes to the pozzolanic activity of FA. The iron content is slightly higher in OPC (3.3%) compared to FA (5.3%). Iron oxide can influence the color of the concrete, and may also affect setting time and strength development. OPC has a significantly higher proportion of calcium oxide (63.1%) compared to FA (3%). Calcium oxide is the main component of Portland cement, and

Table 1: Chemical composition of binders [44].

CHEMICAL COMPOSITION (%)	OPC	FA	MK
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		



(a) (b)

Figure 1: SEM images for mineral admixtures (a) Fly Ash, and (b) Metakaolin.

Table 2: Mix proportions (per m^3).

MIX ID	CEMENT (kg)	MK (kg)	FA (kg)	WATER (kg)	M-SAND (kg)	COARSE AGG. (kg)
CC	437	0	0	197	692	1002
MK5	415	22	0	197	692	1002
MK7.5	404	33	0	197	692	1002
MK10	393	44	0	197	692	1002
MK12.5	382	55	0	197	692	1002
MK15	371	66	0	197	692	1002
FA5	415	0	22	197	692	1002
FA10	393	0	44	197	692	1002
FA15	371	0	66	197	692	1002
FA20	350	0	87	197	692	1002
FA25	328	0	109	197	692	1002

Figure 2: Manufacturing process of concrete specimen.

is essential for its hydration and strength development. The magnesium oxide content is slightly higher in FA (5.2%) compared to OPC (2.5%). Magnesium oxide can influence setting time and strength development, but generally in lesser amounts compared to calcium oxide. The levels of these alkalis are very low in both OPC and FA. However, high alkali content can be detrimental to concrete durability due to a phenomenon called alkali-silica reaction (ASR). The sulfur trioxide content is slightly higher in OPC (2.1%) compared to FA (0.7%). Sulfates can influence setting time and may also contribute to corrosion of steel reinforcement in concrete if present in high amounts.

OPC has a higher specific gravity (3.16) compared to FA (2.3). Specific gravity is the ratio of the material's density to the density of water. A higher specific gravity indicates a denser material. FA has a significantly higher specific surface area (12680 m^2/kg) compared to OPC (312 m^2/kg). Specific surface area refers to the total surface area of particles per unit mass. A higher specific surface area can influence the reactivity of the material and its hydration properties.

2.3. Curing conditions

After demolding at 24 hours, the specimens underwent curing in a water tank maintained at 27°C for durations of 7, 14, and 28 days. Subsequently, they were transferred to a controlled environment with 65% relative humidity and 27°C temperature for further testing.

3. RESULT AND DISCUSSION

3.1. Fresh concrete properties

An investigation was undertaken to explore the effects of varying MK and FA content on the fresh properties of concrete. The experiment utilized a parametric approach, employing a series of concrete mixes formulated with different levels of replacement for OPC by MK (5%, 7.5%, 10%, 12.5%, 15%) and FA (5%, 10%, 15%, 20%, 25%) by weight of cement. This approach allows for the isolation and quantification of the individual and potentially interactive influences of MK and FA on the fresh concrete's behavior. The mixing procedure adopted a meticulous sequential approach. Initially, the cement and fine aggregate were thoroughly dry-mixed to ensure homogenous distribution. Subsequently, the coarse aggregate was incorporated and dry-mixed again to achieve a uniform dispersion throughout the composite material. To potentially enhance specific fresh properties, a pre-determined quantity of polymer was then added. Finally, water was introduced incrementally, and the entire mixture was subjected to thorough mixing until a uniform and cohesive concrete consistency was attained.

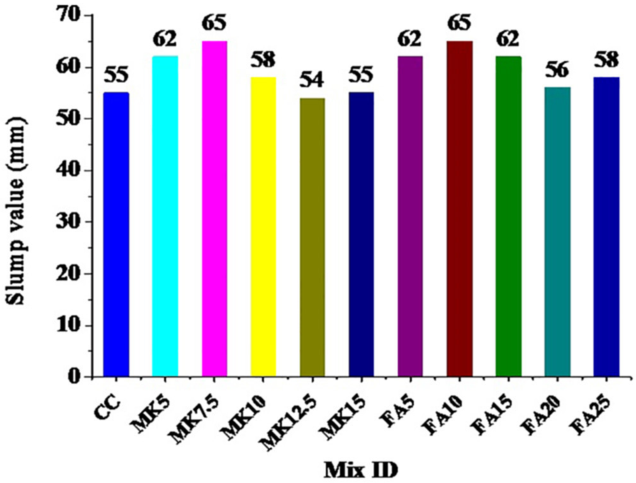


Figure 3: Slump values of concrete mixes.

Workability, a crucial fresh property of concrete that directly impacts its placement and compaction during construction, was assessed using the industry-standard slump test, likely performed in accordance with established procedures outlined in relevant standards such as American Society for Testing and Materials (ASTM) C143 (US), IS: 1199 – 1959 (India), or EN 12350-2 (Europe) [53]. The slump values obtained for both the control mix (without MK or FA) and the formulated concrete mixes containing varying MK and FA contents are likely presented in Table 3 (not included here). It's important to note that designated mix ratios were strictly adhered to throughout the experiment. This ensures consistency in the w/b ratio across all mixes, effectively isolating the impact of MK and FA variations on the slump test results (Figure 3).

3.2. Compressive strength test

CS is an important property of concrete that determines their load-bearing capacity and durability. It represents the amount of force a concrete can withstand before it starts to break or fail [48, 49]. In other words, CS is the maximum pressure or stress that a concrete can tolerate without cracking, crumbling or being crushed. It is a crucial factor in the design, manufacturing and installation of concrete cube specimen as it affects their performance and longevity. The compressive strength of concrete cube specimen is determined through standardized tests and is usually measured in Mega-Pascal (MPa) or Newton per square millimeter (N/mm^2) or pounds per square inch (psi). A higher CS indicates a stronger and more durable concrete specimen that can withstand heavy loads and harsh weather conditions.

Concrete specimens are commonly tested at intervals of 7, 14, and 28 days, with the 28-day testing period generally indicative of the concrete's full strength potential, as illustrated in Table 3. The specifications for conducting compressive strength tests can be found in the IS:516-1959 standards, which offer comprehensive guidelines for ensuring accurate and reliable assessments of concrete strength in compliance with industry standards. The results indicate (Figure 4 and 5) that the introduction of MK and FA in place of some of the cement has a varying impact on CS.

Within the materials under examination, the blend containing 12.5% MK shows the highest CS after 7 days, measuring 19.5 MPa. As the proportion of MK increases, there is a minor rise in CS compared to the control mixture. Notably, the MK 12.5% composition maintains its dominance among the MK mixtures, registering 19.5 MPa at the 7-day mark. Progressing to 14 days, all blends generally exhibit an upsurge in CS compared to the results at 7 days, with MK 12.5% still leading the pack at 29.5 MPa. The MK mixtures, especially the 12.5% variant, demonstrate considerable enhancements in strength from 7 days to 14 days, underscoring the pozzolanic characteristics of MK. By the 28-day milestone, there is a further escalation in the CS of all blends. Notably, MK 12.5% remains the most robust, reaching a value of 32.5 MPa, outperforming all other mixtures at this stage. As the percentage of FA increases, there is a slight decrease in CS compared to the control mix. FA20 displays the highest CS among the FA mixes at 7 days, with a value of 20 MPa. The level of CS all mixes is generally higher by day 14 compared to day 7. The control mix (CC) still maintains the highest strength, now at 24 MPa. The FA mixes, particularly FA20, show significant improvements in strength from 7 days to 14 days, emphasizing the pozzolanic properties of fine FA. By the 28-day mark, there is a further increase in the CS of all mixes. The CC remains the strongest, reaching a value of 29 MPa. Among the FA mixes, FA20 continues to exhibit the highest strength, now at 30 MPa, surpassing all other mixtures at this stage.

