https://doi.org/10.3311/PPci.37980

Periodica Polytechnica Civil Engineering, 69(3), pp. 823–837, 2025

Comprehensive Review of Classes F and C Fly Ash Effects on Clayey Soils: Geotechnical Predictive Correlations

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Received: 28 July 2024, Accepted: 29 March 2025, Published online: 29 April 2025

Abstract

Fly ash, a by-product of coal combustion, enhances the geotechnical properties of soil, primarily through its two types: class F and class C, known for their pozzolanic and cementitious properties, respectively. Numerous studies have explored the benefits of both types of fly ash in stabilizing problematic expansive soils, which are characterized by weak strength, high compressibility, and significant volume changes that can damage infrastructure. However, direct comparisons between class F and class C fly ashes in improving expansive soils are limited. This study aims to fill this gap by conducting a critical review of research from the past 20 years, focusing on the impact of class F and class C fly ashes on the geotechnical properties of expansive clayey soils. Key parameters examined include Atterberg limits, free swell, unconfined compressive strength (UCS), and California bearing ratio (CBR). The findings indicate that both fly ash types reduce liquid limits and plasticity indices of clayey soils, with class C fly ash showing more pronounced effects. Additionally, class C fly ash significantly reduces soil swelling and enhances UCS and CBR, especially due to its higher CaO content. The study provides novel formulas to aid future researchers in predicting the behavior and performance of clayey soils stabilized with these specific fly ash types, offering a comprehensive examination of their geotechnical parameters.

Keywords

clayey soil, fly ash, class C, class F, geotechnical properties

1 Introduction

Soil has a vital role in construction, but its engineering properties can differ depending on its type and the site conditions, which may not consistently meet the desired criteria. Soils with inadequate bearing capacity, excessive settlement, potential for liquefaction, slope instability, swelling and dispersibility tendencies, are classified as problematic soils. Expansive soils fall under this category and are prevalent in numerous regions globally. Due to their weak strength, high compressibility, and substantial volumetric changes, these soils can contribute to damage in roads, buildings, foundations, and other geotechnical infrastructure. Therefore, it becomes crucial to improve the engineering properties of expansive soils before commencing construction. Soil stabilization methods are employed for this purpose and can be categorized into mechanical and chemical stabilization approaches. The mechanical stabilization is performed by changing the physical properties of the soil using several techniques such as compaction, soil reinforcement, etc. Whereas, for the chemical stabilization, the soil is improved through a chemical reaction between the additives (cementitious materials) and the soil minerals (pozzolanic materials). Commonly used additives include cement and lime [1–13]. However, these materials are costly and not environmentally friendly, prompting the exploration of eco-friendly alternatives as stabilizers. In recent years, researchers have turned to eco-friendly materials for stabilization purposes. Among these alternatives, the utilization of industrial by-products has gained significant attention due to its cost-effectiveness and eco-friendliness. Various studies were done to investigate the applicability of using by-products in improving the properties of soil and concrete such as fly ash [14–29], bottom ash [30–33], cement kiln dust [34–38], metakaolin [39–45] etc..

Cite this article as: Zein, Z., Jaber, L., Jahami, A. "Comprehensive Review of Classes F and C Fly Ash Effects on Clayey Soils: Geotechnical Predictive Correlations", Periodica Polytechnica Civil Engineering, 69(3), pp. 823–837, 2025. https://doi.org/10.3311/PPci.37980

Fly ash is a by-product obtained from the combustion process in coal power plants, known for its ability to enhance the geotechnical properties of soil. Globally, approximately 500 million tons and 750 million tons of fly ash were produced in 2005 and 2015, respectively, during the combustion process. However, only 25% of this substantial volume of fly ash is effectively utilized, with the majority being disposed in landfills [46–51]. The fly ash exhibits exceptional pozzolanic characteristics that significantly improve the strength of stabilized soil and enhance the mechanical and fracture properties of soils and cemented rock-like materials [52–55]. The inclusion of fly ash and other fine pozzolans also strengthens the resistance of rocks and soils against erosion caused by chloride and acidic attacks [56, 57]. Additionally, the shape of fly ash particles influences the strength parameters of cemented rock-like materials by effectively filling in pores, contributing to improved durability and structural integrity [58, 59]. One of the major advantages of fly ash is its widespread availability, and its usage can lead to cost reductions in construction projects ranging from 10% to 20% [60–62]. The American Society for Testing and Materials (ASTM) [63] has taken the initiative to create a comprehensive classification system for fly ash, considering its chemical and physical properties. The standard ASTM C618-23 [63] provides a clear classification framework, categorizing fly ash into two main groups: class F and class C (Table 1). Class F fly ash is derived from the combustion of anthracite or bituminous coals, and is characterized by its low calcium content, higher amount of silica, alumina, and iron oxide, and finer particle size. This type of fly ash is known for its pozzolanic properties, meaning it reacts with calcium hydroxide in the presence of water to form additional cementitious compounds. This can improve the strength and durability of concrete and stabilized soils. In contrast, class C fly ash is produced from burning sub-bituminous or bituminous coals with higher calcium oxide content, significant amounts of calcium, silica, and alumina, has a coarser particle size compared to class F fly ash, and exhibits self-cementitious properties due to its higher calcium content. Class C fly ash has both pozzolanic and self-cementitious properties. This means it does not only react with calcium hydroxide but also has hydraulic properties, which contribute to faster strength development in concrete and enhanced soil stabilization [64–67].

