

ORIGINAL ARTICLE

Utilization of Coal Fly Ash as a Supplementary Cementitious Material in Shotcrete for Slope Reinforcement in Mining Areas

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ABSTRACT – The extensive use of Portland cement in mortar for slope reinforcement contributes significantly to carbon dioxide (CO₂) emissions, highlighting the need for more sustainable construction materials. This study investigates the utilization of coal fly ash as a supplementary cementitious material (SCM) in shotcrete mortar for slope stabilization in mining areas. Mortar specimens were prepared using soil from the middle layer, selected due to its higher density, and fly ash contents of 0%, 7%, 14%, 21%, and 28% as partial cement replacements. The physical properties of the soil were evaluated, while the mortar was assessed through compressive strength and water absorption tests. Microstructural and compositional characteristics were analyzed using X-ray fluorescence (XRF), X-ray diffraction (XRD), Fourier-transform infrared (FTIR), and scanning electron microscopy–energy dispersive X-ray (SEM–EDX). In addition, slope stability analysis was conducted using the limit equilibrium method (LEM) to evaluate the effectiveness of fly ash–modified mortar in soil nailing systems. The results demonstrate that fly ash significantly impacts mortar performance through pozzolanic reactions and microstructural densification. The highest and most stable compressive strength was achieved at 21% fly ash content, which provides a more suitable balance between mechanical strength and durability. Characterization results confirm the formation of additional hydration products such as calcium silicate hydrate (C–S–H) and calcium aluminate silicate hydrate (C–A–S–H). Slope stability analysis demonstrates an increase in the factor of safety (FoS) from below 1.0 to 1.039, reducing the probability of failure to 4%. Overall, coal fly ash is proven to be an effective and sustainable SCM for shotcrete mortar, enhancing mechanical performance, durability, and slope stability while reducing cement consumption.

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INTRODUCTION

The application of mortar in geotechnical and mining engineering has become increasingly significant, particularly in slope stabilization and the reinforcement of earthen retaining walls in mining areas. Mortar is favored due to its versatility, high strength, and ease of production. However, conventional mortar relies heavily on Portland cement as its primary binding material. Cement production is an energy-intensive process that emits substantial amounts of carbon dioxide (CO₂), contributing to approximately 7–8% of total global greenhouse gas emissions in the construction sector [1], [2]. This environmental impact highlights the urgent need for more sustainable alternatives that can reduce the dependence on cement while maintaining, or even improving, the mechanical performance of construction materials.

One of the most promising approaches to achieving eco-efficiency in construction materials is the utilization of supplementary cementitious materials (SCMs), such as coal fly ash, a byproduct of coal combustion in thermal power plants [3], [4]. Fly ash is rich in silica (SiO₂) and alumina (Al₂O₃), and its pozzolanic nature allows it to react with calcium hydroxide (Ca(OH)₂) generated during the hydration of cement, forming additional calcium silicate hydrate (C–S–H) gels [5]. This secondary C–S–H formation contributes to a denser and more cohesive microstructure, leading to reduced porosity, lower permeability, and enhanced compressive strength, particularly at later curing ages [6]. Consequently, incorporating fly ash into mortar not only improves durability and strength but also provides a sustainable pathway for waste utilization and reduction of CO₂ emissions associated with cement production [3].

Previous studies have demonstrated the potential of fly ash as a partial replacement for cement in various construction applications. For instance, Purwono et al. (2020) demonstrated that the inclusion of 15% fly ash significantly reduced water absorption while enhancing the 28-day compressive strength of mortar [7]. Similarly, Marina and Pujiyanto (2020) found that substituting 10% of cement with fly ash at a water-to-cement ratio of 0.3 produced a porous concrete with

improved strength and water resistance [8]. Moreover, Budi et al. (2021) observed that up to 20% fly ash replacement maintained acceptable mechanical performance and environmental durability [9]. Razak et al. (2019) [10] further highlighted the potential of fly ash composites for slope surface strengthening.

Despite these contributions, most existing studies focus on conventional construction applications and evaluate limited performance parameters, primarily compressive strength or water absorption, under controlled laboratory conditions. Studies addressing the application of fly ash-modified mortar in geotechnical systems, particularly as shotcrete for slope reinforcement in mining environments, remain limited. In such environments, slope stability is highly sensitive to water infiltration, which directly affects shear strength and the potential for failure. However, the potential role of fly ash not only as a cement substitute but also as a water-regulating and microstructure-enhancing material within slope systems has not been comprehensively explored.

To address this gap, the present study proposes an integrated evaluation of the physical, absorption, and mechanical properties of mortar incorporating various proportions of fly ash (7%, 14%, 21%, and 28% by weight of cement), specifically designed for shotcrete applications in slope reinforcement. This approach enables a systematic assessment of the effects of fly ash across multiple performance indicators under conditions relevant to geotechnical applications. Furthermore, advanced characterization techniques such as X-ray fluorescence (XRF), X-ray diffraction (XRD), Fourier-transform infrared (FTIR) spectroscopy, and scanning electron microscopy coupled with energy-dispersive X-ray analysis (SEM–EDX) were employed to elucidate the microstructural and compositional changes induced by the addition of fly ash. These techniques provide insights into the material's chemical interactions and structural evolution, allowing for a deeper understanding of the mechanisms governing strength development and water absorption reduction.

The novelty of this research lies not only in the multi-parameter assessment of fly ash-modified mortar, but also in its specific application within a geotechnical framework, where material performance is directly linked to slope stability. This study integrates microstructural, physical, and mechanical analyses with slope stability evaluation using the limit equilibrium method (LEM), establishing a direct relationship between material properties and geotechnical performance. By demonstrating the role of fly ash in improving both mechanical strength and water interaction behavior, this study contributes to the development of sustainable shotcrete materials for slope stabilization in mining areas and provides a more application-oriented perspective compared to previous studies.