Table 3: CS value of cube specimen.

MIX ID	COMPRESSIVE STRENGTH (MPa)		
	7 DAYS	14 DAYS	28 DAYS
CC	17	25	29.00
MK5	17.5	26.5	29.20
MK7.5	18	27.5	30.10
MK10	18	28	31.30
MK12.5	19.5	29.5	32.50
MK15	17.5	27.5	31.10
FA5	18	24	28.51
FA10	17	25	29.32
FA15	18	25	30.51
FA20	19	26	31.82
FA25	20	28	30.61

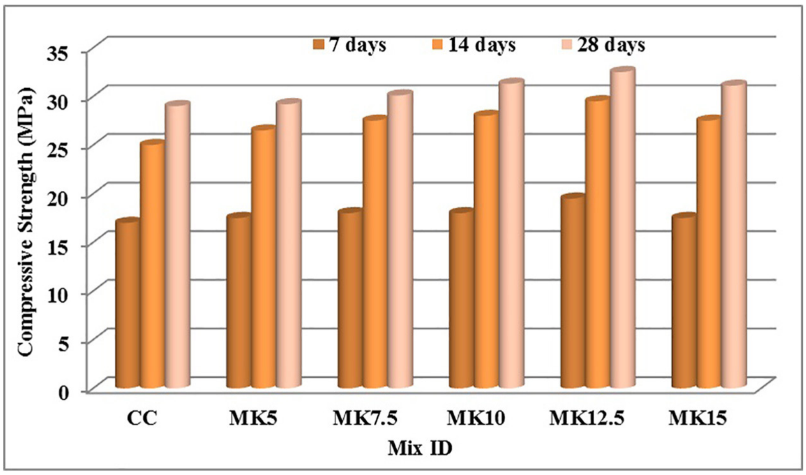


Figure 4: Compressive strength verses various proportions of MK concrete.

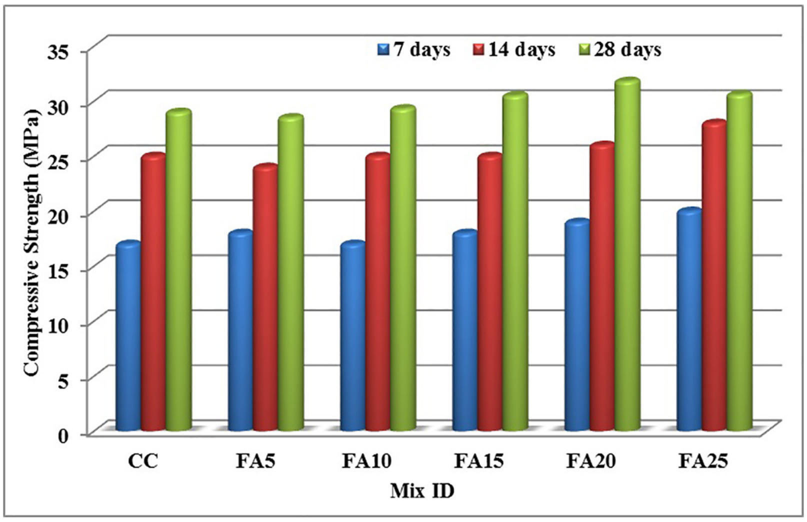


Figure 5: Compressive strength verses various proportions of FA concrete.

3.3. Split tensile strength

Assessing the STS of a concrete specimen (cylinder) involves determining its resistance to tensile forces (Table 4). This test method entails subjecting a cylindrical concrete sample to an applied tensile force until it fractures. The STS of the concrete specimen depends on several crucial factors, including the material type, manufacturing technique, dimensions, shape of the block, and the duration of the curing process [50]. These variables collectively influence the concrete's ability to withstand tensile stresses, highlighting its resilience and durability under various loading conditions.

At 7 days, MK12.5% shows (Figure 6 and 7) a STS of 2.389 MPa, which is the highest among all the mixes at this early stage. As the percentage of MK increases, there is a clear trend of increasing STS. The MK mixes generally exhibit higher strength compared to the control mix. MK12.5 stands out with the highest STS at 7 days, reaching 2.389 MPa. The STS of all mixes increases at 14 days compared to the 7-day results. The MK 12.5% shows a significant improvement, reaching 2.389 MPa. MK12.5% continues to display the highest STS among all mixes, with a value of 3.504 MPa at 14 days. By 28 days, there is a further increase in STS for all mixes. The MK12.5 reaches strength of 4.450 MPa, which is now comparable to some of the MK mixes. MK12.5 maintains its position as the mix with the highest STS, reaching 4.450 MPa. This implies that incorporating 12.5% MK could be an effective proportion for improving concrete's resistance to tensile forces. While the control mix (CC) exhibits improvements in STS with prolonged curing, it is consistently outperformed by the MK mixes, emphasizing the potential

Table 4: STS value of cylinder specimen.

MIX ID	SPLIT TENSILE STRENGTH (MPa)		
	7 DAYS	14 DAYS	28 DAYS
CC	1.59	2.55	3.50
MK5	1.75	2.71	3.80
MK7.5	1.91	2.88	3.98
MK10	2.07	3.03	4.35
MK12.5	2.38	3.50	4.45
MK15	2.07	2.87	4.25
FA5	1.7	2.5	3.60
FA10	1.8	2.8	3.90
FA15	2	2.9	4.60
FA20	2.3	3.3	5.10
FA25	2.2	3.2	4.10

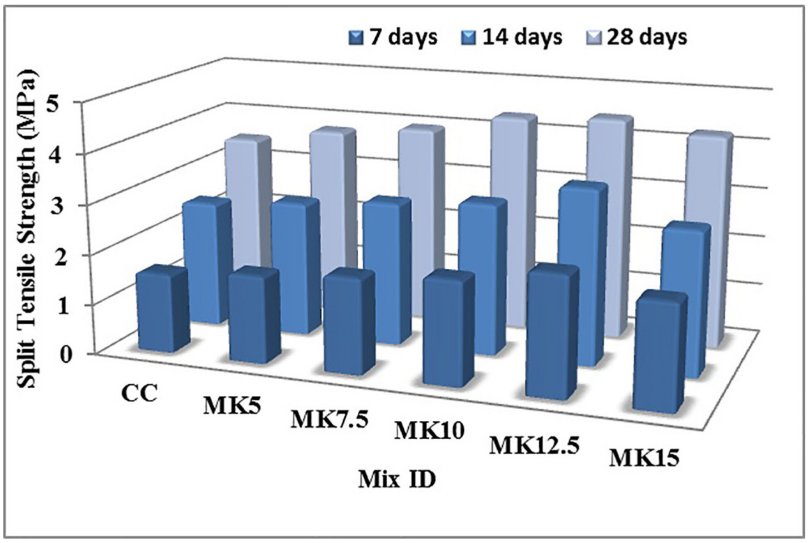


Figure 6: STS verses various mix proportions of MK concrete.