Table 1 Chemical requirements for class F & class C fly ash

	ASTM C618-23 [63]	
Component (wt.%)	Class C	Class F
$SiO_2 + Al_2O_3 + Fe_2O_3$	50%–70%	> 70%
CaO	> 20%	< 10%
LOI	< 6%	< 12%

Numerous researchers have investigated the influence of both types of fly ash in improving the geotechnical properties of clayey soils in terms of Atterberg limits, free swell, unconfined compressive strength, and CBR [68–86]. Regarding the Atterberg limit, when 20% fly ash was used to stabilize clayey soil, there was an observed decrease in the liquid limit and plasticity index. For class F fly ash, the reduction ranged between 21% and 30% for the liquid limit and 38% to 48% for the plasticity index [87–94]. In the case of class C fly ash, the reductions were more substantial, falling within the range of 38% to 43% for the liquid limit and 75% to 82% for the plasticity index [87, 89]. Furthermore, several studies investigated the swelling and shrinkage characteristics of soils stabilized with fly ash, evaluating swelling potential. The results demonstrated a notable decrease in free swelling of clayey soil, with reductions of 50–66% attributed to class F fly ash [82, 87, 89, 90, 92, 94, 95], and 70–85% associated with class C fly ash [87, 89, 93]. In terms of unconfined compressive strength, both varieties of fly ash contributed significantly to enhancing the strength of clayey soils. The utilization of 25% class F fly ash led to a 100–166% increase in UCS [82, 87, 91], while the use of 25% of class C fly ash with a CaO content of 20% led to a strengthening of 103–177% [75, 87, 91]. Furthermore, when class C fly ash with a CaO content exceeding 20% was employed, it yielded a remarkable UCS improvement ranging from 230% to 400% [17, 23, 74]. Nevertheless, there have been few investigations that directly compare the influence of class F and class C fly ashes when added to expansive soils, aiming to identify their distinctions [87, 89, 91, 96, 97]. Therefore, this study aims to address this gap by analyzing recent research findings that explore the effects of class F and class C fly ashes on clayey soils. The primary goal is to develop novel formulas that can guide future researchers in predicting the behavior and performance of clayey soils stabilized by these specific fly ash types. The study's focus encompasses a comprehensive comparison between the two categories across all examined outcomes, including Atterberg limit, free swell index, unconfined compressive strength, and California bearing ratio.

2 Overview of recent research

Over the past two decades, there has been significant interest among researchers in exploring the impact of two types of fly ash, namely class F and class C, on improving various geotechnical parameters of different types of soils. Over 65 studies have been conducted on this subject, with a specific focus on expansive soils. These studies were distributed over recent years, as indicated in Fig. 1. The findings of these investigations have been published in various academic journals, with 20% of them appearing in Elsevier publications, such as "Materials Today" and "Resources, Conservation and Recycling". Additionally, 7.7% of the studies were featured in "Geotechnical and Geological Engineering", 4.6% in "Materials in Civil Engineering", and another 4.6% in "Case Studies in Construction Materials". The remaining 44.5% were published in various other scientific journals, showcasing the wide dissemination of research on this subject across the academic community (Fig. 2). This growing interest and dissemination of knowledge demonstrate the importance of understanding the potential benefits of using fly ash to enhance the geo technical properties of soils and its relevance in various engineering applications.

3 Properties of class F and class C fly ash

In this study, the findings of recent research papers that explored the influence of class F and class C fly ash on the engineering properties of clayey soil were analyzed. The goal was to assess their impact on various clayey soil properties, namely Atterberg Limit [17, 19, 25, 82, 87–89, 95–98], free swell index [17, 89, 95, 98–101], Ultimate Compressive Strength (UCS) [23, 87, 94, 95, 99, 102], and California Bearing Ratio (CBR) [17, 24, 77, 85, 90, 93, 95, 103–106]. To conduct a comprehensive comparative analysis of fly ash as a soil stabilizer, the research articles were organized based on the type of clayey soil and the chemical composition of the two fly ash types as sorted in Table 2 [17, 23, 24, 25, 73, 74, 77–79, 81, 82, 84, 85, 87–89, 91–95, 107].

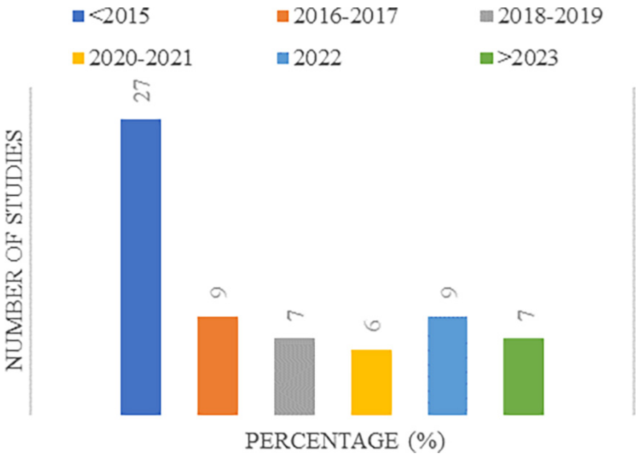

Fig. 1 Experimental studies in recent years

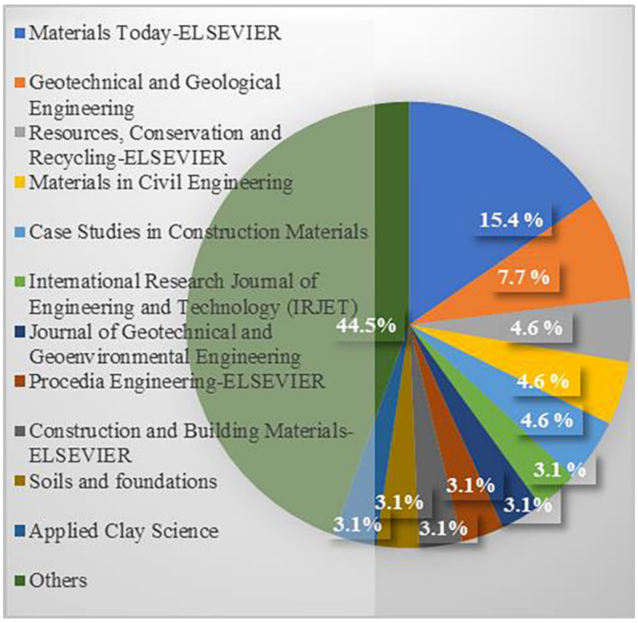

Fig. 2 Academic journal publication patterns: key insights

Regarding the chemical composition, for the percentage of Aluminosilicate ($SiO_2 + Fe_2O_3 + Al_2O_3$), class C fly ash exhibited a range of 50% to 81.6%, and 69.62% to 96.6% for class F fly ash. Notably, the key distinguishing factor between the two classes was the lime (CaO) content, which varied from 12% to 42.25% for class C fly ash (higher concentration) and from 0.48% to 2.65% for class F fly ash (lower concentration). According to ASTM criteria [63], all the reviewed studies on class F fly ash fell within the specified range where Aluminosilicate exceeded 70%, and CaO was less than 10% (Fig. 3). For class C fly ash (Fig. 4), four studies [23, 73, 74, 87] were within the range where Aluminosilicate was between 50–70%, and CaO exceeded 20%. However, some studies did not meet the ASTM criteria, where Aluminosilicate exceeded 70%, and CaO was less than 20% [17, 75, 81, 89]. Still, they were categorized as class C fly ash due to CaO percentages surpassing 10%. The added percentage of fly ash used in the reviewed studies varied from 5% to 90%, with the majority falling within the range of 5% to 30%, as illustrated in Fig. 5. For each soil property examined in the study, appropriate formulas were derived to identify common trends in clayey soil behavior when stabilized with fly ash.

