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Strength Characteristics and Rheological Behavior of a High Level of Fly Ash in the Production of Concrete

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ABSTRACT: This study investigates the valorization of coal fly ash (FA-C) generated by the Jerada thermal power plant, aiming to address the pressing need for sustainable construction practices and reduced greenhouse gas emissions in the concrete industry. It is widely used as a pozzolanic material. The key objective is to harness the potential of FA-C as a supplementary material in concrete production, which not only reduces costs but also contributes to environmental sustainability. To achieve this objective, various concrete mixtures were formulated, with FA-C serving as a partial substitute for cement at percentages ranging from 15 to 50%. According to ASTM standards, compressive strength tests were conducted on standard-sized cylinders at 7 and 28 days. The results revealed that the blend containing 15% FA-C exhibited the highest compressive strength, indicating its effectiveness as a concrete additive. Furthermore, this study delves into the rheological properties of concrete mixes, an essential aspect of successful concrete processing. It was observed that a higher replacement level of FA-C significantly improved the rheology, leading to reduced water demand and a linear decrease in plastic viscosity over time. The rheological parameters stabilized after a certain period, demonstrating the controllability of concrete flow behavior with FA-C. The investigation also employed three analytical methods—Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM)—to comprehensively analyze both raw materials and processed samples. FTIR analysis highlighted the minimal impact of FA particles on hydration product formation, emphasizing the role of FA-C in enhancing the concrete's strength. XRD analysis confirmed the presence of an amorphous phase crucial for FA's reactivity. SEM observations revealed that concrete with 15% FA-C exhibited a more uniform microstructure with aluminosilicate gel, while 50% FA-C mixes showed increased porosity and nonhomogeneity due to unreacted FA particles.

1. INTRODUCTION

Many studies have demonstrated the importance of using leftover coal as a new material for concrete production. Sustainable development has become a subject of the modern world.[1] Everyday life has witnessed the progress of this process. In this vein, global electricity demand is expected to grow by 5% in 2021 and 4% in 2022, as per the International Energy Agency (IEA). In 2022, it is expected to grow by 3% and may reach a new record high.[2] The growth of CO_2 emissions plays a crucial role in coal production. In this regard, the demand for coal is anticipated to increase by 60% by 2021, resulting in a 5% increase in global CO_2 emissions. The cement industry is the third-largest industrial energy consumer and source of 8% of global CO_2 emissions.[3]

To avoid these greenhouse gas emissions, which are involved in global warming and climate change, the concrete construction industry is not sustainable as it uses many virgin materials. In addition, cement is a main component of concrete.[4] More importantly, the consequence of finding solutions is a key to energy efficiency and the transition to an economical process (from a wet process to a dry process with a preheater and precalciner); the substitution of fuel and the application of a lower clinker/cement led to an increase of blended cement production and the elimination of CO_2 from flue gases.[5] The cementing material fly ash (FA) is considered a supplement product, and its use is highly recommended nowadays. However, it is still rare to be involved in masonry works as a partial replacement for cement; therefore, it is often

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difficult to find the desired mortar properties without altering the fresh or cured state like initial strength.

FA is a pozzolanic material; the term pozzolanic refers to the materials exposed to lime and water that form an insoluble cementitious compound despite having less or no cementing action when they occur alone.[6] In addition, the particles are spherical and amorphous, with a particle size of less than 50 μm. Generally, two FA classes are associated with all elements, Si, Fe, and Al. If the element's total content is 50% or more, it is class C; if it is 70% or more, it is class F.[7] The usage of coal FA in concrete production is of utmost importance for promoting sustainable growth and reducing greenhouse gas emissions.[8] This coal combustion byproduct provides a sustainable option by recycling industrial waste, lessening the reliance on limited natural resources, and reducing the carbon footprint of concrete production. The building sector supports international efforts to mitigate climate change while possibly obtaining cost savings by partially substituting cement with FA. FA utilization can also increase concrete's durability, comply with strict environmental requirements, and progress technology.[9,10] Their advantages, which are shown and studied by many scientists, include low cost, higher compressive strength, best rheological behavior, and durability.[11−13]

This paper aims to study the physical and chemical characteristics and rheological behavior of a high-volume FA (HVFA) of class F. To facilitate this investigation, raw and synthesized materials were analyzed by using analytical techniques including Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM).

This study's findings emphasize how important it is to use coal FA as an alternative material for making concrete. A more environmentally conscious and sustainable concrete construction sector can be achieved by strongly emphasizing sustainable development and lowering greenhouse gas emissions.

2. MATERIALS AND METHODS

2.1. Materials. The raw materials used in this study for concrete production include the following.

2.1.1. Cement. The Portland CP cement used in this investigation, namely, CEM I 52.5, was purchased from the Lafarge Holcim cement plant in OUJDA. It is characterized by a specific gravity (ρc) of 3.15.[14] The primary binding component of concrete, Portland cement, is essential to the final product's strength and durability.

2.1.2. Fine Aggregate. Natural sand and gravel, known as fine aggregate, are essential for producing concrete and considerably impact its mechanical qualities. It affects mixture proportion, water consumption, workability, strength, and durability. For concrete to perform as expected, fine aggregate selection and properties are essential.[15]

2.1.3. Coarse Aggregates. Coarse aggregates, obtained from quarries or riverbeds, exhibit diverse characteristics in size, shape, and properties.[16] In this study, they meet the IS 383-1970 standards and can pass through a 12.5/20 mm sieve. These aggregates are essential in concrete for providing bulk, stability, and an interlocking matrix that enhances the mechanical strength. They help control shrinkage, affect workability, and improve the concrete's appearance. Careful selection of coarse aggregates is vital for achieving the desired concrete performance and aesthetics. The sand that was utilized in the mixtures had a 0.5 mm tail. Table 1 provides a list of the characteristics of both fine and coarse aggregates.