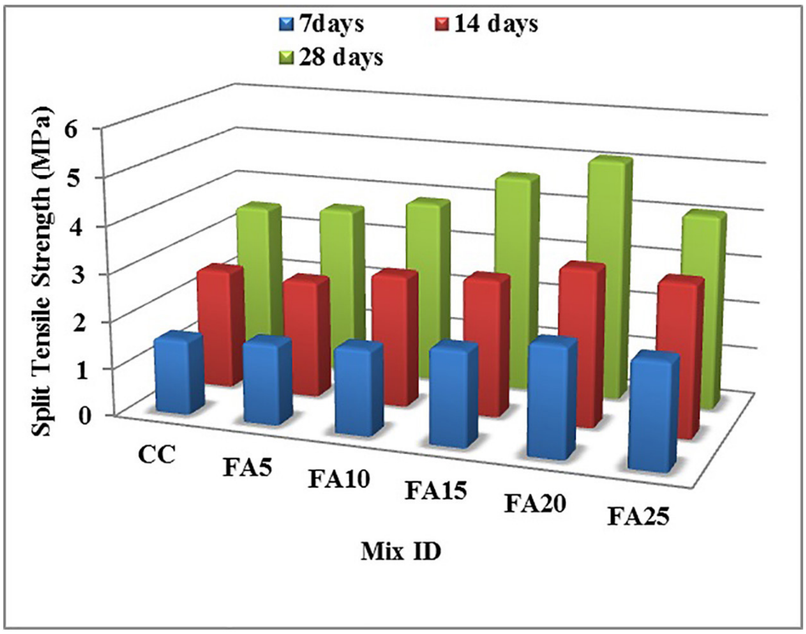


Figure 7: STS verses various mix proportions of FA concrete.

advantages of incorporating MK. This suggests that around 12.5% MK may be an effective proportion to enhance the resistance of concrete to tensile forces. The CC also displays improvements in split tensile strength as the curing period extends, but it is generally surpassed by the MK mixes, highlighting the potential benefits of using MK.

At 7 days, the CC shows a STS of 1.6 MPa, which is the lowest among all the mixes at this early stage. As the percentage of FA increases, there is a clear trend of increasing STS. The FA mixes generally exhibit higher strength compared to the control mix. FA20 stands out with the highest STS at 7 days, reaching 2.3 MPa. The STS of all mixes increases at 14 days compared to the 7-day results. The CC shows a significant improvement, reaching 2.4 MPa, but it is still outperformed by the FA mixes. FA20 continues to display the highest STS among all mixes, with a value of 3.3 MPa at 14 days. By 28 days, there is a further increase in STS for all mixes. CC reaches strength of 3.3 MPa, which is now comparable to some of the FA mixes. FA20 maintains its position as the mix with the highest split tensile strength, reaching 5.1 MPa.

3.4. Flexural strength test

FS in concrete specimens (prisms) characterizes the specimen's capacity to withstand bending stresses without fracturing or developing cracks. This attribute is particularly critical for concrete, especially in load-bearing elements such as beams. The concrete's capability to endure flexural stress is pivotal in preserving its structural integrity and aesthetic appeal over an extended lifespan [51]. Evaluating the FS of concrete involves standardized testing, often quantified in units of pounds per square inch (psi) or Newtons per square millimeter (N/mm^2). This testing procedure provides valuable insights into the concrete's ability to withstand applied loads and bending forces, ensuring its suitability for various construction applications requiring robust and resilient materials. Table 5 delves the testing values of the FS of MK and FA concrete.

In Figure 8 and 9, MK 12.5% (7days) displays the highest FS at 3.25 MPa. With an increasing percentage of MK, there is a consistent trend of rising FS. MK10 and MK12.5 exhibit notably higher strengths than the control mix during this early stage. MK12.5, achieving 3.25 MPa, holds the highest FS at 7 days. By the 14-day mark, there is a significant overall increase in FS for all mixes compared to the 7-day results. MK12.5 continues to showcase high strength, now at 7.5 MPa. The MK mixes maintain a positive trend of increasing FS, with MK12.5 reaching the highest value of 5.75 MPa at 14 days. At 28 days, there is a further enhancement in FS for all mixes. The CC reaches strength of 4.5 MPa, while the MK mixes continue to demonstrate improvement. MK12.5 retains its position as the mix with the highest FS, reaching 7.5 MPa.

At 7 days, the CC shows the highest FS with a value of 1.5 MPa. FA20 and FA25 have notably higher strengths than the control mix at this early stage. FA20, with 2.9 MPa, exhibits the highest FS at 7 days. The FS

Table 5: Flexural strength value of prism specimen.

MIX ID	SPLIT TENSILE STRENGTH (MPa)		
	7 DAYS	14 DAYS	28 DAYS
CC	1.5	2.25	3.50
MK5	1.5	3	3.80
MK7.5	1.75	4	3.98
MK10	2.75	4.75	4.35
MK12.5	3.25	5.75	4.45
MK15	2	4.75	4.25
FA5	1.4	2.6	4.8
FA10	1.5	3.8	5.1
FA15	2.4	4.3	6.5
FA20	2.9	5.3	7.3
FA25	2.5	4.5	6.8

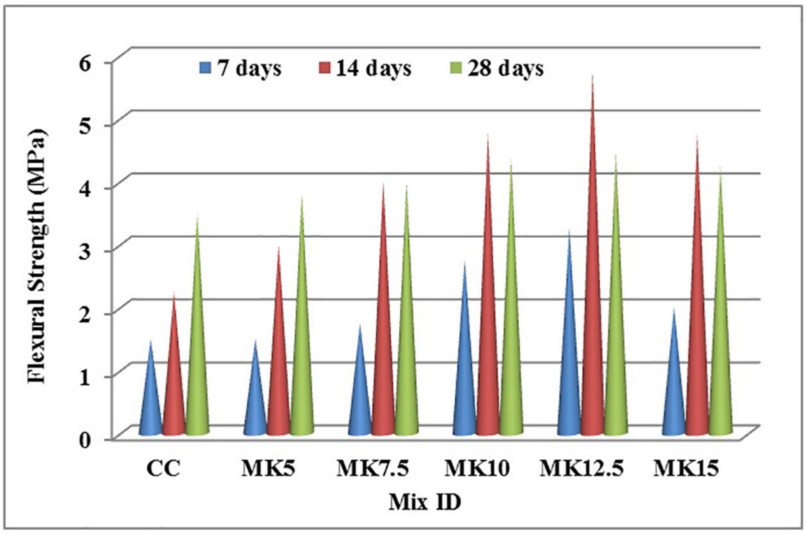


Figure 8: FS verses various mix proportions of MK concrete.