Table 2 Properties of clayey soil and fly ash adopted by each reference

Reference	Soil type	Plasticity index %	Class	Added percentage %	Fly ash-Chemical composition			
					SiO_2	Fe_2O_3	Al_2O_3	CaO
Nalbantoğlu [17]	CL, CH	23,47	C	0,15,25	47.4	5.7	25.5	14.8
Turan et al. [23]	CI	24	F	0,5,10,15,20,25,30	48.6	9.2	22.5	2.2
			C	0,5,10,15,20,25,30	28.3	6.6	15.8	32.4
Behera and Das [24]	CH, 3 samples	20,21,32	F	0,10,20,30,40	-	-	-	-
Munda et al. [25]	CH	31	F	0,10,15,20,25,30	59.28	0.65	9.69	0.48
Senol et al. [73]	CH	35	C	0,10,20	50	24.3		
Reyes and Pando [74]	CH	49	C	0,5,10,15,20	31.17	5.3	18.76	27.9
Bose [77]	EXPANSIVE SOIL	20	F	0,20,40,60,80,90	52.55	-	24.12	2.65
Mishra [78]	CL	12.1	C	0,10,20,30,40,50	-	-	-	-
Takhelmayum et al. [79]	BLACK COTTON	28.88	F	0,5,10,15,20,25,30	-	-	-	-
Ozdemir [81]	CL	12	C	0,3,5,7,10,15,20	48.2	5.3	22.3	15.8
Phanikumar and Nagaraju [82]	CH	55	F	0,5,10,15,20,25,30	59.83	0	30.48	1.74
Amadi [84]	CL	22	F	0,5,10,15,20	46.02	13.68	24.16	1.78
Ramadas et al. [85]	CH	38	F	0,10,15,20,25,30	-	-	-	-
Seyrek [87]	CL, CH	29,45	F	0,5,10,15,20,25,30	54.46	7.38	26.5	1.6
			C	0,5,10,15,20,25,30	40.07	4.62	21.49	20.48
Murmu et al. [88]	CH	46	F	0,5,10,15,20	64.3	2.65	27.45	0.85
Çokça et al. [89]	CH	52	F	0,3,5,8,10,15,20,25	58.62	10.18	19.44	2.18
			C	0,3,5,8,10,15,20,25	44.18	4.85	22.13	18.98
Nath et al. [91]	OH	22.67	C	0,10,15,20	50.2	5.17	22.5	20.3
			F	0,10,15,20	65.6	6	25	1.78
Jose et al. [92]	EXPANSIVE SOIL	28	F	0,10,15	-	-	-	-
Sharma et al. [93]	CL	13.34	C	0,10,15,20,25	-	-	-	-
Phani Kumar and Sharma [94]	CH	52	F	0,5,10,15,20	-	-	-	-
Brooks et al. [95]	CH	21	C	0,15,25,30	55	6.3	20.3	12
Sezer et al. [107]	CH	41.3	C	0,5,10,15,20	24.23	3.89	15.27	42.25