EXPERIMENTAL METHOD

Materials and Instruments

Fly ash was obtained from the Coal-Fired Power Plant (Pembangkit Listrik Tenaga Uap, PLTU) Kupang, located in Panaf Hamlet, Lifuleo Village, West Kupang District, Kupang Regency, East Nusa Tenggara, Indonesia. Portland cement (Tiga Roda brand) was purchased from a local construction material supplier in Kupang. Soil originating from Lembata Regency, East Nusa Tenggara, Indonesia. Sand was collected from a local source (Takari, Kupang Regency, East Nusa Tenggara, Indonesia), while clean water was used as a mixing component in the preparation of the concrete.

The morphological characteristics and elemental composition of the samples were examined using a scanning electron microscope equipped with an energy-dispersive X-ray (SEM–EDX) detector from Hitachi SU-3500. The crystalline structure of the samples was identified through X-ray diffraction (XRD) analysis using a Rigaku instrument. The chemical composition of the marble powder was determined by X-ray fluorescence (XRF) spectroscopy employing a Bruker S2 PUMA device. Fourier-transform infrared (FTIR) spectra were obtained using a Shimadzu IR Prestige 21 spectrometer within the wavenumber range of 500–4000 cm^{-1} .

Method and Procedure

Preparation of mortar

The mortar was prepared by mixing Portland cement, fine aggregate (soil), clean water, and fly ash as a partial replacement for cement. Fly ash was incorporated into the concrete mixture in five variations: 0% (without fly ash, serving as a control), 7%, 14%, 21%, and 28% of the cement weight. All materials were weighed using a digital balance according to the specified proportions. The mixing process was carried out manually, and the mixture was then placed into cylindrical molds. After thorough mixing to achieve a homogeneous mixture, the concrete was cast into cylindrical molds with a diameter of 6 cm and a height of 12 cm. Each mold was manually compacted. After 24 hours, the specimens were demolded and then immersed in clean water in a curing tank for 28 days.

Physical property test

Physical property testing was conducted on the soil to determine its basic characteristics at the location in Lembata Regency, following the SNI 1965:2008 method [11]. Several physical property tests were conducted in the laboratory, including specific gravity, bulk density, moisture content, and shear strength.

The tests for specific gravity, bulk density, and moisture content were conducted in accordance with SNI 1964:2008 using a 500 mL pycnometer. The shear test was performed following the SNI 2813:2008 standard using an electric direct shear machine [12].

Compressive strength test

Cylinder specimens of mortar (6 × 12 cm) were prepared and tested to determine their compressive strength. After curing periods of 7, 14, 21, and 28 days, the specimens were subjected to compressive testing using a hydraulic press, following the standard procedure outlined in ASTM C 109/C 109M with Compression Testing Machine Controls MCC8 50-C10A00.

Water absorption test

The water absorption test was conducted in accordance with SNI 03-6491-1999 and SNI 2847:2019 standards [13]. The specimens of mortar were first oven-dried using a Memmert UF75 oven at a temperature of 100–110 °C for 24 hours, until a constant weight was achieved. Afterwards, the dry weight (W_1) was recorded. Subsequently, the specimens were immersed in clean water for durations of 5 minutes, 30 minutes, 1 hour, 2 hours, 12 hours, and 24 hours in an immersion tank. After each immersion period, the specimens were removed, the surface water was gently wiped off with a cloth, and the wet weight (W_2) was measured.

Water absorption was calculated using the following equation:

$$\text{Water absorption} = \frac{W_2 - W_1}{W_2} \times 100\% \quad (1)$$

where W_1 is the dry weight, and W_2 is the wet weight of the specimen.

RESULT AND DISCUSSION

Physical property test

The physical property test examines the characteristics of soil collected from Lembata Regency, East Nusa Tenggara, Indonesia, which was classified into three layers based on the natural stratification of the site. Understanding these physical properties is essential, as they significantly influence the soil's shear strength, compressibility, and stability, particularly in slope reinforcement applications within mining environments. The results indicate that the upper and middle soil layers exhibit relatively higher density and specific gravity, with an average value of 1.68 g/cm³, suggesting a more compact structure. In contrast, the lower layer exhibits a lower density of approximately 1.25 g/cm³, indicating a looser and less consolidated soil structure (Table 1) [14]. Such variation in density and structure plays a crucial role in determining the shear behaviour of the soil, particularly when it is used as a foundation or as a reinforced material in slope stabilization systems. As Ndubuisi and Arinze (2024) pointed out, a high specific gravity and bulk density value will build a strong and stable shotcrete as it increases the compressive and shear strength [15]. This pattern suggests that the upper and middle layers exhibit better compaction and load-bearing capacity, whereas the lower layer remains relatively loose due to higher moisture content and limited stress history.

Figure 1 discusses the results of the direct shear strength test conducted on soil samples to evaluate their shear resistance under different normal stresses. Understanding the shear behaviour of the soil is essential for assessing its stability and load-bearing capacity, particularly in slope reinforcement applications within mining environments. Shear strength measures the inherent capacity of the soil to resist failure or deformation due to external forces [16]. The R^2 values, ranging from 0.9086 to 0.9868, indicate a strong linear correlation between normal stress and shear stress for all samples. This linearity suggests that the soil exhibits a granular-like behaviour, similar to dense sand or silty soils, which typically possess higher shear stability. The slopes of the regression lines (1.37, 1.73, and 1.69) represent the shear strength parameters, indicating that samples with steeper slopes have higher internal friction angles and, consequently, greater resistance to shear deformation. Shear stress 3 (Middle layer) has an R^2 value close to 1, indicating a sample with higher shear strength, corresponding to denser soil layers with reduced pore spaces, enhanced particle contact, and increased frictional resistance. Conversely, samples with lower shear strength are likely associated with higher plasticity or moisture content, which decreases particle interlocking and weakens the shear resistance (shear stress 2/ lower layer). A reduced shear strength will escalate a soil sliding velocity and instability, causing a more possible factor that triggers catastrophic landslide events at the slope reinforcement [17]. These findings confirm that denser soil layers with higher internal friction angles (Middle layer) are more capable of resisting shear stress, making them more suitable as foundation or reinforcement layers in mining slope stabilisation systems. These discoveries also align with the high specific gravity and density value of the middle layer, which intensifies the strength of the soil to sustain shear stress.