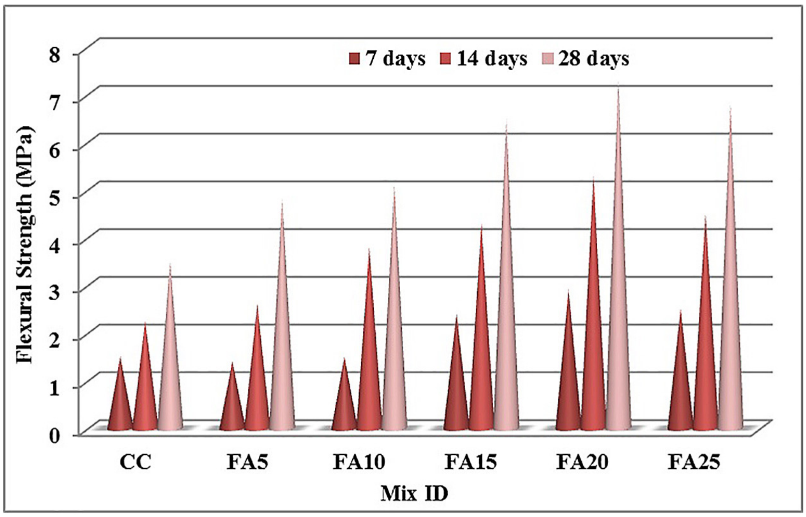


Figure 9: FS verses various mix proportions of FA concrete.

of all mixes significantly increases at 14 days compared to the 7-day results. The CC continues to demonstrate high strength, now at 2.0 MPa. The FA mixes continue to show a positive trend of increasing FS, with FA20 reaching the highest value of 5.3 MPa at 14 days. At 28 days, there is a further increase in FS for all mixes. The CC reaches strength of 4.0 MPa, while the FA mixes continue to improve. FA20 maintains its position as the mix with the highest FS, reaching 7.3 MPa.

3.5. Modulus of elasticity

MoE is calculated in both R-sand and M-sand mixes, and the MoE is calculated from the 15 mm diameter and 300 mm length cylinder specimens. The compresso and extenso meter are fixed on the cylinder and placed on CTM;load and deflections are noted from all samples, and the experimental test was conducted as per IS - 516: 1959 [53]. Figure 10, shows the CS and MoE of different types of concrete mixes. CS is the amount of pressure a material can withstand before crushing, while MoE is a measure of a material's stiffness.

The CS of the concrete mixes ranges from 28.5 MPa to 32.5 MPa. This range is typical for normal-strength concrete used in a variety of construction projects. The MoE of the concrete mixes ranges from 26.45 GPa to 31.52 GPa (Table 6). This range of stiffness values can influence the design of concrete structures. Stiffer concrete will deflect less under load, which can be important for tall buildings or structures that experience significant loads. The range of CS increased by 14.04% and the range of MoE increased by 19.17%. It seems to be a positive correlation between CS and MoE. In other words, concrete mixes with higher CS also tend to have a higher MoE. This is because the factors that contribute to a strong concrete mix, such as the quality of the ingredients and the curing process, also tend to contribute to a stiffer material.

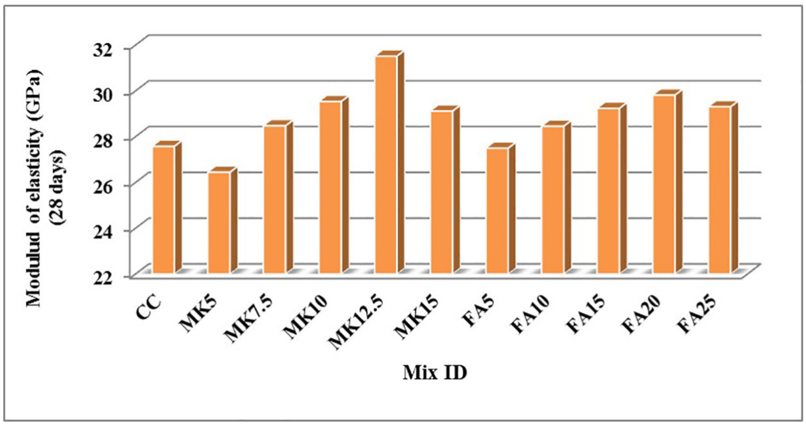


Figure 10: MoE versus various proportions of concrete using MK and FA.

Table 6: MoE of concrete using MK and FA.

MIX ID	MODULUS OF ELASTICITY (GPa)
CC	27.58
MK5	26.45
MK7.5	28.48
MK10	29.54
MK12.5	31.52
MK15	29.12
FA5	27.5
FA10	28.46
FA15	29.24
FA20	29.82
FA25	29.31

3.6. Overall summary

In summary of mechanical properties of all mix proportions, incorporating MK, especially at the 12.5% replacement level, resulted in the most significant improvements in all three mechanical properties (CS, STS, and FS) compared to the control mix. While FA did not outperform the control mix in CS, it still led to improvements in STS and FS, with FA20 showing the most promise. These findings suggest that MK and FA can be effective supplementary cementitious materials (SCMs) for enhancing the mechanical performance of concrete, with MK 12.5% offering the most optimal replacement level in this study. However, further research might be necessary to explore the long-term durability implications of using these SCMs in concrete. The Modulus of Elasticity (MoE) of the concrete mixes ranged from 26.45 GPa to 31.52 GPa, as measured in both R-sand and M-sand mixes (Table 6). This range falls within the typical values for MoE observed in normal-strength concrete commonly used in various construction projects.

3.7. Relationship between CS and STS

The study utilizes regression analysis on experimental data for STS and CS obtained from MK and FA concrete mixes. This analysis leads to the development of Equations (1) and (2) for predicting f_{sp} in MK and FA concretes, respectively. The high R-squared values (0.8081 for MK and 0.929 for FA) indicate a strong correlation between the predicted f_{sp} values from the equations and the observed experimental values. This suggests that Equations (1) and (2) provide robust models for estimating f_{sp} based on f_{ck} in these SCM concretes. Table 7 provides a comparison of f_{sp} values predicted by various established building codes. This comparison serves as a baseline for understanding how code provisions approach split tensile strength prediction in concrete (Figure 11). Table 4 presents a crucial comparison. Here, the experimentally measured f_{sp} values in MK and FA concrete are compared with predictions from Equations (1) and (2), alongside predictions from multiple building codes (refer to Table 8 for details). Notably, the results demonstrate that the f_{sp} values predicted by the regression equations (developed specifically for MK and FA concretes) exhibit closer agreement with the experimental data compared to code-based predictions. This suggests that Equations (1) and (2) offer a more accurate

Table 7: STS of concrete with MK and FA was estimated using the existing formulas.