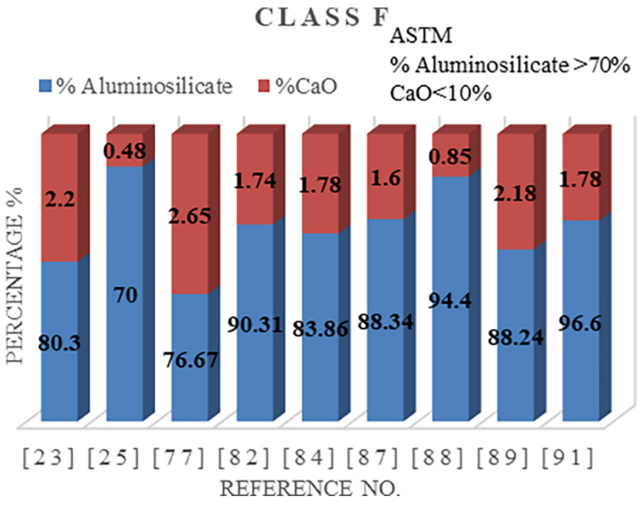

Fig. 3 Percentages of aluminosilicate and CaO in class F fly ash

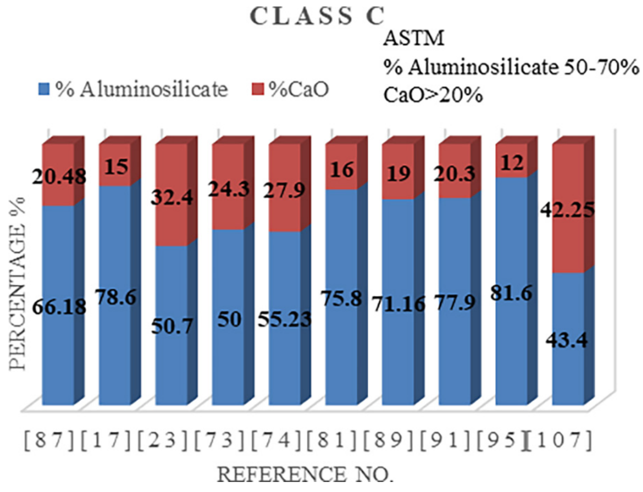

Fig. 4 Percentages of aluminosilicate and CaO in class C fly ash

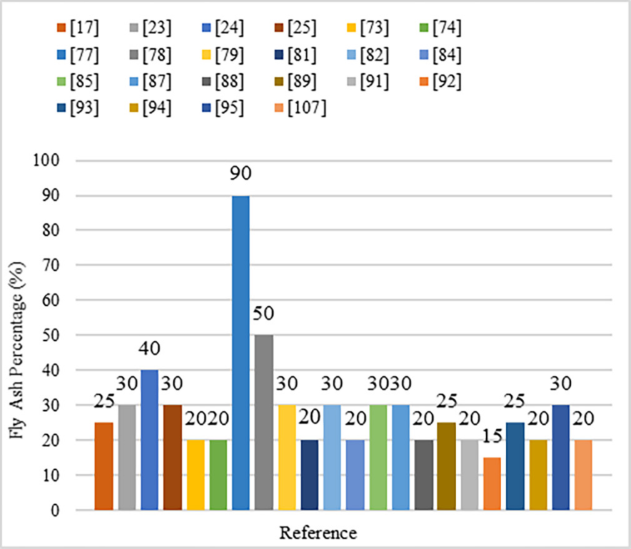

Fig. 5 Percentage of added fly ash adopted by each reference

4 Influence of classes F and C fly ash on geotechnical properties of clayey soil

4.1 Atterberg limit

Clayey soils typically exhibit higher values for both the liquid limit (LL) and plastic limit (PL) when compared to other soil types, highlighting the importance of these limits in the classification and evaluation of soil behavior within the fields of geotechnical engineering and construction. The plasticity of the stabilized soil decreases as the fly ash content increases due to calcium in the fly ash, increasing clay flocculation and reducing plasticity. This observation is common for both class C and class F fly ashes.

In the case of class C, it is generally observed that the inclusion of this fly ash results in a decrease in the liquid limit and plasticity index of stabilized soil [17, 87, 89, 95–97]. For instance, Çokça [89] reported a reduction of 43.24% in the liquid limit and a 75% reduction in the plasticity index when 25% class C fly ash was added to CH soil. Similar trend was observed by Nalbantoğlu [17], with reductions of 25.37% and 68.09% in the liquid limit and plasticity index, respectively. Notably, Seyrek [87] demonstrated that the rate of reduction is more pronounced in high plasticity clay (CH) than in low plasticity clay (CL). Specifically, the addition of 25% class C fly ash to CH soil resulted in a reduction of 43.07% in the liquid limit and a 91.1% reduction in the plasticity index, while in CL stabilized soil, the reductions were 38.3% and 79.3%, respectively. This decrease in plasticity can be attributed to the higher moisture content in CH, facilitating a faster hydration rate, and the reduction rate diminishes with higher fly ash content.

In the case of class F fly ash-stabilized samples, a similar pattern can be observed [19, 25, 82, 87–89, 98]. For instance, Phani Kumar and Sharma [94] found that the plasticity index was reduced by 50% with the addition of 20% FFA to CH soil. Çokça [89] observed that the addition of 25% class F fly ash resulted in a 37.8% reduction in the liquid limit and a 50% reduction in the plasticity index. Similar trends were reported by Murmu et al. [88] and Munda et al. [25], with reductions of 30.64% and 21.3% in the liquid limit, and 41.9% and 45.7% in the plasticity index, respectively.

The changes in the consistency limits can be attributed to two distinct factors. Firstly, fly ash contains silt-sized particles, and as the quantity of fly ash increases, the proportion of clay fractions decreases. Secondly, fly ash promotes the flocculation of clay soil particles, causing them to come together and reducing the thickness of the diffuse double layer around the clay particles. When the expansive clay particles are substituted with silt-sized fly ash particles, the moisture content needed to achieve a fluid-like consistency in the mixture decreases, resulting in a lower liquid limit (LL). This decrease in LL is because fly ash, being pozzolanic, induces flocculation, leading to larger particle sizes in the mixture, which also contributes to the reduced moisture content required for fluidity. Additionally, there was a variation in the plastic limit (PL), which can also be attributed to the flocculation phenomenon. Regarding the differing performance between the two types of fly ash, the primary reason lies in the higher lime content of class C fly ash. This higher lime content enhances its pozzolanic reactivity compared to class F fly ash, thus leading to variations in their effects on the soil mixture.

To assess the effectiveness of the clay-fly ash mixture, the average enhancement ratio (increase/decrease) for the Atterberg Limits was calculated, namely the liquid limit (LL), the plastic limit (PL), and the plasticity index (PI), function of the different fly ash concentrations. Fig. 6 and Table 3 illustrate the enhancement ratio (ER) of the liquid limit (LL), with negative and positive values indicating

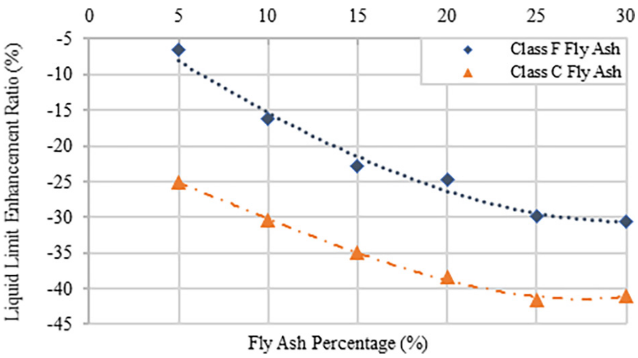

Fig. 6 Liquid limit enhancement with fly ash addition

Table 3 Number of data used in determining the average percentage change of LL shown in Fig. 6

Added %	Class F			Class C		
	No. of data count	Average	STD	No. of data count	Average	STD
5	6	−6.51	4.28	3	−25.08	9.22
10	9	−16.28	8.82	3	−30.41	5.57
15	8	−22.75	7.05	3	−34.98	3.77
20	9	−24.73	7.83	3	−38.39	2.19
25	6	−29.88	6.85	3	−41.54	2.81
30	5	−30.64	10.02	2	−40.98	0.79

a reduction and increase in LL respectively. Notably, for both classes F and C fly ash, the liquid limit decreases as the fly ash percentage increases, although at different rates. Class F fly ash demonstrates an ER increase from 6.5% to 30.64% as the fly ash content rises from 5% to 30%. Conversely, class C fly ash exhibits a more favorable performance, with ER increase from 25.07% to 40.98% for the same fly ash percentage range. Regarding the plastic limit (Table 4), Fig. 7 reveals a different behavior, with an increase observed as fly ash content rises from 5% to 20%, followed by a subsequent decrease. This behavior depends on the soil type and its chemical composition when interacting with fly ash. Consequently, the plasticity index diminishes, as depicted in Fig. 8 and Table 5. Notably, the maximum enhancement ratio was reached at 30% where the percentage decrease for class F was 53.08% and 79.04% for class C fly ash.