Table 1. Physical properties test results of soil samples

	Specific gravity	Bulk density	Moisture content
Upper layer	1.60	2.05	27.08
Middle layer	1.68	1.92	38.3
Lower layer	1.25	1.96	37.6

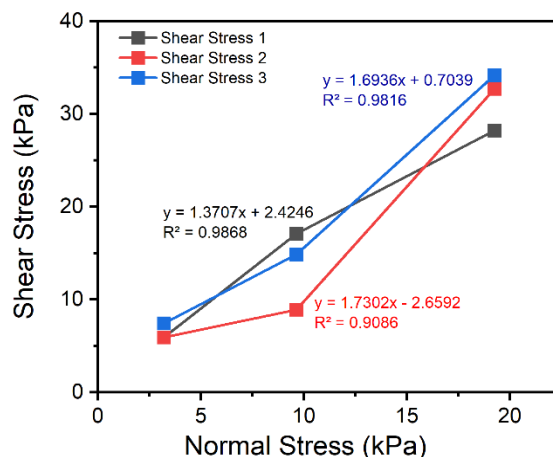


Figure 1. Direct shear strength test conducted on soil samples to evaluate their shear resistance under different normal stresses

Compressive Strength Test of Mortar

Figure 2 discusses the compressive strength performance of mortar incorporating different fly ash contents, which is essential for understanding its mechanical behavior and suitability for slope reinforcement applications in mining environments. Mortar is made by mixing Portland cement, soil, clean water, and fly ash as a partial substitute for cement. The mortar is made using soil from the middle layer, as this layer has better density, making it suitable as a mortar component for mine slope stabilization. Evaluating the strength development over curing time is necessary to determine the optimal fly ash proportion that provides adequate load-bearing capacity while maintaining material stability.

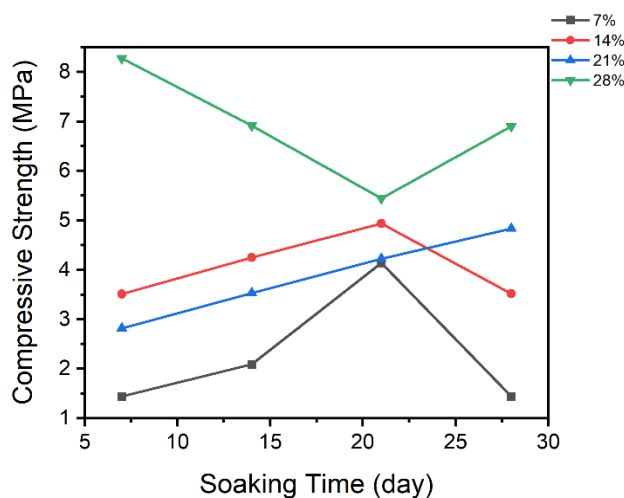


Figure 2. Compressive strength performance of mortar incorporating at different fly ash contents and soaking time

Figure 2 illustrates the relationship between curing duration (7, 14, 21, and 28 days) and the compressive strength of mortar for four fly ash replacement levels: 7%, 14%, 21%, and 28%. From the figure, the mortar containing 21% fly ash demonstrates the most consistent increase in compressive strength up to 28 days, indicating a stable hydration and pozzolanic reaction phase.

Among the tested variations, the mortar containing 21% fly ash shows a relatively stable, progressive increase in compressive strength throughout the curing period, with minimal fluctuations compared to other compositions. In contrast, the 7% and 14% mixtures exhibit moderate strength development at early ages but show a reduction at 28 days, suggesting less stable long-term performance. Meanwhile, the 28% mixture shows higher strength at early curing stages but exhibits greater variability at later ages, suggesting less uniform microstructural development. The optimal performance of the 21% mix suggests a balanced pozzolanic reaction, where sufficient calcium hydroxide (Ca(OH)_2) from fly ash is available to form additional calcium silicate hydrate (C-S-H) gels without causing excessive dilution of cementitious components [18]. The formation of C-S-H has a pore-filling effect on the mortar, as they are formed amongst particles in the pore, making them less porous [19]. It also reduces the void structure of the mortar due to its bridging effect on each particle [20]. Reducing the porosity of the mortar lessens the water absorption, leading to a rise in compressive strength. Increasing the compressive strength of the mortar will enhance the soil stabilization system, considering that it lowers the possibility of soil deformation. Conversely, the decreased performance at 28% fly ash

indicates that excessive replacement may introduce excess unreacted particles, increasing porosity and disrupting matrix uniformity. Overall, the results confirm that 21% fly ash provides the most favorable compressive strength behavior, making it the optimal mix for mortar intended for slope stabilization and shotcrete applications.

Water absorption test

Figure 3 examines the water absorption performance of mortars containing varying proportions of fly ash, which is crucial for evaluating their durability, pore structure, and resistance to moisture infiltration. Understanding how fly ash affects the water absorption behavior is important for determining the suitability of the mortar for slope reinforcement applications, where exposure to water significantly influences long-term mechanical stability. Figure 3 illustrates the water absorption values of mortar measured at soaking durations of 5 minutes, 30 minutes, 1 hour, 2 hours, 12 hours, and 24 hours for various fly ash contents (7%, 14%, 21%, and 28%) as well as a control mix without fly ash. The results show that water absorption increases with immersion time for all mixtures, reflecting typical capillary suction behavior in cementitious materials.