TYPE OF CONCRETE	SPLIT TENSILE STRENGTH (f_{sp})
Plain cement concrete	$f_{sp} = 0.55 \times (f_{ck})^{0.5}$ [54]
	$f_{sp} = 0.301 \times (0.8 \times f_{ck})^{0.65}$ [55]
	$f_{sp} = 0.19 \times (f_{ck})^{0.75}$ [56]

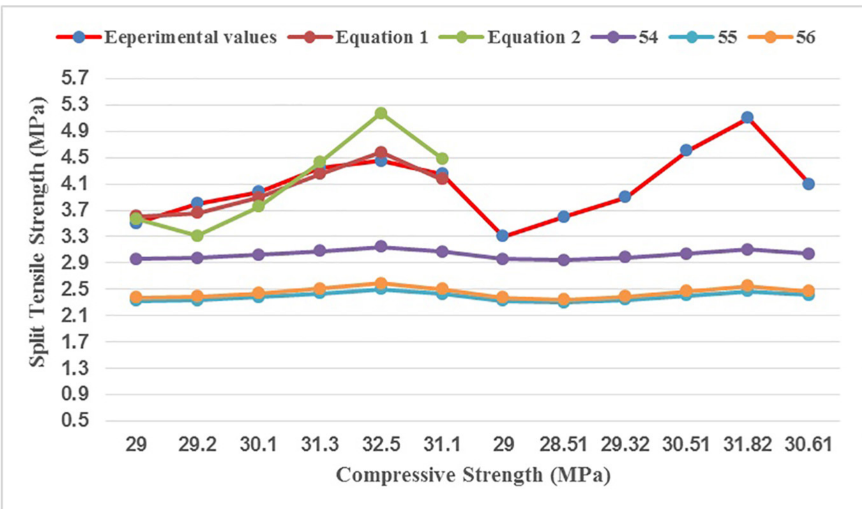


Figure 11: Exp. STS values of MK/FA concrete are compared to predictions from regression & design codes.

Table 8: Comparison of the experimental STS of concrete using MK and FA with regression equations and code practice formulas.

MIX ID	EXPERIMENTAL VALUES (MPa)		PREDICTED SPLIT TENSILE STRENGTH (MPa)				
	f_{ck}	f_{sp}	EQ.1	EQ.2	[54]	[55]	[56]
CC	29.00	3.50	3.61	–	2.96	2.32	2.37
MK5	29.20	3.80	3.66	–	2.97	2.33	2.39
MK7.5	30.10	3.98	3.89	–	3.02	2.38	2.44
MK10	31.30	4.35	4.25	–	3.08	2.44	2.51
MK12.5	32.50	4.45	4.58	–	3.14	2.50	2.59
MK15	31.10	4.25	4.17	–	3.07	2.43	2.50
CC	29.00	3.30	–	3.57	2.96	2.32	2.37
FA5	28.51	3.60	–	3.31	2.94	2.30	2.34
FA10	29.32	3.90	–	3.75	2.98	2.34	2.39
FA15	30.51	4.60	–	4.43	3.04	2.40	2.47
FA20	31.82	5.10	–	5.17	3.10	2.47	2.55
FA25	30.61	4.10	–	4.48	3.04	2.41	2.47

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

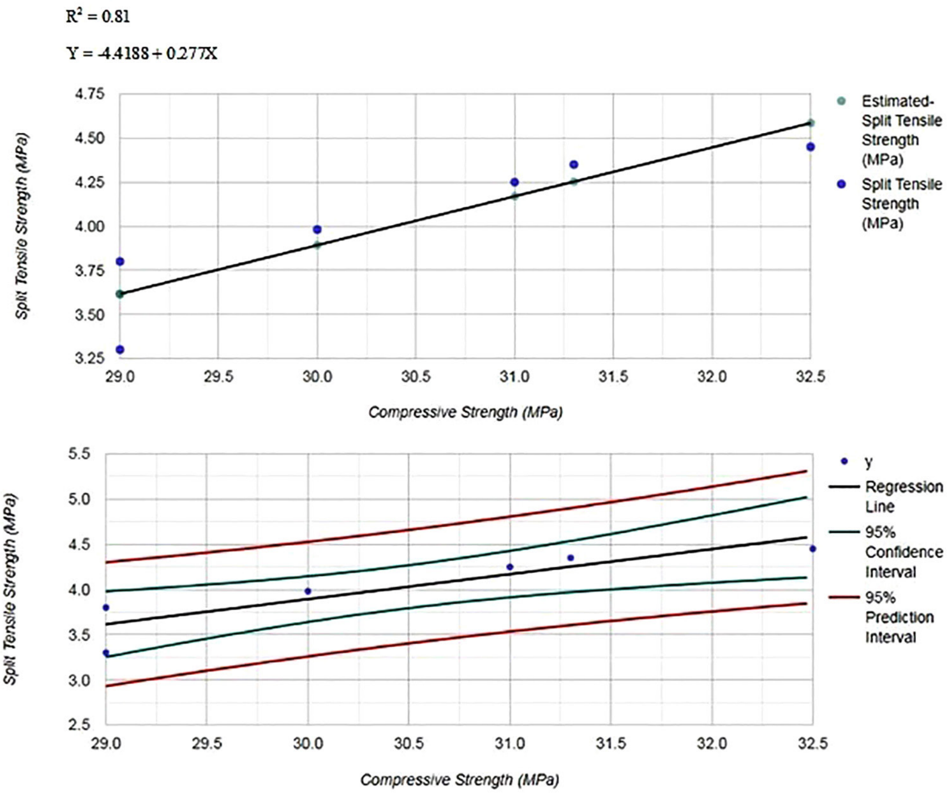


Figure 12: Relationship between CS and STS with mixes of MK.

estimation of f_{sp} in these SCM concretes. Figures 12 and 13 visually depict the relationship between f_{sp} and f_{ck} in MK and FA concretes based on the experimental data.

$$f_{sp} = 0.277\, f_{ck} - 4.4188 \text{ (MK)} \quad (1)$$

$$f_{sp} = 0.5697\, f_{ck} - 12.949 \text{ (FA)} \quad (2)$$

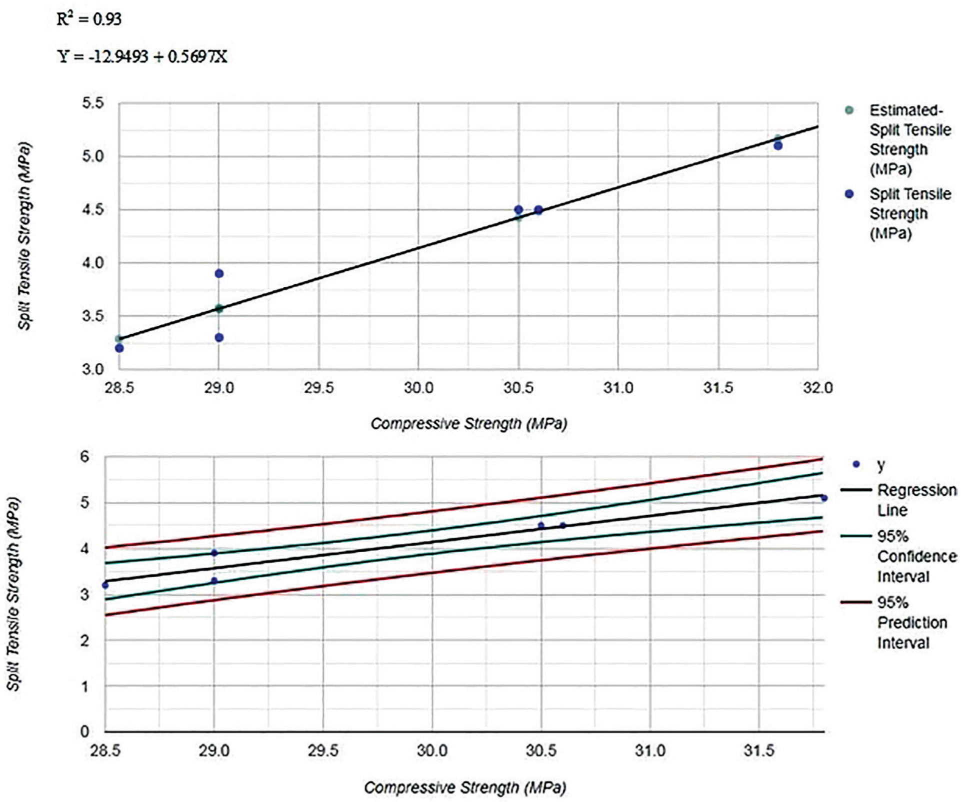


Figure 13: Relationship between CS and STS with mixes of FA.