Table 4 Number of data used in determining the average percentage change of PL shown in Fig. 7

Added %	Class F			Class C		
	No. of data count	Average	STD	No. of data count	Average	STD
5	2	10.56	0.79	3	25.51	7.59
10	4	24.27	10.5	3	42.42	13.12
15	4	32.27	11.7	3	51.16	17.74
20	4	32.97	11.9	3	53.48	10.23
25	3	28.49	17.4	3	45.24	17.48
30	2	11.11	15.7	2	36.11	19.64

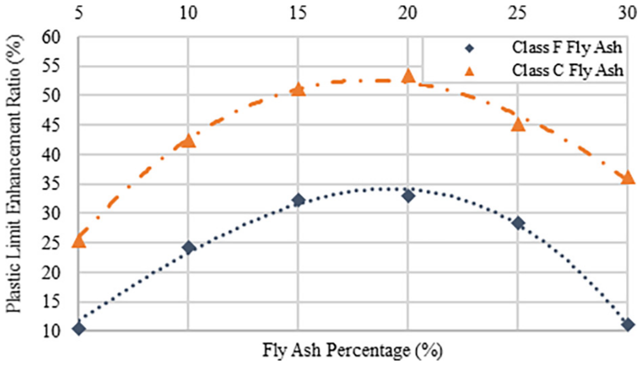

Fig. 7 Plastic limit enhancement with fly ash addition

Based on the data collected from all the references incorporating both class F and class C fly ash, an equation can be derived for LL, PL, and PI relating enhancement ratio (ER) percentage to fly ash (FA) percentage as follows:

$$\mathrm{ER} = 0.0004(\mathrm{FA})^3 + 0.0105(\mathrm{FA})^2 - 1.68(\mathrm{FA}) \quad (1)$$

$$\mathrm{ER} = 0.0010(\mathrm{FA})^3 + 0.0214(\mathrm{FA})^2 - 0.84(\mathrm{FA}) - 20.54 \quad (2)$$

where Eq. (1) corresponds to class F, and Eq. (2) to class C. The coefficient of determination (R^2), which measures the goodness of fit for the regression model, is 0.98 for both equations.

In Eqs. (3) and (4):

$$\mathrm{ER} = -0.004(\mathrm{FA})^3 + 0.04(\mathrm{FA})^2 + 2.25(\mathrm{FA}) \quad (3)$$

$$\mathrm{ER} = 0.001(\mathrm{FA})^3 - 0.20(\mathrm{FA})^2 + 6.14(\mathrm{FA}) \quad (4)$$

where Eq. (3) corresponds to class F, Eq. (4) to class C, with $R^2 = 0.98$ for both equations.

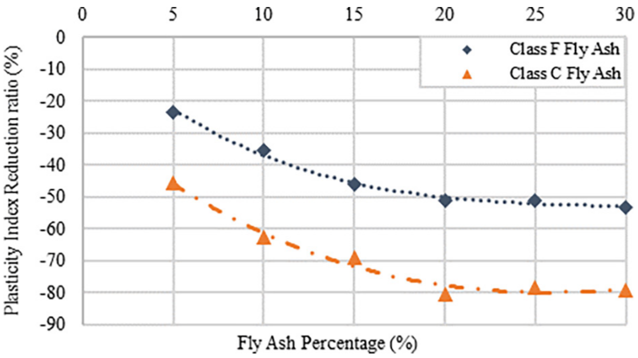

Fig. 8 Plasticity index reduction with fly ash addition

Table 5 Number of data used in determining the average percentage change of PI shown in Fig. 8

Added %	Class F			Class C		
	No. of data count	Average	STD	No. of data count	Average	STD
5	5	−23.53	10.6	3	−45.69	13.5
10	8	−35.55	13.7	3	−62.66	6.74
15	7	−46.05	9.07	4	−69.03	10.5
20	8	−51	10.9	3	−80.64	3.23
25	6	−51.32	7.09	4	−78.38	9.67
30	4	−53.08	18.9	2	−79.04	4.49

In Eqs. (5) and (6):

$$ER = -0.0023(FA)^3 + 0.188(FA)^2 + 5.35(FA) \quad (5)$$

$$ER = -0.0008(FA)^3 + 0.123(FA)^2 - 4.79(FA) - 24.95 \quad (6)$$

where Eq. (5) corresponds to class F, Eq. (6) to class C, with $R^2 = 0.986$ for both equations.

4.2 Free swell

The pozzolanic reaction of fly ash has been demonstrated to enhance shear strength and reduce the swelling potential of expansive soil. In the case of class C fly ash, Salim [99] conducted laboratory experiments to assess the impact of fly ash content in terms of Free Swell Index (FSI), swell potential, and swelling pressure in expansive soil. The results revealed that the percentage of swelling and swell pressure increased with a rise in bentonite content, whereas they decreased with higher levels of fly ash. The optimum fly ash percentage was found to be 5%, resulting in a significant reduction in swelling and swell pressure. Nalbantoğlu [17] investigated the performance of Tuzala and Degirmenlik soil samples at a depth of 1.5 meters from the surface. The study was conducted in two phases, involving compacted soil samples without mixing and soil samples mixed with various percentages of fly ash. The findings showed that untreated Degirmenlik soil had a swelling rate of 19.6%, which was reduced to 6.5% with the addition of 15% class C fly ash, and 3.7% with 25% fly ash. Brooks et al. [95] reported that both fly ash and Limestone Dust significantly impacted soil stabilization, with a focus on free swell index. The results indicated a reduction in the swell potential for all additive soil mixtures. When the fly ash content was 15%, the swell potential decreased by about 25% compared to the untreated samples, and with 25% fly ash, the reduction was about 37.5% compared to the control soil.