Among the tested variations, the 14% fly ash mixture exhibits the lowest water absorption throughout the entire soaking period. This trend indicates a denser and more refined pore structure, likely resulting from a favorable pozzolanic reaction that promotes the formation of additional C–S–H gel and reduces pore connectivity. In contrast, the 28% fly ash mixture shows the highest water absorption, suggesting that at higher replacement levels, the balance between cement hydration and pozzolanic reaction becomes less optimal. Although the fly ash is chemically reactive, the reduced cement content may limit the availability of $\text{Ca}(\text{OH})_2$ required for complete pozzolanic reactions, leading to a less dense microstructure and increased porosity. At higher replacement levels, the dilution of cement becomes dominant, resulting in increased porosity and greater water absorption. Increased porosity facilitates water transport through the mortar structure, which may accelerate long-term microstructural degradation due to weakened C–S–H bonding and reduced service life [21], [22]. In the context of slope stability, higher water content may also contribute to reduced soil strength and increased susceptibility to slope failure. The control sample (0% fly ash) also shows relatively high absorption values, highlighting the role of fly ash as a supplementary cementitious material (SCM) that enhances microstructural compactness. Although the 14% fly ash mixture demonstrates the best performance in terms of minimizing water absorption, this parameter is considered a durability indicator rather than the primary design criterion for slope reinforcement. When evaluated together with compressive strength results, the overall performance suggests that a higher fly ash content (21%) provides a more suitable balance between mechanical strength and durability for shotcrete applications in slope stabilization.

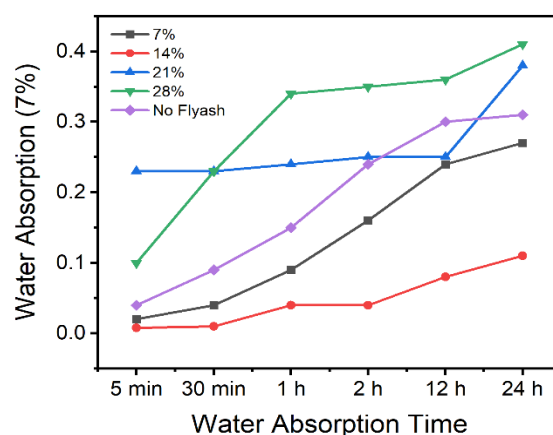


Figure 3. The influence of fly ash content on the water absorption performance of mortar at different adsorption times

Characterizations

X-Ray Fluorescence (XRF)

Based on the XRF analysis (Table 2), the soil sample shows that the most dominant oxides are silica (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3), at approximately 45.8%, 2.37%, and 19.8%, respectively. This composition indicates that the soil has undergone moderate to advanced chemical weathering [23]. The relatively high proportions of Al_2O_3 and Fe_2O_3 compared with SiO_2 further suggest an advanced degree of chemical weathering, typically characterized by the depletion of bases and easily soluble silicates [24]. Moreover, soils with high Al_2O_3 and Fe_2O_3 contents generally exhibit adsorptive properties due to the abundance of anion-exchange sites on Fe and Al oxides, making them potentially useful as adsorbents or as construction materials such as lateritic soil after stabilization [25]. The presence of Fe_2O_3 is directly proportional to the specific gravity and bulk density and significantly affects the shear strength [26], [27]. This result is in accordance with the shear resistance property of the soil. Meanwhile, the XRF results for the fly ash sample (Table 3) show that calcium oxide (CaO) is the most dominant oxide. Based on this relatively high CaO content (~30%), the fly ash used in this study can be classified as Class C fly ash according to ASTM C618, which is known to exhibit both pozzolanic and self-cementing (hydraulic) properties. The high CaO content indicates that the fly ash possesses

cementitious characteristics, enabling it to partially replace Portland cement or be used as a component in self-cementing concrete mixtures [28]. The substantial CaO and magnesium oxide (MgO) contents also support the occurrence of pozzolanic reactions, namely the reaction of silica or alumina with $\text{Ca}(\text{OH})_2$, as well as additional hydration processes associated with its self-cementing behavior. These combined reactions contribute to pore refinement and reduced water absorption [29]. Additionally, the relatively high Fe_2O_3 content may influence the physical properties and reactivity of the fly ash [30].

Table 2. The composition of soil analyzed by XRF

No	Compounds	Percentage (%)
1	SiO_2	45.8
2	Al_2O_3	27.3
3	Fe_2O_3	19.8
4	MgO	1.6
5	CaO	1.3
6	TiO_2	1.3
7	P_2O_5	1.0
8	SO_3	0.5
9	MnO	0.40
10	K_2O	0.30
11	Cl	0.2
12	Gd_2O_3	0.2
13	V_2O_5	0.1

Table 3. The composition of fly ash analyzed by XRF

No	Compounds	Percentage (%)
1	CaO	30.0
2	Fe_2O_3	24.4
3	SiO_2	20.3
4	MgO	9.4
5	Al_2O_3	9.2
6	SO_3	2.8
7	TiO_2	0.8
8	K_2O	0.6
9	P_2O_5	0.6
10	Tb_4O_7	0.5
11	MnO	0.4
12	SrO	0.3
13	Cl	0.2
14	Sc_2O_3	0.2
15	CoO	0.1

Table 4. The composition of mortar analyzed by XRF

No	Compounds	Percentage (%)
1	CaO	43.4
2	SiO_2	22.6
3	Fe_2O_3	16.3
4	Al_2O_3	7.4
5	MgO	4.5
6	SO_3	1.9
7	P_2O_5	0.7
8	TiO_2	0.7
9	K_2O	0.6
10	MnO	0.4