Table 1. Physical Properties of Aggregates according to ASTM C33-18[17]

property	coarse aggregate (gravel)	fine aggregate (sand)
bulk specific gravity	2.42	2.63
apparent specific gravity	2.40	2.72
dense dry density (kg/m^3)	1632	1870
loose dry density (kg/m^3)	1452	1720
sulfate content (%)	0.02	0.23
absorption (%)	0.85	1.61

2.1.4. Fly Ash. Understanding the specific properties of fly ash class C (FA-C) from Morocco's Jerada thermal power plant is crucial for its effective use as a supplementary material in concrete production. These characteristics include chemical composition, particle size distribution, reactivity, and consistency. Due to its chemical composition and tiny particle size, FA-C has pozzolanic qualities that help create long-lasting and sustainable concrete. The best concrete performance, including strength and durability, is ensured by evaluating its reactivity. By lowering the need for energy-consuming Portland cement, adequate characterization promotes quality control and benefits the environment.[18] The chemical composition of this material is shown in Table 2.

2.2. Spectroscopic Analysis. The SEM analysis was performed on an FEI Quanta 450 FEG focused ion beam system of the Moroccan Foundation for Advanced Science, Innovation, and Research (Mascir). Using a fluorescence X-ray method, the chemical composition of both synthetic and raw components was identified. The mineralogical phases were determined using an Expert Pro diffractometer with Cu-K1 radiation (λ = 1.54056 Å) at angles between 10 and 70° with 0.02° increments. The XRD pattern of FA is shown in Figure 1. The FTIR analysis was performed on a VERTEX 70 instrument using 8 scans for each sample in MIR transmission mode, and the results were shown between 4000 and 400 cm^{-1}.

2.3. Methods. The concrete mixtures were prepared by mixing FA powder with different percentages of cement, aggregates, and sand by using a laboratory electric mixer at high speed after performing a sizing analysis of the aggregates, including sizes G1 (6.3/16 mm) and G2 (12.5/20 mm). Meanwhile, we prepare our cylinder of 15 *30 cm^3 by pouring a little oil into it before pouring the mixture into the cylinders, and we first determine the consistency of the concrete to pass through the ABRAMS cone to know the vibration tool. Fifteen samples were made. All of the specimens were stored at a temperature of about 21 °C in a casting room, as shown in Figure 2. They were demolded after 24 h, and then we can measure the compressive strength and quality of the produced concrete as a function of the different volumes of FA added. We can see the changes in 7 and 28 days. The mixed proportions of specimens are given in Table 3.

2.4. Rheology Measurements. In our study, we focused on measuring two key rheological parameters, yield stress and plastic viscosity, while examining different cement−fly ash ratios. We conducted tests on five different mixes, including one mix without FA and varying levels of FA replacement (20,

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Table 2. Chemical Composition of FA-C (%)

constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	TiO_2	SO_3	P_2O_5
% (by weight)	48.03	24.63	4.25	9.8	2.08	2.3	2.05	2.66	0.13

SO_3	ZrO_2	BaO	SrO
1.18	0.17	0.29	0.34

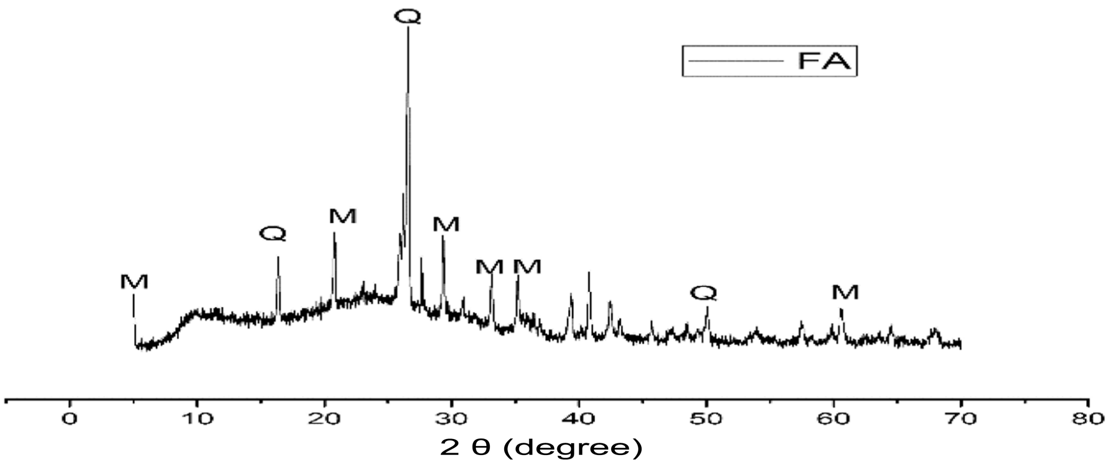

Figure 1. XRD patterns of FA (Q: quartz; M: mullite).

Figure 2. Green concrete.