In the case of class F fly ash, Zha et al. [98] explored the stabilization of expansive soil using class F fly ash and fly ash-lime as additives. Their findings revealed that the inclusion of fly ash and lime-ash in the soil reduced its capacity for swelling and shrinkage. Moreover, increasing the content of fly ash and lime-ash in the sample led to reductions in free swell, swelling capability, swelling pressures, and linear shrinkage. Even with longer curing times, both FA and Lime-ash soil samples exhibited reduced swelling capacity and inflation pressure. Phanikumar et al. [100] examined the effect of class F fly ash and sand on the swelling behaviour of expansive clay soil and concluded that the free swelling index was reduced by 29% and 50.32%, and swelling potential by 80.4% and 32.7%, with an increase in fine sand and fly ash content from 0 to 25% in the expansive clay soil, respectively.

Phanikumar [101] investigated the impact of fly ash on expansive soil and found that adding 20% fly ash resulted in a 50% reduction in both swelling pressure and swelling potential. However, no significant decrease in swell characteristics was observed beyond 20% fly ash addition.

Curing time also plays a role in influencing swelling potential and swelling pressure, with both significantly decreasing over time. Çokça [89] reported a notable reduction in swelling potential with an extended curing period, aligning with the earlier findings of Zha et al. [98]. This reduction in swell potential due to curing time is attributed to the pozzolanic and self-cementing properties of fly ash. Similarly, Nalbantoğlu [17] observed a decrease in swelling potential with an increase in curing time, with 30 days of curing resulting in nearly zero swelling potential.

Fig. 9 and Table 6 illustrate the impact of introducing fly ash into clayey soil in relation to the free swell index. The addition of fly ash resulted in a noticeable reduction in the free swell index, with class C fly ash exhibiting a more significant influence compared to class F. The degree of improvement ranged from 13.63% to 67.10% for class F

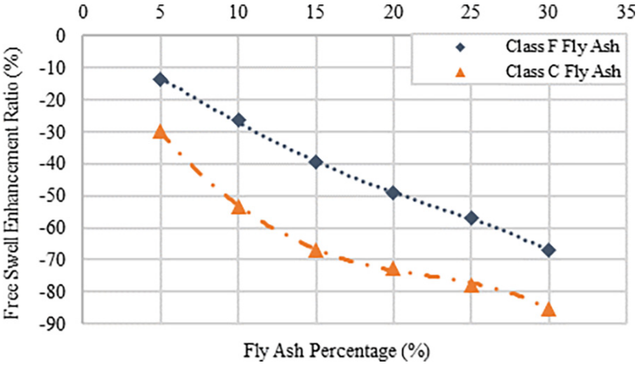

Fig. 9 Reduction in free swell index with fly ash addition

Table 6 Number of data used in determining the average percentage change of free swell index shown in Fig. 9

Added %	Class F			Class C		
	No. of data count	Average	STD	No. of data count	Average	STD
5	5	−13.63	5.17	3	−29.87	16.9
10	5	−26.47	5.32	3	−53.51	9.77
15	5	−39.51	5.48	4	−66.87	6.73
20	5	−49.21	2.94	4	−72.44	5.00
25	3	−56.99	3.12	4	−77.83	5.58
30	3	−67.10	4.45	2	−85.27	0.09

fly ash, and from 29.87% to 85.27% for class C fly ash as the proportion of fly ash increased from 5% to 30%. This reduction in the free swell index can be attributed primarily to the pozzolanic reaction between fly ash and calcium hydroxide within the soil. Class C fly ash, owing to its higher calcium content, exhibits a more pronounced effect in enhancing this reduction. This reaction leads to the formation of stable compounds that bind the clay particles together and alter the soil's microstructure. Consequentley, this modification reduces the size of pore spaces, which limits water permeability, resulting in decreased water absorption and reduced soil swelling. Furthermore, the incorporation of fly ash enhances the soil's strength and cohesion, reducing therefore its vulnerability to swelling. The findings from the analyzed studies establish a correlation between the average enhancement ratio percentage and the percentage of both types of fly ash, as follows:

$$\mathrm{ER} = -0.0001(\mathrm{FA})^4 + 0.007(\mathrm{FA})^3 - 0.096(\mathrm{FA})^2 - 2.32(\mathrm{FA}) \tag{7}$$

$$\mathrm{ER} = -0.0002(\mathrm{FA})^4 + 0.007(\mathrm{FA})^3 + 0.088(\mathrm{FA})^2 - 6.66(\mathrm{FA}) \tag{8}$$

where Eq. (7) corresponds to class F, Eq. (8) to class C, with $R^2 = 0.989$ for both equations.

4.3 Unconfined compressive strength

The examined studies indicated that the inclusion of fly ash in clayey soil led to an increase in unconfined compressive strength (UCS) (Table 7). This strength enhancement is attributed to the pozzolanic activity of the fly ash mixture, which leads to the formation of cementing gel that binds the aggregates together [95]. It is important to note that the UCS is expected to rise as the curing period increase since pozzolanic activity is a time dependent.

Table 7 Number of data used in determining the average percentage change of unconfined compressive strength shown in Fig. 10

Added %	Class F			Class C		
	No. of data count	Average	STD	No. of data count	Average	STD
5	3	8.24	4.67	4	35.22	52.2
10	4	38.15	13.7	4	70.42	51.0
15	4	64.82	16.9	4	84.89	48.2
20	4	78.33	17.7	4	104.04	75.0
25	3	77.22	15.9	3	106.74	72.7
30	3	61.84	26.2	3	71.21	1.71

In the case of class C fly ash, Kang et al. [102] observed that the compressive strength of CL soil increased to 181.2 kPa after adding 10% class C fly ash and continued to increase gradually with longer curing times. All samples (10%, 15%, and 20% fly ash) achieved nearly identical strength after 28 days of curing. Notably, the 15% and 20% fly ash-stabilized samples reached their maximum strength within 14 days, with no further noticeable improvement after that. While the strength gain was faster with higher fly ash additions, the UCS of all samples (10%, 15%, and 20% fly ash) was virtually the same after 28 days of curing. Additionally, Seyrek [87] demonstrated that the inclusion of 25% class C fly ash to both CL and CH soil resulted in an increase in unconfined compressive strength (UCS). For low plasticity clay (CL), the UCS increased from 215.41 kPa to 409.28 kPa, 667.78 kPa, and 883.181 kPa at curing days 1, 7, and 28. In the case of high plasticity clay (CH), the increase was from 285.65 kPa to 542.74 kPa, 942.65 kPa, and 1371.12 kPa at curing days 1, 7, and 28. The UCS increased with both higher fly ash content and longer curing times, although no further increase was detected beyond 25% fly ash, which was considered the optimum. This behavior was consistent with findings by Turan et al. [23], where the percentage increase in UCS was 181% and 229% at 7 and 28 days of curing.