Table 9: FS of concrete using MK and FA was estimated using the existing formulas.

TYPE OF CONCRETE	FLEXURAL STRENGTH
Plain cement concrete	$f_b = 0.62 \times (f_{ck})^{0.5}$ [54]
	$f_b = 0.81 \times (f_{ck})^{0.5}$ [57]
	$f_b = 0.70 \times (f_{ck})^{0.5}$ [58]

3.8. Relationship between CS and FS

The study compares experimental data for FS and CS in MK and FA concrete mixes. This data undergoes regression analysis, resulting in Equations (3) and (4) for MK and FA concrete, respectively. The high R-squared values (0.9203 for MK and 0.8542 for FA) indicate a strong correlation between the predicted f_b values from the equations and the observed experimental values. This suggests that Equations (3) and (4) provide robust models for estimating f_b based on f_{ck} in these SCM concretes. Table 9 provides a crucial comparison of 'f_b' values for plain cement concrete (without SCMs) with predictions from various building codes. This comparison serves as a baseline for understanding how code provisions handle FS prediction in traditional concrete. Table 10 presents a key comparison. Here, the experimentally measured f_b values in MK and FA concrete are compared with predictions from Equations (3) and (4), alongside predictions from multiple building codes (refer to Table 6 for details). Notably, the results demonstrate that the f_b values predicted by the regression equations (developed specifically for MK and FA concretes) exhibit closer agreement with the experimental data compared to code-based predictions (Figure 14). This suggests that Equations (3) and (4) offer a more accurate estimation of f_b in these SCM concretes. Figures 15 and 16 visually depict the relationship between f_b and f_{ck} in MK and FA concretes based on the experimental data.

$$f_b = 0.8633\ f_{ck} - 20.594\ (MK) \quad (3)$$

$$f_b = 0.9478\ f_{ck} - 22.588\ (FA) \quad (4)$$

3.9. Relationship between CS and MOE

The analysis leverages experimental data on MoE and CS obtained from concrete specimens incorporating MK and FA. This data is then subjected to regression analysis, resulting in Equations (5) and (6) for MK and FA concrete mixes, respectively. The high R-squared values (0.91 for Equation (5) and 0.893 for Equation (6)) indicate a strong correlation between the predicted and observed values of Ec. Table 11 presents a comparison between the E_c values predicted using Equations (5) and (6) with those obtained using established code provisions from the American Concrete Institute (ACI) and Indian Standard (IS) codes (refer to Table 12 for the experimental data).

$$E_c = 1.307\, f_{ck} - 10.311 \text{ (MK)} \tag{5}$$

$$E_c = 0.719\, f_{ck} + 7.145 \text{ (FA)} \tag{6}$$

The established relationships between E_c and f_{ck} in MK and FA concrete can be valuable for various engineering applications. These equations can be incorporated into structural analysis models to predict the behavior of concrete structures containing these SCMs.

Table 10: Comparison of the experimental FS of concrete using MK and FA with regression equations and code practice formulas.

MIX ID	EXPERIMENTAL VALUES (MPa)		PREDICTED FLEXURAL STRENGTH (MPa)				
	f_{ck}	f_b	EQ.3	EQ.4	[54]	[57]	[58]
CC	29.00	4.5	4.44	–	3.33	4.36	3.77
MK5	29.20	4.75	4.61	–	3.35	4.37	3.78
MK7.5	30.10	5.5	5.39	–	3.40	4.44	3.84
MK10	31.30	6	6.43	–	3.47	4.53	3.91
MK12.5	32.50	7.5	7.46	–	3.53	4.62	3.99
MK15	31.10	6.5	6.25	–	3.46	4.52	3.90
CC	29.00	4.5	–	4.89	3.34	4.36	3.77
FA5	28.51	4.8	–	4.43	3.31	4.32	3.73
FA10	29.32	5.1	–	5.20	3.36	4.38	3.79
FA15	30.51	6.5	–	6.33	3.42	4.47	3.87
FA20	31.82	7.3	–	7.57	3.50	4.57	3.95
FA25	30.61	6.8	–	6.42	3.43	4.48	3.87

f_{ck} – Compressive strength; f_b – Flexural strength.

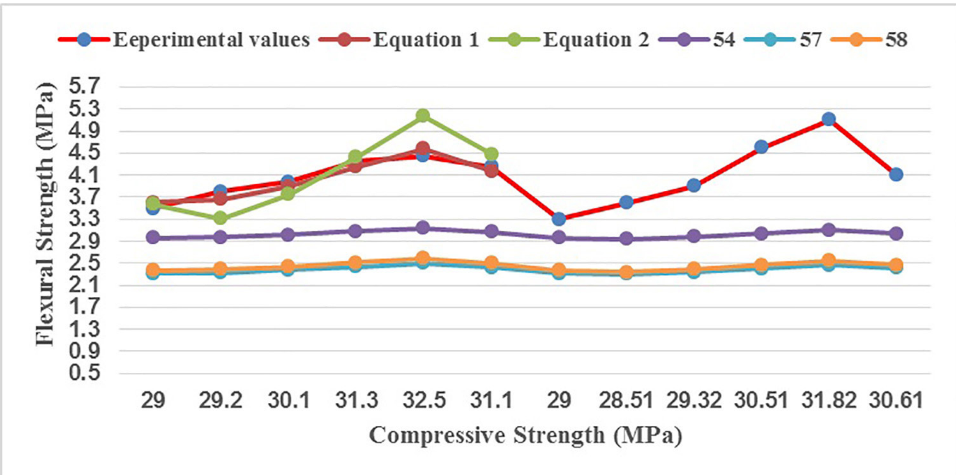


Figure 14: Exp. FS values of MK/FA concrete are compared to predictions from regression & design codes.