Table 3. Typical Mix Proportion Volume of FA-C % for Different Strength Tests

FA-C %	0	15	20	25	50
	Mix Proportions kg/m^3				
water	3.6	3.2	2.88	2.85	2.42
fine aggregate	9.18	9.18	9.18	9.18	9.18
course aggregate	14.1	14.1	14.1	14.1	14.1
sand	15.3	15.3	15.3	15.3	15.3
cement	6.44	5.474	5.152	4.83	4.3
fly ash	0	0.966	1.288	1.61	1.932

30, 40, and 50%). All mixtures had a consistent water-to-cementitious materials ratio of 0.3.

2.4.1. Plastic Viscosity. To measure plastic viscosity, we used a rotational viscometer, which determines a fluid's absolute viscosity. This device involves a rotating spindle immersed in a test fluid. The torque applied to the rotating shaft helps us gauge the fluid's resistance to flow. Unlike methods involving gravity, this measurement relies on the fluid's internal shear stress to calculate its absolute viscosity.[19]

2.4.2. Yield Stress. In this study, yield stress is a crucial rheological parameter investigated by using a rotational viscometer. It represents the minimum shear stress needed for a fluid to transition from a solid-like state to a fluid-like state. Understanding yield stress is essential for materials like concrete and pastes as it informs their behavior during mixing and placement in construction.[20]

This study examined how yield stress varied with different cement/FA ratios, providing insights into the impact of FA as a supplementary material. Mathematical models such as the Bingham model describe this relationship, helping predict material behavior under different conditions. Yield stress data aid in optimizing mix designs for construction applications, ensuring efficient processing and placement.

There are several models used to describe the rheological behavior of the fluids. In the context of our study: Herschel—Bulkley model: this model describes fluids that exhibit nonlinear behavior in flow curves. It characterizes viscosity as a power-law function of the shear rate.

Bingham model: this model is useful for fluids that behave somewhat like Newtonian fluids but have a critical yield stress (τ_0) before they start flowing. The fluid's shear stress increases linearly with the rising shear rate (τ_0), is equivalent to the yield stress, and is determined by the shear rate (γ) and the shear stress, as shown in eq 1

$$\tau = \tau_0 + \eta_p \gamma \tag{1}$$

where τ represents the shear stress, η_p denotes the plastic viscosity, τ_0 denotes the yield stress, and γ signifies the shear rate.

Understanding this mathematical relationship helps in predicting how the material will behave under various conditions.

In conclusion, we measured plastic viscosity using a rotational viscometer and employed mathematical models such as the Herschel—Bulkley and Bingham models to understand and describe the flow behavior of the tested fluids.

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Table 4. Changes in the Compressive Strength of Concrete with Different FA-C Contents at 7 and 28 Days

FA %	15			20			25			30			50		
	Compressive Strength (MPa)														
7 days	11.22	10.74	11.56	8.3	7.21	7.74	7.1	6.8	6.31	5.8	5.98	4.09	3.02	3.2	3.49
28 days	13.03	12.8	18.33	11.25	11.94	11.71	11.04	10.73	9.12	8.36	8.9	8.15	4.83	5.5	5.43

The Bingham model is particularly useful for fluids that exhibit yield stress before flowing under increased shear stress.

3. RESULTS AND DISCUSSION

3.1. Mechanical Properties. *3.1.1. Compressive Strength Measurements.* The results presented in Table 4 and Figure 3 show the mechanical performance of the prepared concrete mixes at both 7 and 28 days of curing. Notably, the mixes containing 15% FA-C demonstrated higher compressive strength values at the 28 day mark compared to the 7 day results, with the best-performing formulation achieving 18.33 MPa. This increase in compressive strength can be attributed to the pozzolanic action of FA. The enhanced strength can further be explained by the higher content of amorphous silica present in FA. This silica reacts with the hydration product (calcium hydroxide, CH) from Portland cement to form a dense matrix of secondary strength-enhancing compounds, such as calcium−silicate−hydrate (C−S−H) and calcium−aluminate−hydrate (C−A−H). This gel-like matrix contributes significantly to the overall compressive strength of the concrete, explaining the observed increase.

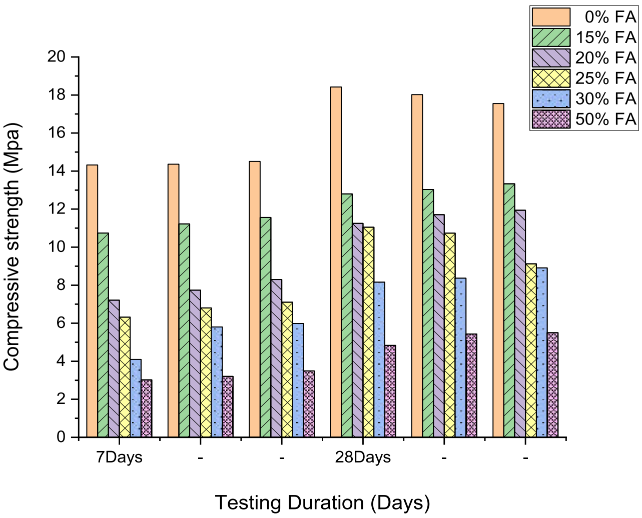

Figure 3. Strength development of concrete containing the amount of FA-C.

It is important to note that while the addition of HVFA did not lead to a significant improvement in strength, it did result in a reduction in the water−cement ratio,[21] as previously indicated in Table 4.

This reduction in the water−cement ratio can have multiple effects on concrete performance. The impact of FA-C on concrete's compressive strength can be attributed to several factors, including the pozzolanic reaction, where FA reacts with lime and moisture to form cementitious products, as well as its influence on water demand and its capacity to act as a water-reducing admixture.