11	Tb ₄ O ₇	0.4
12	Sc ₂ O ₃	0.3
13	Cl	0.2
14	SrO	0.2
15	Gd ₂ O ₃	0.1

The XRF results for the mortar sample (Table 4) indicate that CaO is the most dominant oxide (43.40%), providing evidence that the chemical characteristics of fly ash are more pronounced in the mixture. This value is considerably higher than that reported by Naibaho and Rahman (2020), who found a CaO content of only around 14.70% [31]. Mortar with a high CaO content (~43.4%) has the potential to undergo faster setting and hardening [32]. These findings align with the results of the compressive strength test and the water absorption test of the mortar. Furthermore, the presence of silica (SiO₂ at 22.6%) and alumina (Al₂O₃ at 7.4%) suggests contributions to the formation of hydration gels such as calcium silicate hydrate (C–S–H) and calcium aluminate silicate hydrate (C–A–S–H), as well as potential contributions from fine aggregates or additional mineral sources such as fly ash. As stated by Li et al. (2021) and Wang et al. (2022), it will lessen the porosity and, hence, block continuous capillary pathways for water penetration [33], [34]. Thus, the mortar containing fly ash will help improve slope stability. The relatively high Fe₂O₃ content (16.3%) indicates a significant presence of iron in the mortar, which may influence its color (brownish or reddish) and reflects the contribution of ferrite phases [35].

Fourier-Transform infrared (FTIR)

Figure 4 and Table 5 present the comparative FTIR spectra of soil, fly ash, and the mortar produced from their combination, highlighting the major functional groups responsible for the chemical interactions within the composite system. A broad absorption band near 3400 cm⁻¹ appears prominently in the spectra of soil and mortar but is nearly absent in fly ash. This feature corresponds to O–H stretching vibrations originating from adsorbed or structurally bound water, a characteristic typical of hydrophilic soil minerals. Its appearance in the mortar spectrum indicates that soil's hydroxyl-rich surface chemistry is retained after blending with cementitious components, contributing to the moisture affinity and microstructural behavior of the mortar. Similarly, the H–O–H bending mode, observed at approximately 1636–1648 cm⁻¹ in both soil and fly ash, is preserved in the mortar, indicating that both materials contribute structurally or adsorbed water to the composite [36].

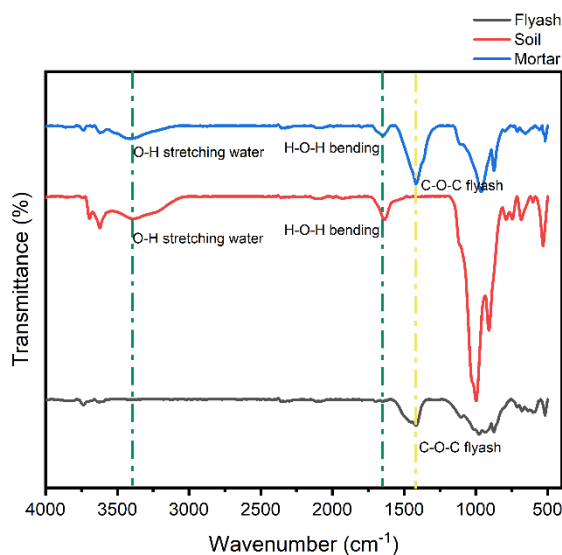


Figure 4. FTIR absorption spectra of fly ash, soil, and mortar

Table 5. Functional group analysis of fly ash, soil, and mortar

Soil	Fly ash	Mortar	Functional groups
3621	3736 and 3626	3736 and 3620	O–H stretching (Al–OH or Si–OH)
	2356-2300		Adsorption CO ₂
1636	1695-1648		H–O–H bending
	1450 and 1417	1415	O–C – O from CO ₂
997	1103 and 976-934	962	Si–O stretching
907	873	873	Si–O–H or Al–O–H
788, 682, 530	709, 677, 516	709, 653, 557	Si–O or Al–O

In contrast, carbonate-related absorption bands at $1450\text{--}1417\text{ cm}^{-1}$, clearly observed in fly ash, are also found in the mortar but are absent in the soil spectrum. This similarity indicates that the carbonate species, likely associated with calcium carbonate (CaCO_3) or secondary carbonation products in fly ash, are incorporated into the mortar without significant alteration. All three materials exhibit strong absorptions in the silicate region between 1100 and 900 cm^{-1} , corresponding to Si–O–Si and Si–O–Al stretching vibrations [37]. However, the mortar displays a broadened peak around 962 cm^{-1} , representing the combined contribution of soil's crystalline silicates and fly ash's amorphous aluminosilicate glass. This broadening indicates chemical integration and the potential formation of new aluminosilicate species during hydration and pozzolanic reactions. Additional low-wavenumber bands between $700\text{--}550\text{ cm}^{-1}$, associated with Al–O–Si bending and crystalline phases such as quartz or mullite, further reflect the composite's mixed mineralogical characteristics.

X-Ray Diffraction (XRD)

The soil diffractogram shows sharp and intense peaks, particularly a dominant peak at $\sim 26\text{--}27^\circ$, characteristic of quartz (SiO_2). Additional peaks at $20\text{--}30^\circ$ indicate the presence of kaolinite, illite, or other layered aluminosilicate minerals, which are typical constituents of natural soil (Figure 5). These sharp reflections confirm that soil possesses a high proportion of crystalline phases. The fly ash diffractogram, in contrast, exhibits broad, low-intensity peaks with smaller crystalline reflections, which contain a significant amount of amorphous aluminosilicate glass, accompanied by minor crystalline phases such as quartz, mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), and hematite (Fe_2O_3). The reduced intensity and broader halos reflect the predominantly amorphous nature of fly ash, which is directly linked to its pozzolanic reactivity. The mortar diffractogram displays a more complex pattern with multiple high-intensity peaks, particularly a dominant reflection at $\sim 29\text{--}30^\circ$, which corresponds to calcite (CaCO_3). This indicates that carbonation or cement hydration products contribute significantly to the crystalline composition of the mortar. The mortar also retains several peaks from both soil (quartz at $\sim 26^\circ$) and fly ash (minor mullite or quartz traces), demonstrating that the crystalline components of the raw materials are largely preserved in the final composite.