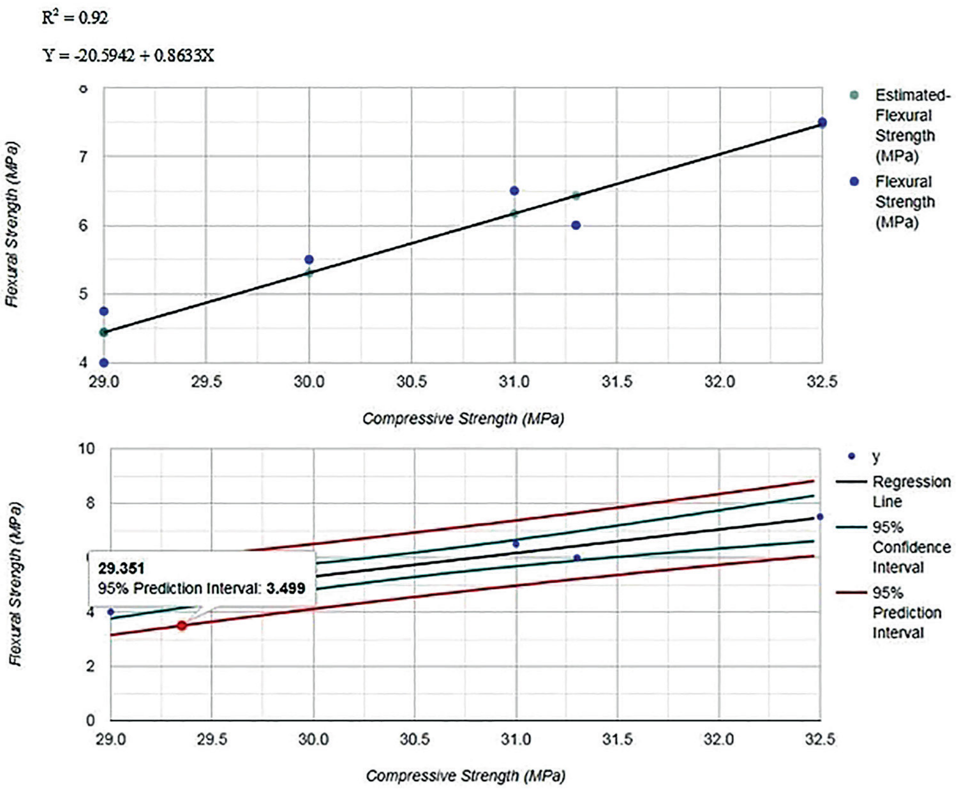


Figure 15: Relationship between CS and FS with mixes of MK.

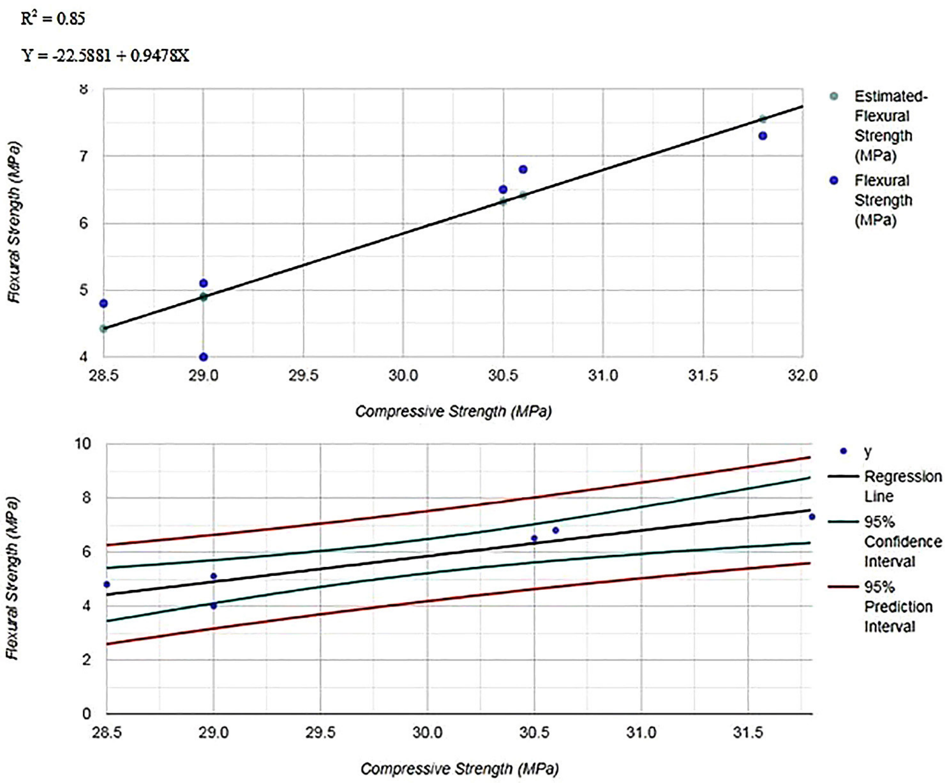


Figure 16: Relationship between CS and FS with mixes of FA.

The results demonstrate that Equations (5) and (6), derived from the experimental data, provide a closer match to the observed E_c values compared to the code-based predictions (Figure 17). This suggests that the developed equations may offer more accurate estimations for E_c in concrete containing MK and FA. Figures 18 and 19 visually depict the relationship between E_c and f_{ck} for both MK and FA concrete mixes based on the experimental data. These plots serve as valuable tools for understanding the trends and potential interactions between these two critical concrete properties.

Table 11: MoE of concrete using MK and FA was estimated using the existing formulas.

TYPE OF CONCRETE	MOE (GPa)
Plain cement concrete	$E_C = 4700 \times (f_{ck})^{0.5}$ [54]
	$E_C = 5000 \times (f_{ck})^{0.5}$ [58]

Table 12: Comparison between the experimental MoE of polymer concrete values with regression equations and code practice formulas.

MIX ID	EXPERIMENTAL VALUES (MPa)		PREDICTED MODULUS OF ELASTICITY (GPa)			
	f_{ck}	E_c	EQ.5	EQ.6	[54]	[58]
CC	29.00	27.58	27.59	–	25.31	26.92
MK5	29.20	26.45	27.85	–	25.39	27.02
MK7.5	30.10	28.48	29.02	–	25.79	27.43
MK10	31.30	29.54	30.59	–	26.29	27.97
MK12.5	32.50	31.52	32.17	–	26.79	28.50
MK15	31.10	29.12	30.33	–	26.21	27.88
CC	29.00	27.50	–	27.99	25.31	26.92
FA5	28.51	28.46	–	27.64	25.10	26.69
FA10	29.32	29.24	–	28.22	25.44	27.07
FA15	30.51	29.82	–	29.08	25.96	27.62
FA20	31.82	29.31	–	30.02	26.51	28.20
FA25	30.61	27.58	–	29.15	26.00	27.66

f_{ck} – Compressive strength; E_c – Modulus of elasticity.

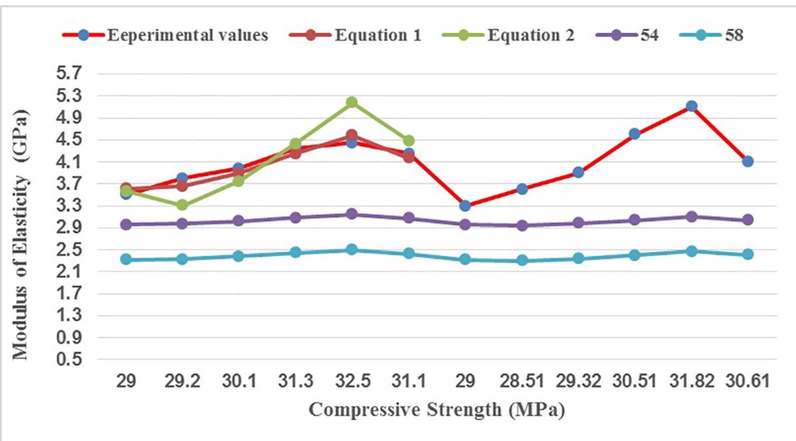


Figure 17: Exp. MoE values of MK/FA concrete are compared to predictions from regression & design codes.