This study's results indicate that the inclusion of 15% FA-C in the concrete mixture significantly improved compressive strength at 28 days, primarily due to pozzolanic reactions and the formation of a dense, strength-enhancing matrix. The addition of HVFA reduced the water/cement ratio, affecting concrete performance in various ways, including water demand and water-reducing capacity.

3.1.2. Density. The density of our samples was calculated by measuring the dimension and the mass of the samples according to Archimedes' principle, as shown in Figure 4.

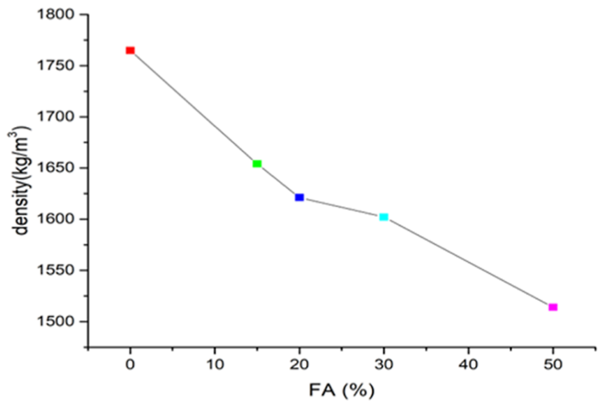

Figure 4. Density variation according to FA %.

The variation in density observed in this study, particularly with the addition of different levels of FA (FA %), can be explained as follows: we observe a reduction of density due to the incorporation of HVFA. It can be attributed to a higher specific gravity of FA with a higher incorporation.[18]

Specific gravity is a measure of the density of a substance relative to the density of water. Since FA particles tend to be denser than water, their inclusion in the concrete mixture contributes to a reduction in the overall density of the samples.

The specimen without FA is denser than that of the authors, likely due to CP's higher specific gravity than that of the FA.

In conclusion, the observed variation in density is a consequence of the interplay between the specific gravity of the materials used in the concrete mix. Adding HVFA, with its lower specific gravity, reduces the overall density of the samples. Conversely, the concrete tends to be denser when CP is the primary binding agent due to its higher specific gravity. This information is valuable for understanding the material properties and behavior of concrete mixes with different FA percentages.

3.2. Rheological Properties: Impact of the FA-C Percentage on Apparent Viscosity and Yield Stress. The rheological characteristics of cementitious materials are crucial to optimizing their performance in construction applications. This section provides an in-depth analysis of the rheological properties of cementitious mixtures with varying percentages of FA-C. Figures 5−8, along with Table 5, offer insights into the mixtures' viscosity, shear time, yield stress, and plastic viscosity.

3.2.1. Apparent Viscosity and Solid Concentration. This study delves into the rheological properties of cementitious

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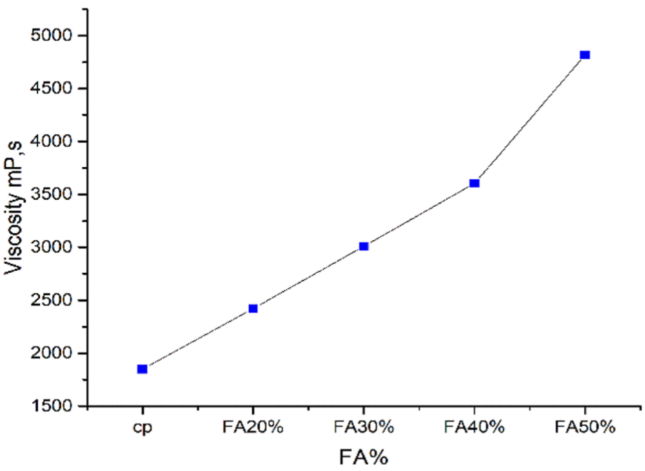

Figure 5. Viscosity development of pastes containing the amount of FA-C %.

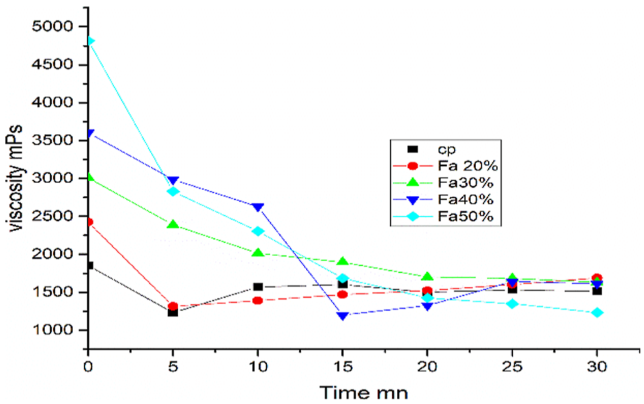

Figure 6. Plastic viscosity as a function of time of pastes with different amounts of FA-C %.

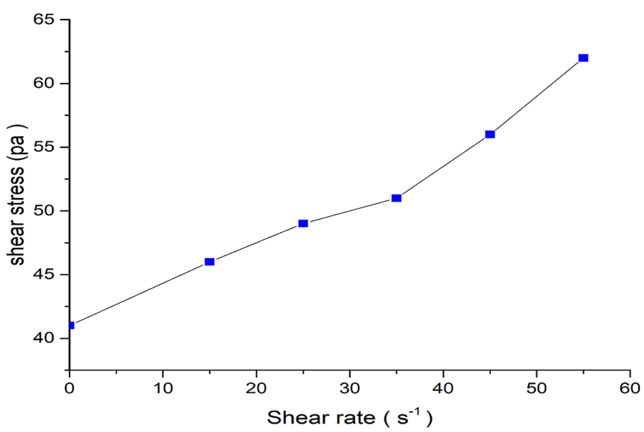

Figure 7. Shear stress vs shear rate of the sample with FA.

materials, specifically focusing on the influence of varying percentages of FA-C. Figure 5 depicts the apparent viscosity of mixtures with different FA-C percentages, revealing a substantial increase in viscosity when 50% FA-C is added compared to that of traditional cement paste (CP) and other FA-C ratios.