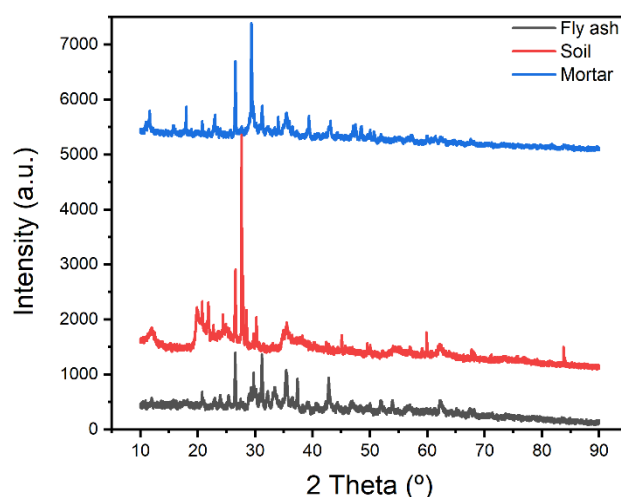


Figure 5. XRD patterns of fly ash, soil, and mortar

Scanning Electron Microscopy–Energy Dispersive X-ray (SEM-EDX)

The SEM micrograph of the soil sample at $1000\times$ magnification reveals an irregular, angular, and highly fragmented microstructure (Figure 6 (a)). The particles display plate-like and blocky morphologies with rough, uneven surfaces, characteristic of natural clay-rich soils. The absence of spherical particles and the dominance of sheet-like and irregular aggregates demonstrate that the soil is primarily composed of crystalline aluminosilicate minerals. The SEM image of fly ash shows a distinct contrast to the soil sample, with the microstructure dominated by smooth, rounded, and hollow or solid spherical particles (Figure 6 (b)). These spherical morphologies are typical of fly ash formed through high-temperature combustion processes, where molten mineral droplets solidify into glassy aluminosilicate spheres. The SEM micrograph of the mortar sample exhibits a denser and more cohesive microstructure compared to both raw soil and fly ash. The matrix is characterized by gel-like and fibrous features associated with hydration products, primarily calcium silicate hydrate (C–S–H) and calcium aluminate silicate hydrate (C–A–S–H). The presence of reaction rims around some fly ash particles suggests ongoing pozzolanic activity, where the amorphous aluminosilicate phases dissolve and participate in the formation of additional hydration gels. Overall, the mortar morphology appears more compact with reduced pore space, reflecting the beneficial interaction between soil, fly ash, and mortar, which contributes to improved mechanical strength and lower permeability.

The EDX results show that oxygen is the most abundant element in all samples (Table 6). The soil is characterized by aluminosilicate signatures, with Si (21.39 wt%) and Al (13.53 wt%) as the dominant elements, accompanied by a significant Fe content (12.39 wt%), which is typical of clay-rich residual soils. Fly ash is characterized by a very high Ca

content (26.38 wt%) together with appreciable Mg (6.61 wt%) and moderate Si (9.20 wt%) and Fe (8.98 wt%), indicating a calcium-rich. In the mortar, Ca remains high (16.40 wt%), while Si (9.62 wt%) and Al (3.92 wt%) are reduced relative to the raw soil, reflecting the contribution of fly ash/Ca sources, as well as dilution by cementitious phases. These findings align with the results of the XRF, FTIR, and XRD data, which also clarify the beneficial effects of fly ash on the durability of the mortar.