For class F fly ash, Phani Kumar and Sharma [94] demonstrated that the addition of 30% class F fly ash led to an increase in UCS from 120 kPa to 440 kPa and 530 kPa at curing days 7 and 28, respectively. Furthermore, Seyrek [87] confirmed that the optimal addition percentage of class F fly ash was 25% for both CL and CH soil types. The percentage enhancement was 64.3% and 166% for CL soil and 41.67% and 133% for CH soil at curing days 7 and 28. Similar findings were reported by Nath et al. [91], where the percentage increase in UCS for stabilized organic clay OH was 62.5% and 100% at 7 and 28 curing days.

Notably, class C fly ash exhibited superior performance in enhancing UCS compared to class F fly ash. For fly ash contents of 5% and 25%, the enhancement ratio ranged from 8.23% to 78.33% for class F fly ash, while class C fly ash showed a more substantial increase, varying from 35.2% to 106.7%, respectively. The most favorable UCS values were observed at fly ash percentages of 20% to 25% for both types, beyond which a decline in UCS was noted. This trend aligns with the accepted principle that a higher CaO/SiO_2 ratio in fly ash correlates with greater unconfined compressive strength. Class C fly ash, used in the analyzed studies, possessed a higher CaO/SiO_2 ratio, resulting in greater compressive strength due to its self-cementing properties, including the presence of lime and the formation of gypsum through the reaction of anhydrite. Conversely, class F fly ash, with its lower calcium content, exhibited fewer cementitious properties and weaker reactivity with soil. Regarding the optimal fly ash content, the pozzolanic and hydration reactions between fly ash components and soil particles created a stronger soil matrix, increasing compressive strength while also enhancing bulk density. However, once the available calcium hydroxide (CH) was depleted, the pozzolanic reaction ceased. Excessive fly ash lacked binding properties and only adsorbed onto soil particles through van der Waals forces, offering no further strength improvement. Consequently, the effect of fly ash on stabilized soil strength reached a peak, with the optimal fly ash content identified at 20% to 25% for both types, as depicted in the Fig. 10.

In Eqs. (9) and (10):

$$\mathrm{ER} = 0.0006(\mathrm{FA})^4 - 0.044(\mathrm{FA})^3 + 0.96(\mathrm{FA})^2 - 1.98(\mathrm{FA}) \tag{9}$$

$$\mathrm{ER} = -0.0006(\mathrm{FA})^4 + 0.027(\mathrm{FA})^3 - 0.53(\mathrm{FA})^2 + 9.72(\mathrm{FA}) \tag{10}$$

where Eq. (9) corresponds to class F, Eq. (10) to class C, with $R^2 = 0.989$ for both equations.

4.4 California Bearing Ratio (CBR)

The analyzed studies indicated that the incorporation of fly ash into clayey soil resulted in an increase in the California Bearing Ratio (CBR). In the context of class C fly ash, Sharma et al. [93] found that the most significant improvement in the stabilization of clay soil was achieved with a 20% fly ash addition, resulting in a CBR increase of approximately 5.7%. The use of fly ash also enhanced the geotechnical properties of the soil. Brooks et al. [95] recommended the use of approximately 25% of class C fly ash for optimal performance. Trivedi et al. [103] investigated the impact of various fly ash percentages mixed with soil samples and observed that even small fractions of fly ash had a considerable effect on the soil. The addition of 20% fly ash increased the CBR value from 5.64% to 20.53%. It was evident that the soil containing 20% fly ash yielded the most favorable results in terms of soil stability compared to other percentages. Bin-Shafique et al. [104] reported that the CBR value of Scenic Edge soil (CL) increased from 1 to 62 with the addition of 20% fly ash. However, the CBR gain was not significant beyond the 15% fly ash addition. In the case of silty clay, the CBR value increased from 3 (unstabilized) to 50 after adding 20% fly ash, and the rate of CBR increase was not substantial above a 10% fly ash addition. This improvement can be attributed to the formation of cementing gels (hydrates) resulting from the reactions between the CaO in fly ash and the aluminosilicate in the soil. Extensive research by prominent experts in the field indicates that the maximum CBR value achieved by adding fly ash to various soil types falls within the range of 15% to 20% fly ash content.