The heightened viscosity suggests improved rheological behavior, indicating that higher levels of FA-C replacement significantly impact the mixture's flow characteristics. Importantly, this viscosity enhancement correlates with reduced water demand, which is a crucial factor in concrete production. This reduction in water demand can lead to enhanced workability and a lowered risk of segregation during construction.[22]

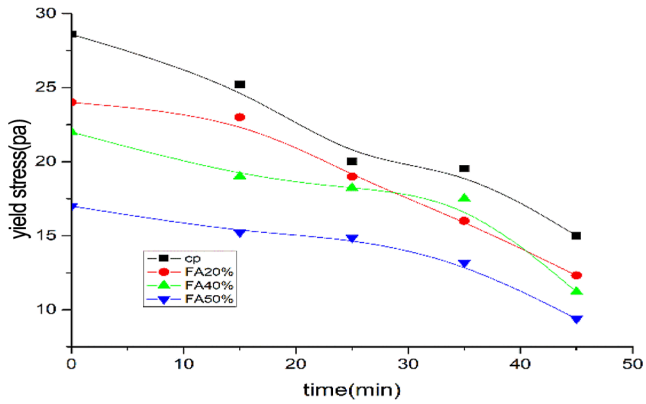

Figure 8. Yield stress of pastes with different amounts of FA.

Table 5. Plastic Viscosity and Yield Stress with Different FA Mixtures

mixes	yield stress (Pa)	plastic viscosity (Pa·s)
FA 0%	37.5	0.21
FA 20%	22.9	0.31
FA 40%	2.84	0.27
FA 50%	1.06	0.061

3.2.2. Shear Time and Long-Term Viscosity. Figure 6 delves into the plastic viscosity of pastes over time, revealing that a higher percentage of FA-C leads to an extended increase in shear time. This finding is crucial for understanding the rheological behavior of the concrete mixture during construction.

The prolonged increase in shear time indicates that FA-C plays a role in modifying the viscosity of the mixture over time. This characteristic can significantly influence the ease of handling and placement during construction activities, emphasizing the practical benefits of using FA-C in concrete mixes.[23]

3.2.3. Yield Stress and Plastic Viscosity. Table 5 provides a comprehensive overview of yield stress and plastic viscosity with different FA-C mixtures. The data clearly show a significant reduction in yield stress as the percentage of FA-C increases. This reduction is attributed to the proportional decrease in the density of the cement particles in the mixture. It is important to note that this behavior is not strictly linear, suggesting nuanced interactions within the mixture.

3.2.4. Shear Rate−Shear Stress Relationship. Figure 7 explores the shear stress versus shear rate relationship, visually reinforcing the consistent trend observed in Table 5, showcasing a decrease in yield stress with an increase in the FA-C content.

The observed reduction in yield stress aligns with the general understanding of how FA affects the rheology of cementitious materials. As the amount of FA-C increases, the lubricating effect of high-calcium FA becomes more prominent, reducing the resistance to deformation. This behavior is consistent with the mitigation of volume expansion due to the alkali−silica reaction, a common issue in concrete, attributed to the alkalinity reduction caused by low-calcium FA.[24]

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3.2.5. Yield Stress Variation. Figure 8 and Table 5 collectively confirm a consistent reduction in yield stress as the percentage of FA-C in the mix increases. The specific properties of FA, such as its low calcium content, play a significant role in these observed effects.

The behavior observed is characteristic of low-calcium FA, which is known for effectively reducing the alkalinity of porous solutions. This reduction plays a crucial role in mitigating volume expansion due to the alkali−silica reaction in concrete.[25]

The observed changes in yield stress and viscosity emphasize the profound impact of the composition and nature of materials on the rheological behavior of cementitious mixtures. Specifically, the low calcium content of FA-C plays a significant role in these effects, influencing the overall rheology.

In conclusion, both Table 5 and Figure 7 affirm a consistent reduction in yield stress with the inclusion of FA-C, which is primarily attributed to the proportional decrease in the density of cement particles. These findings highlight the crucial role of FA-C in optimizing the rheological properties of concrete mixtures, providing valuable insights for construction applications.[26]

3.3. Material Characterization. This section will present and discuss the characterization of raw materials and concrete-based FA samples that are the lowest and optimal in terms of compressive strength, bulk density, and rheology.

3.3.1. FTIR Spectroscopy Analysis. FTIR spectroscopy was employed as a vibrational technique to examine the functional groups and characterize the raw materials. Figure 9 displays the infrared spectra of both the raw and synthesized materials, revealing the presence of various bands in different regions.

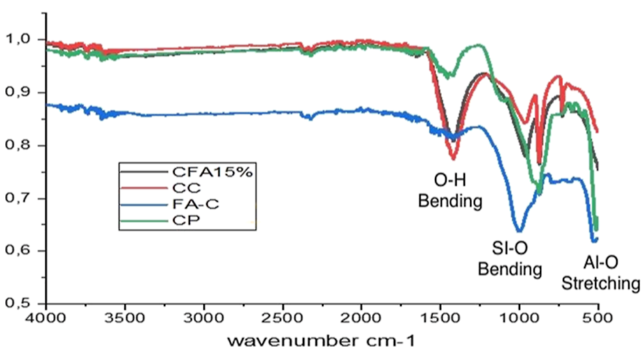

Figure 9. FTIR spectra of CFA15%, FA-C, CC, and CP.