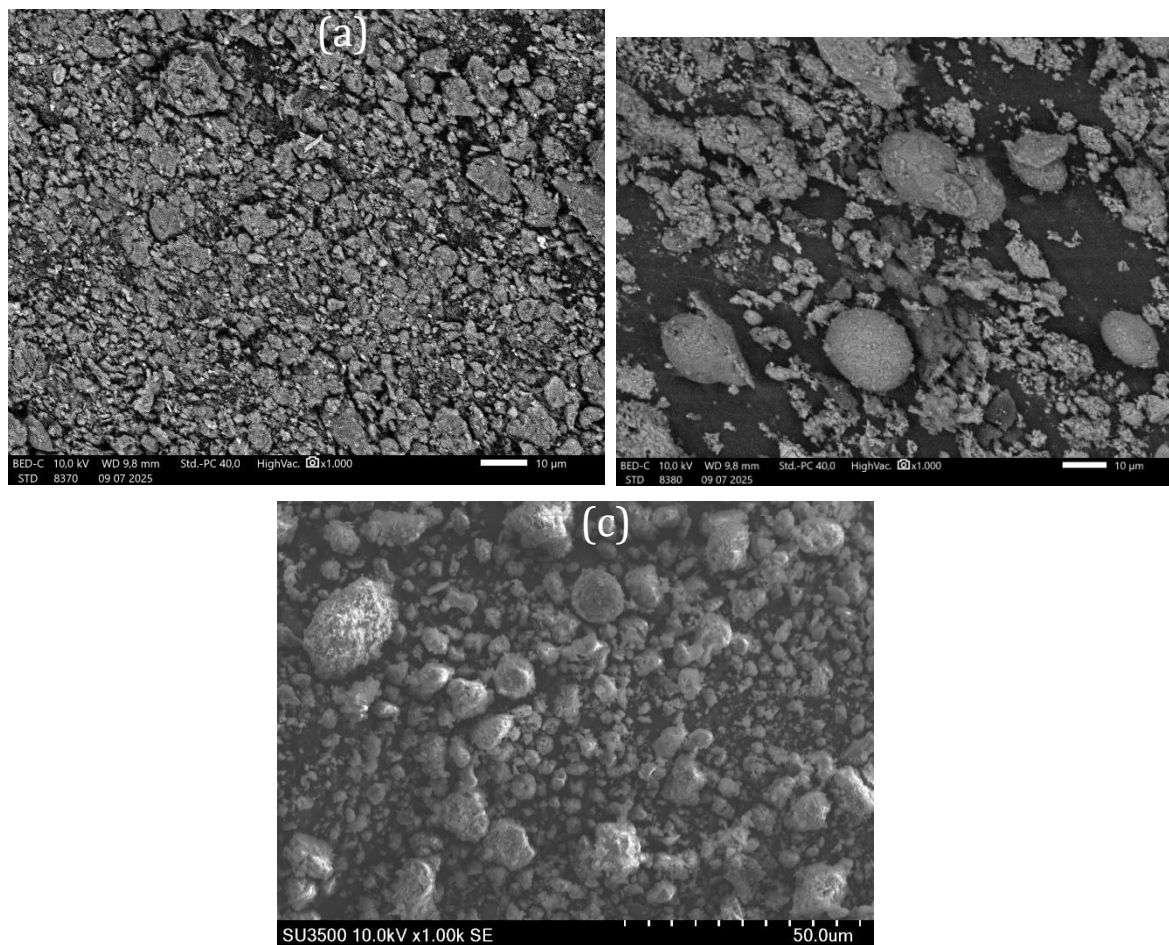


Figure 6. Morphology of (a) soil, (b) fly ash, and (c) mortar- analyzed by SEM-EDX

Table 6. Elemental composition of the sample in Wt% by SEM-EDX

Element	Wt (%)		
	Soil	Fly ash	Mortar
O	53.06	41.39	60.28
Al	13.53	5.49	3.92
Si	21.39	9.20	9.62
Fe	12.39	8.98	3.97
Mg		6.61	4.12
S		1.95	0.37
Ca		26.38	16.40
Na			0.66
Ti			0.20

Slope Stability Analysis

Based on the laboratory test results, a slope stability analysis was conducted for conditions before and after the installation of support in the form of soil nailing on the face of a former mine slope with a slope angle of 40° and a slope height of 56 m. The results are summarized as follows. For the original slope condition without any support, the slope stability analysis using the limit equilibrium method (LEM) indicated a factor of safety (FoS) of less than 1.00, with a probability of failure (PoF) of 89%, as shown in Figure 7. This result indicates that the slope was in a critical or unstable condition. The instability is primarily attributed to the susceptibility of the soil mass to water infiltration from rainfall and groundwater. In contrast, the slope after the application of fly ash–modified mortar (as shotcrete) in the soil nailing system exhibited an increase in the FoS to a value greater than 1.00, indicating improved slope stability. This improvement is associated with the water absorption capability of the fly ash SCM, particularly at a fly ash content of 21% in the mortar mixture (Figure 8).