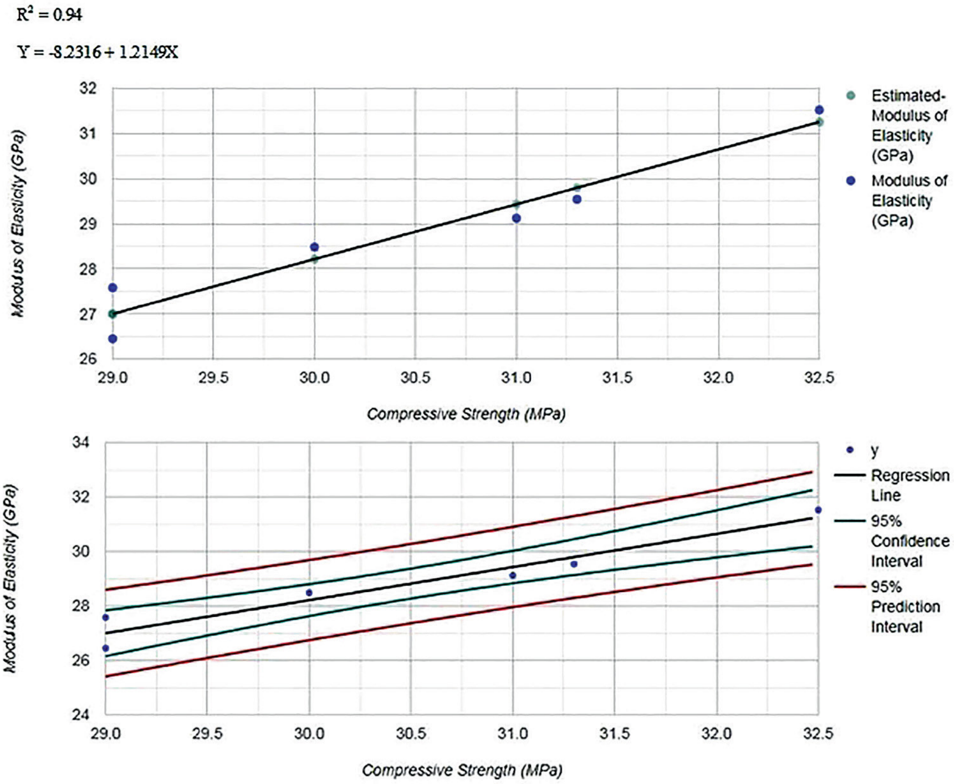


Figure 18: Relationship between CS and MoE with mixes of MK.

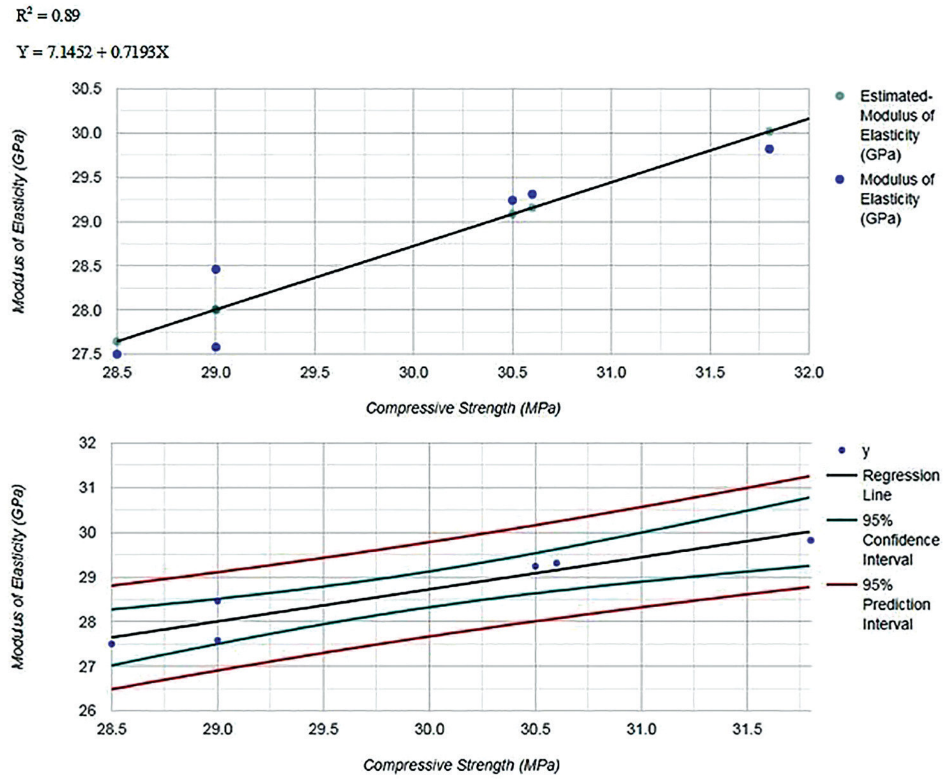


Figure 19: Relationship between CS and MoE with mixes of FA.

4. CONCLUSION

This study examined the impact of using FA and MK as partial replacements for cement in concrete, focusing on their effects on mechanical properties Notably, concrete mixtures containing MK exhibited superior strength properties compared to those with FA mixes concrete. According to the test results, the following conclusions were drawn:

1. At 7 days, partial cement replacement with MK yielded the highest compressive strength (CS) of 19.5 MPa for the MK12.5 mix (12.5% replacement level). Conversely, FA replacements exhibited a slight decrease in CS compared to the control mix at this early curing age. However, by 28 days, FA mixtures surpassed the control, with FA20 (20% replacement) demonstrating the most notable improvement (30 MPa CS). Notably, MK12.5 remained the strongest mix throughout the testing period, reaching a CS of 32.5 MPa at 28 days.
2. MK replacements consistently exhibited superior split tensile strength (STS) compared to both FA replacements and the control mix across all curing periods. Notably, the MK12.5 mix (12.5% replacement) achieved the highest STS values throughout the testing program, reaching 2.389 MPa at 7 days, 3.504 MPa at 14 days, and 4.450 MPa at 28 days. Among the FA mixtures, FA20 (20% replacement) demonstrated the best performance in terms of STS.
3. Both MK and FA replacements increased FS compared to the control mix. MK12.5 again demonstrated the highest strength at all stages (7 days: 3.25 MPa, 14 days: 7.5 MPa, 28 days: 7.5 MPa). FA20 showed the best performance among FA mixes.
4. Concrete mixtures containing both optimal MK and FA replacements demonstrated a significant improvement in their modulus of elasticity (MoE) by 19.17% compared to the control mix.
5. Regression analysis also studied the strength properties of MK and FA mixes concrete. The existing formulas and regression equations correlate better than the experimental test results.

MK-based concrete might have a marginally stronger relationship with density based on the R-squared values, but the negligible early-age strength improvement at 7 days with MK12.5 may not justify its potentially higher cost compared to FA. FA presents itself as the more favorable alternative for achieving long-term strength and cost-effectiveness. Research indicates that FA replacement levels of 20% can yield comparable long-term strength characteristics to MK, while potentially offering greater economic benefits.

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