The 4000−3500 cm^{-1} band region corresponds to portlandite $Ca(OH)_2$, and 3500−1600 cm^{-1} is related to the bond stretching of (−OH) and of FA-C at various times.

Vibrational bending (H−O−H) at 1600 cm^{-1} indicates the presence of a 1000 cm^{-1} typical Si−O−Si bond of quartz.[19] In addition, the $CaCO_3$ gel was confirmed by the detection of bands between 1000 and 800 cm^{-1}, whereas the range of 800−500 cm^{-1} is attributed to symmetric stretching of Si−O−Si and Al−O−Si bonds. The last band below 500 cm^{-1} indicates the bending vibrations of Si−O−Si and O−Si−O bonds.[27]

Comparing the FTIR spectra between the four samples, the intensities and the wavenumber of bands observed in the region 3700−1600 cm^{-1} are the same. However, the bands in the region 1600−500 cm^{-1} are substantially different. Appearing peaks in the regions 3660 to 3340 and 2390 to 2350 cm^{-1} in all the samples show the presence of the stretching and deformation vibration of OH and H−O−H groups, respectively, from the weakly bound water molecules;[28] the attributions of the detected bands are reported in Table 6.

Table 6. Attributions of the FTIR Bands

	FA-C	CP	CFA15%	CC
Si−O−Si bending vibration	472	462	404	455
Si−O−Al bending vibration		510		
Si−O−M (M = Al or Si) bending vibration	783	663	727	715
Si−O−M (M = Al or Si) bending vibration	1436	1422	960	960
O−C−O bending vibration	1427	1424	1434	1430
OH and HOH bending vibration	2359	2323	2331	2390
OH bending vibration	3342	3627	3627	3652

The FA-C and CP spectra displayed a peak intensity band at 1436 cm^{-1} assigned to the asymmetric stretching of Si−O−M (M = Si or Al). All samples showed the presence of tetrahedron [SiO_4], confirmed by the band detected at around 472 cm^{-1} and assigned to the bending vibrations of Si−O−Si. The bands at 788 and 663 cm^{-1} are characteristic of symmetric Al−O bending vibration.[29]

All four samples showed a peak at around 1427 cm^{-1}, which belongs to O−C−O carbonates (CaCO3).[30] The peaks observed at 404 and 455 cm^{-1} are assigned to the bending vibrations of Si−O−Si in the tetrahedron [SiO_4]. On the other hand, the bands detected at 727 and 960 cm^{-1} correspond to the symmetric stretching and bending vibrations of Si−O−M (M = Al or Si).[31] Comparing the spectra of the synthesized materials and raw materials, several new bands can be observed, indicating the transformation of their structures.

Finally, based on the observations from FTIR analysis, it can be concluded that the presence of FA (FA particles) has a minimal effect on the formation of hydration products during the concrete mixing process. In concrete, calcium silicate hydrate (CSH) and lime are typically formed when the cement reacts with water. These hydrated silicates contribute to the strength of the concrete, and lime helps to fill voids. Properly selected FA, such as FA-C, can react with lime to form CSH, which is the same cement product found in traditional Portland cement (CP). This reaction between FA-C and lime in concrete ultimately enhances the concrete's strength.[32]

The FTIR analysis provides valuable insights into the chemical composition and structural changes occurring in the materials, helping to understand their behavior and interactions during the concrete production process.

3.3.23.3.2. X-ray Diffraction. The XRD patterns of two important samples synthesized are displayed in Figure 10.

The XRD results revealed a characteristic broad hump in the sample diffraction pattern, which is indicative of the presence of an amorphous phase within the range of 18−40° (2θ). This amorphous phase, primarily composed of aluminum and silicon (Al−Si), holds significant importance in influencing the reactivity of FA and plays a pivotal role in its subsequent application as a pozzolanic additive in construction materials.[33]

The pozzolanic properties of FA stem from its ability to react with portlandite ($Ca(OH)_2$), a hydration product of Portland cement (CP). This pozzolanic reaction results in the formation of calcium silicate hydrate (C−S−H) and calcium aluminate silicate hydrate (C−A−S−H). Additionally, the presence of quartz in the sample with 15 and 50% FA content

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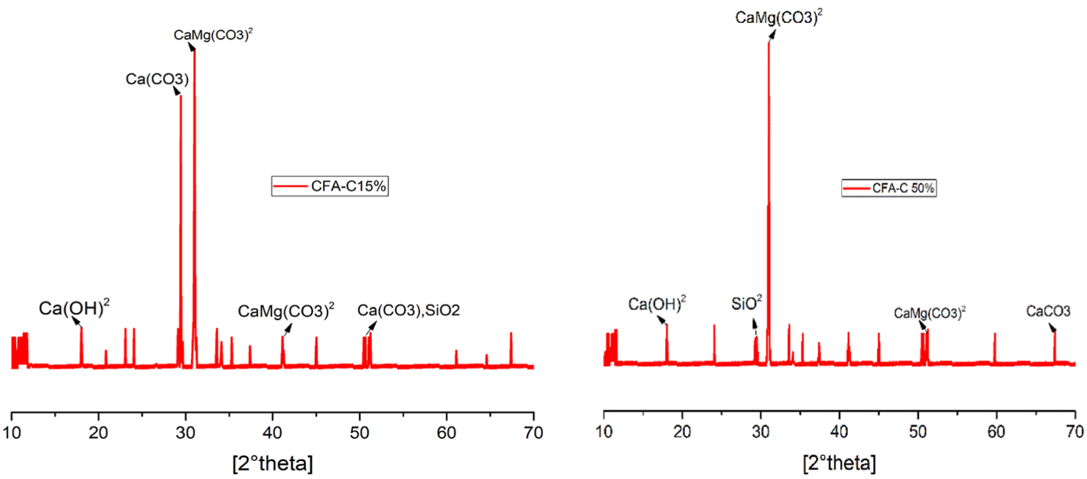