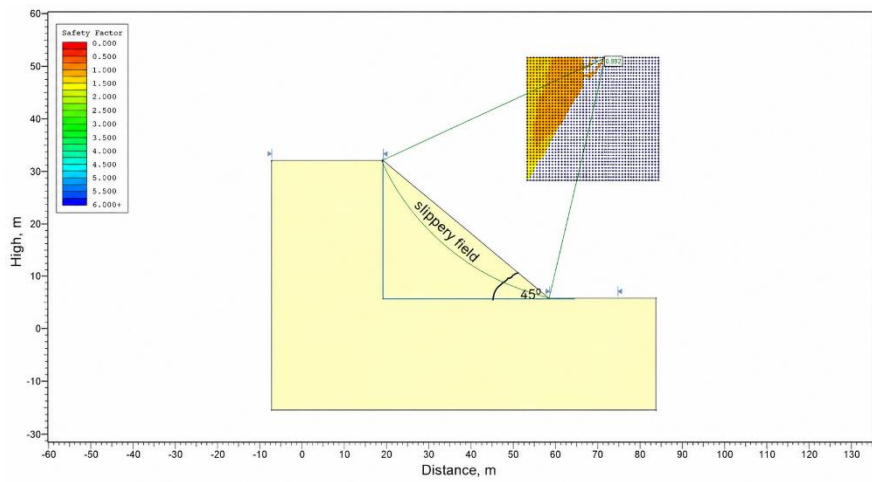


Figure 7. Slope modelling with a safety of FoS of 0.9

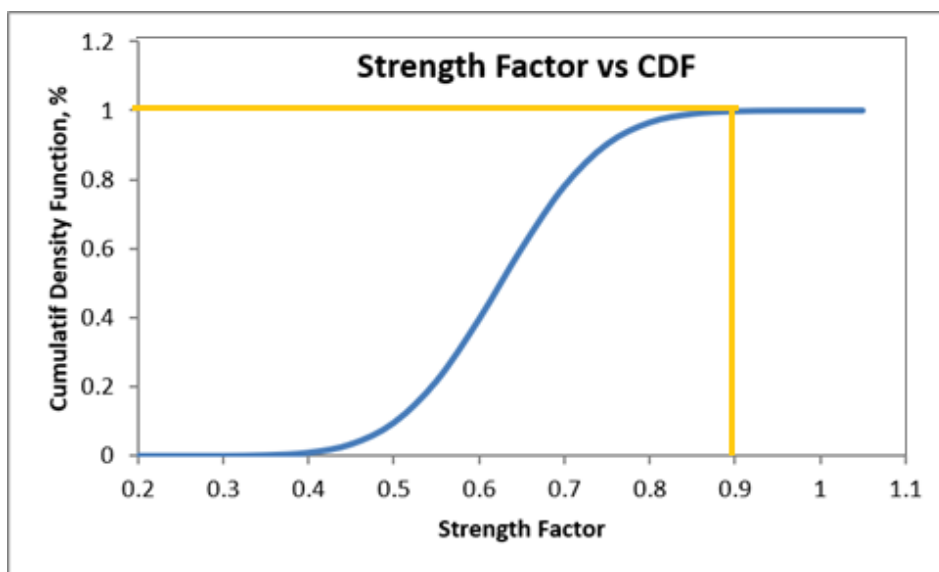


Figure 8. Probability of failure curve with a FoS of 0.9

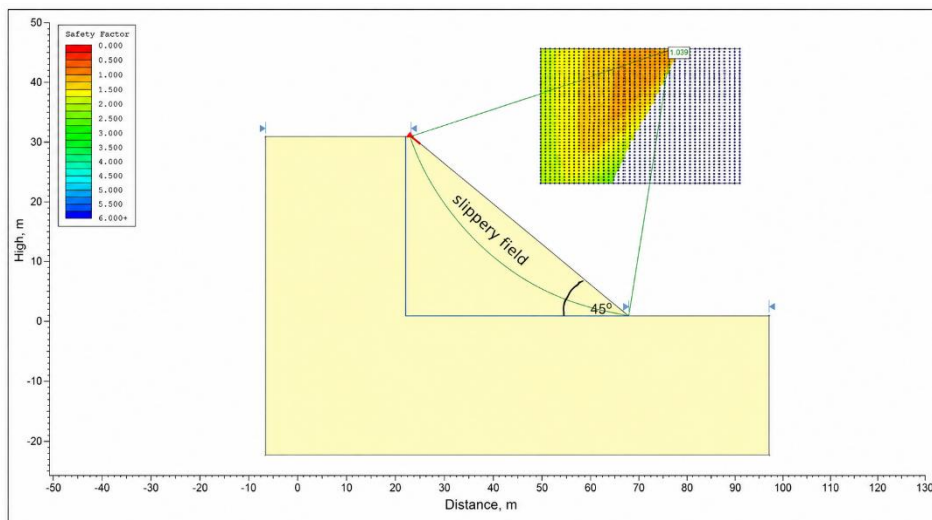


Figure 9. Slope modelling with a safety of FoS of 1.03

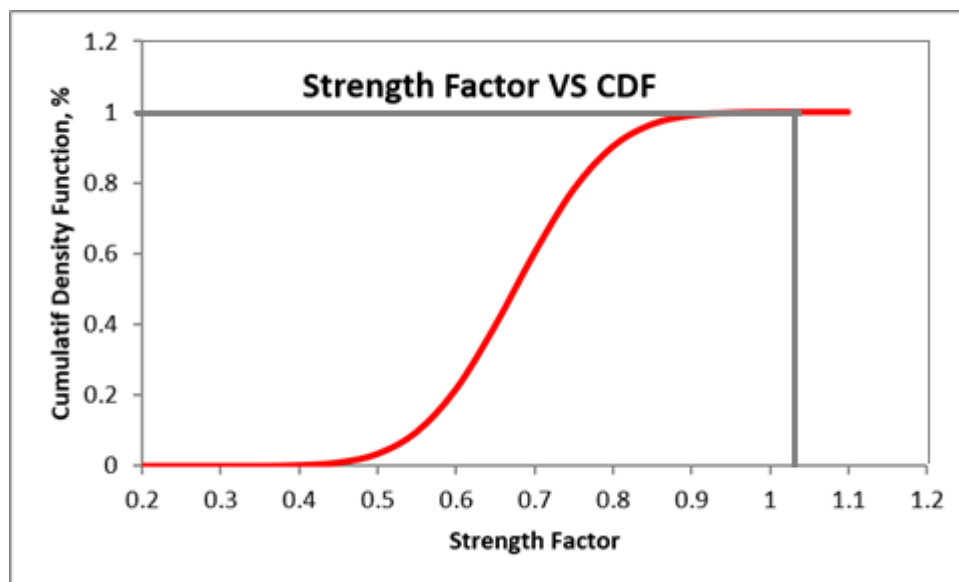


Figure 10. Probability of failure curve with a FoS of 1.03

The increase in the FoS is further illustrated in Figure 9, which shows more extensive changes in contour colors within the analysis grid. This phenomenon reflects the reduction in soil moisture content due to water absorption by the fly ash. As a result, the slope becomes more stable, achieving a FoS of 1.039. Furthermore, Figure 10 shows a cumulative probability of failure of 96%, indicating that the likelihood of slope failure decreased to 4% after the incorporation of fly ash as a mortar SCM in the soil nailing system.

CONCLUSION

This study demonstrates that coal fly ash can be effectively utilized as a supplementary cementitious material (SCM) in mortar for shotcrete applications aimed at mine slope reinforcement. Soil characterization shows that the middle soil layer, with a higher density, offers better suitability as a fine aggregate. Compressive strength testing indicates that the incorporation of fly ash enhances strength development, with 21% fly ash identified as the optimum proportion due to its consistent and superior performance over 28 days. Water absorption results further confirm that 14% fly ash produces the lowest absorption, indicating a denser pore structure and improved durability. However, water absorption is considered a durability indicator rather than the primary design criterion for slope reinforcement. Therefore, when both mechanical and durability aspects are considered simultaneously, the 21% fly ash content provides a more suitable balance for engineering applications. Characterization X-ray fluorescence (XRF), Fourier-transform infrared (FTIR), X-ray diffraction (XRD), and scanning electron microscopy–energy dispersive X-ray (SEM–EDX) reveals that fly ash introduces reactive calcium oxide (CaO) and amorphous aluminosilicate phases that contribute to the formation of additional hydration products such as calcium silicate hydrate (C–S–H) and calcium aluminate silicate hydrate (C–A–S–H), resulting in a more compact and cohesive mortar matrix. Collectively, these findings confirm that fly ash not only improves mechanical and durability properties but also reduces reliance on Portland cement, offering a more sustainable alternative for geotechnical applications.

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