Figure 10. XRD diffractograms of CFA-C 15% and CFA-C50%.

is attributed to the chemical composition of the ash and unreacted particles of this content, while a noticeable increase in calcite $Ca(CO_3)$ peaks is observed in the sample of CFA-C15%, which is related to the hydration of Portland cement (CP).

The XRD analysis highlights the amorphous phase in the sample, which is crucial for FA's reactivity and its role in forming essential compounds like C−S−H and C−A−S−H during the pozzolanic reaction with CP. Additionally, the presence of quartz and calcite peaks further underscores the chemical interactions and changes occurring within the materials; this result is in agreement with the FTIR analysis.

3.3.3. Scanning Electron Microscopy. Microstructural characterization and EDS microanalysis of the samples, including CC, FA-C, CFA-C15%, and CFA-C 50%, after 28 days were conducted using SEM. Figure 11 presents images revealing particles of varying shapes and sizes.

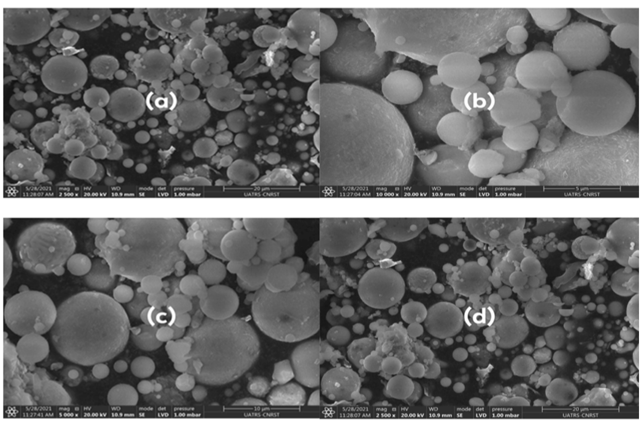

Figure 11. SEM micrograph analysis images of FA-C (a—25000×), CC (b—1000×), CFA-C15% (c—2500×), and CFA-C 50% (d—2500×).

The SEM images indicate that the control slurry CC exhibits a homogeneous structure with fewer unreacted FA particles and a denser sample. This result is consistent with the presence of the aluminosilicate gel. This improvement in microstructure and density is likely a result of higher pozzolanic activity, which has been correlated with enhanced compressive strength, as corroborated by FTIR analysis.[34]

Overall, the SEM analysis and microstructural observations suggest that the control slurry CC possesses a more uniform and denser structure, potentially due to increased pozzolanic activity. This improved microstructure is a contributing factor to the enhanced compressive strength, as supported by FTIR analysis.

The SEM analysis reveals distinct structural characteristics in the samples, particularly in relation to CFA-C 15% and CFA-C 50%.

CFA-C15% exhibits a relatively homogeneous structure with observable changes. Additionally, EDX analysis indicates the presence of an aluminosilicate gel. This suggests that the incorporation of 15% FA contributes to a more uniform microstructure, likely due to increased pozzolanic activity. Such improvements in microstructure are associated with enhanced compressive strength, as previously confirmed by FTIR analysis.

Conversely, in the sample with a higher FA content (CFA-C50%), increased porosity, nonhomogeneity, and the presence of large microcracks are observed. This phenomenon can be attributed to unreacted FA particles, which remain inert and do not actively participate in chemical reactions. As a result, the unconnected matrix in CFA-C50% is responsible for its lower resistance and structural integrity.

The EDX patterns for the FA and synthesized samples are listed in Figure 12. These patterns reveal the elemental composition of each sample.

For the FA, the elemental composition includes significant percentages of Na (0.43%), O (42.40%), Si (27.77%), and Al (10.82%), which are the primary constituents of the aluminosilicate gel. After the addition of 15 and 50% FA, the weight percentage of Na increases. This increase in Na content is responsible for inhibiting the formation of the gel C−S−H, which, in turn, leads to lower compressive strength, as supported by the obtained results.

In conclusion, the SEM and EDX analyses provide insights into the structural changes and elemental compositions of the samples. CFA15% exhibits improved homogeneity and the presence of an aluminosilicate gel, contributing to enhanced compressive strength. On the other hand, CFA50% exhibits increased porosity and nonhomogeneity due to unreacted FA particles, resulting in reduced structural integrity and resistance. The changes in the Na content in the samples are linked to variations in the compressive strength.

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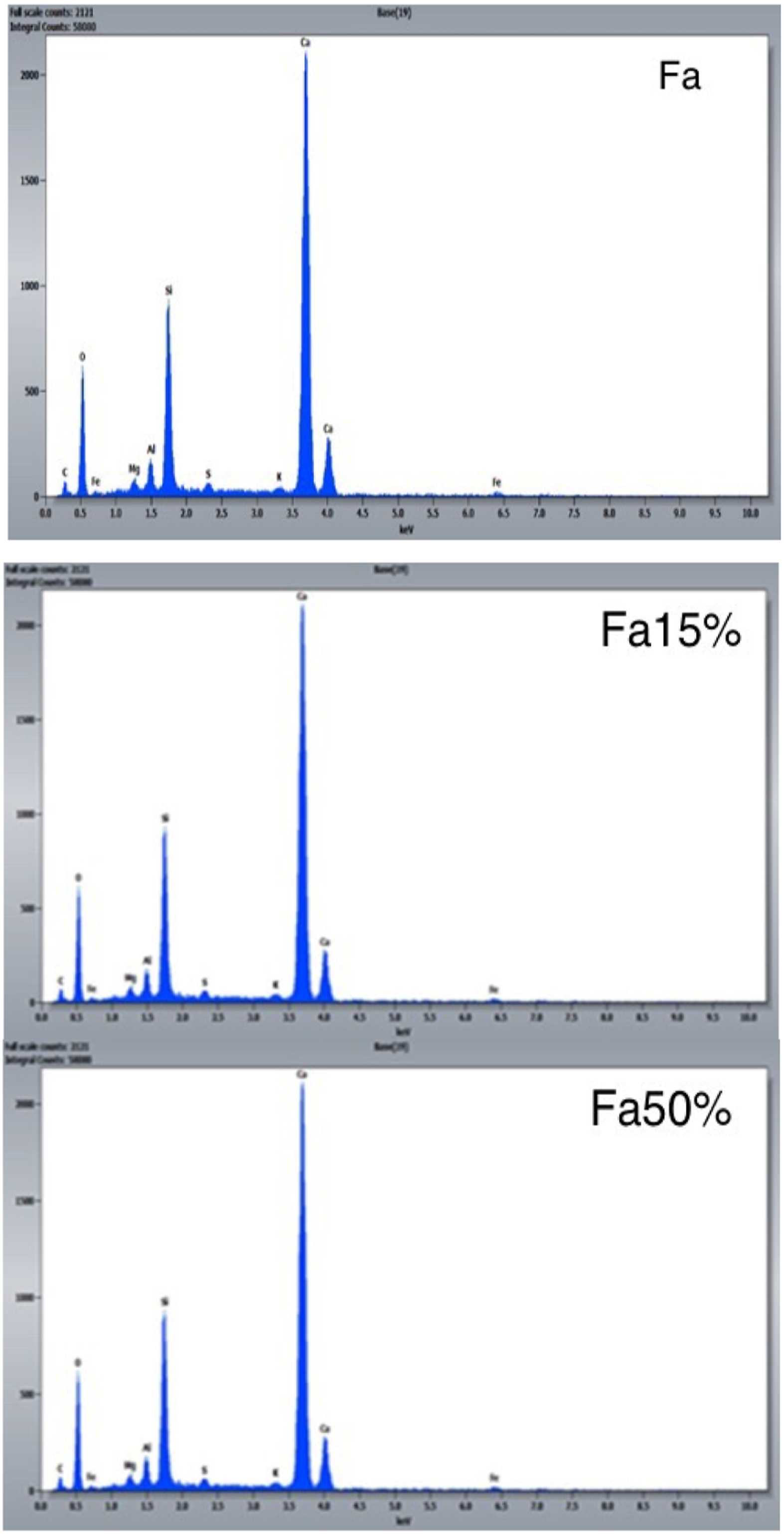

Element	Weight %	Atom %
C	2.80	4.99
O	42.40	56.77
Na	0.43	0.40
Mg	1.52	1.34
Al	10.82	8.59
Si	27.77	21.19
P	0.92	0.63
k	2.37	1.30
Ca	1.95	1.89
Ti	1.94	0.26
Fe	6.05	2.63
Total	100	100

Element	Weight %	Atom %
C	13.3	20.98
O	43.85	52.22
Na	0.51	0.36
Mg	1.52	0.97
Al	10.50	7.43
Si	20.79	14.11
P	0.92	0.95
k	2.37	0.92
Ca	3.53	1.89
Ti	0.90	0.26
Total	100	100

Element	Weight %	Atom %
C	3.43	6.67
O	41.40	60.42
Na	1.44	1.31
Mg	4.46	3.86
Al	6.16	5.12
Si	0.32	0.24
P	0.52	0.38
k	25.37	14.78
Ca	0.66	0.32
Ti	0.67	0.30
Total	100	100

Figure 12. EDX analysis of Fa, Fa15%, and Fa50%.

4. CONCLUSIONS

This research paper showed the potential of using coal FA as a sustainable alternative material in concrete production. The analytical techniques used indicate that FA-C is a pozzolanic material and, thus, was fully characterized; they exhibited the formation of the amorphous aluminosilicate hydrate gel (C−S−H) in all formulated concrete, and the mechanical properties examination of concrete showed higher compressive strength, bulk density, and compacted microstructure; they are attributed to the samples with 15% of FA added at 28 days; so, to obtain a better performance, a lower quantity of FA must be replaced with the CP. Replacing cement with FA reduces water demand, so the FA makes the concrete more workable. In other words, the rheological properties showed a clear effect on

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the increase of fluidity with FA-C; the presence of FA-C can increase the viscosity, decrease the yield stress, and prevent the development of the flocculation of particles, so the addition of FA-C can substantially enhance the rheology of blended cements.

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