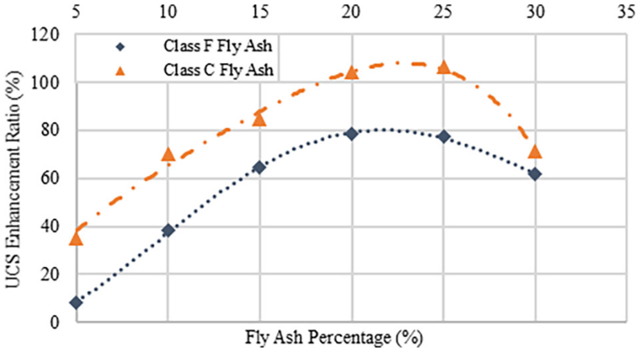

Fig. 10 UCS enhancement with fly ash addition

In the case of class F fly ash, Dixit et al. [105] indicated that using fly ash as an additive to enhance soil stability with varying percentages increased the CBR value, making it more suitable for constructing road pavements. Similar results were obtained by Bose [77]. Gireesh Kumar and Harika [90] examined the influence of fly ash on the stabilization of expansive subgrade black cotton soil. The CBR value for untreated soil was approximately 2.189%, while treated soil with 10% fly ash achieved a CBR value of 2.33%. The study suggests that mixing up to 10% fly ash with black cotton soil is suitable for foundation and pavement work. Pandian et al. [106] investigated the improvement of CBR using FFA in CH soil. They observed two peak CBR values as the fly ash percentage gradually increased from 0% to 100%. The highest unsoaked CBR value of 11 was achieved with the addition of 20% fly ash, and the CBR values decreased after samples were soaked for four days, with the highest soaked CBR value reaching 5. Therefore, the addition of FFA to soil only slightly enhances the CBR value. Ramadas et al. [85] demonstrated that the addition of 25% of class F fly ash increased the CBR value from 2.1 (for untreated samples) to 4.2. Furthermore, Behera and Das [24] studied the impact of class F fly ash on three different samples of high plasticity clay (CH) and concluded that this stabilization increased the percentage enhancement of the CBR value by an average of 76.3% with 30% fly ash content.

Notably, class C fly ash exhibited superior performance in enhancing CBR compared to class F fly ash (Fig. 11). For 30% of class F fly ash, the average enhancement ratio was 93.2% [24, 85], whereas it was 124% for class C fly ash [17, 93, 95]. This enhancement reflects the pattern observed in the Ultimate Compressive Strength where fly ash, particularly class C fly ash containing lime (CaO), enhances soil strength by filling voids, increasing cohesion, and friction between soil particles. It reduces soil plasticity, making it more stable and less prone to volume changes. Chemical reactions between fly ash and soil minerals create cementitious compounds, further strengthening the soil. Consequently, researchers have established the effectiveness of both class F and class C fly ashes in enhancing CBR. However, due to the limited data available for this geotechnical parameter, there is insufficient information to formulate precise equations for identifying consistent patterns in CBR enhancement when stabilized with fly ash.

5 Conclusions

The primary objective of this research was to conduct a critical review to investigate the impact of both class F and class C fly ashes on expansive clayey soils. The study focused on providing a comparative analysis between these two fly ash categories across various geotechnical parameters, including Atterberg limits, free swell index, unconfined compressive strength, and California bearing ratio. This study has resulted in the development of novel formulas aimed at aiding future researchers in predicting the behavior and performance of clayey soils stabilized with these specific fly ash types:

- In terms of Atterberg limit, both class F and class C fly ash have a beneficial impact on the Atterberg limits of clayey soils, primarily reducing the liquid limit and plasticity index as their content increases.

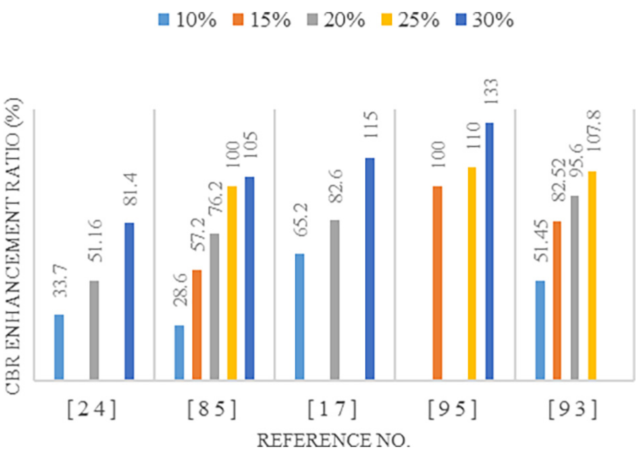

Fig. 11 CBR enhancement with fly ash addition

- Class F fly ash demonstrated an enhancement ratio increase in liquid limit from 6.5% to 30.64% as fly ash content increased from 5% to 30%, while class C fly ash showed a more favorable performance, with an ER increase from 25.07% to 40.98% in the same range Additionally, the plastic limit exhibits variability with an initial increase and subsequent decrease as fly ash content rises, influenced by soil type and chemical interactions with fly ash. Consequently, the plasticity index decreased with a maximum enhancement ratio achieved at 30%, with a 53.08% reduction for class F and a 79.04% reduction for class C fly ash.
- In terms of free swell index, the incorporation of fly ash, particularly class C, has a substantial and favorable impact on reducing the free swell index of clayey soils. The extent of improvement ranged from 13.63% to 67.10% for class F fly ash and from 29.87% to 85.27% for class C fly ash as the fly ash proportion increased from 5% to 30%. This reduction in the free swell index can be attributed primarily to the pozzolanic reaction that takes place between the fly ash and the calcium hydroxide present in the soil. Notably, class C fly ash, with its higher calcium content, exhibits a more significant influence in enhancing this reduction.
- In terms of UCS, the inclusion of fly ash into clayey soil significantly improved its unconfined compressive strength with class C fly ash proved to be more effective than class F, demonstrating a positive correlation with the CaO/SiO_2 ratio in the fly ash. For fly ash contents of 5% and 25%, the enhancement ratio ranged from 8.23% to 78.33% for class F fly ash, while class C fly ash exhibited a more substantial increase, varying from 35.2% to 106.7%, respectively. The study revealed that the most favorable UCS values were consistently observed when the fly ash content ranged from 20% to 25% for both types, revealing the importance of selecting the optimal fly ash content for soil stabilization. Class C fly ash, with its higher CaO/SiO_2 ratio and self-cementing properties, displayed superior reactivity with the soil. It was also emphasized that excessive fly ash offered no additional strength improvement once calcium hydroxide was depleted, emphasizing the importance of balanced fly ash proportions in soil stabilization projects.

- In terms of CBR, class C fly ash demonstrated superior performance in enhancing California bearing ratio (CBR) compared to class F fly ash. At 30% of class F fly ash, the average enhancement ratio was 93.2%, whereas it was 124% for class C fly ash. This enhancement aligns with the pattern observed in Ultimate Compressive Strength, where fly ash, particularly class C fly ash containing lime (CaO), enhances soil strength by filling voids, increasing cohesion, and friction between soil particles. It reduces soil plasticity, making it more stable and less susceptible to volume changes. Chemical reactions between fly ash and soil minerals create cementitious compounds, further reinforcing the soil.
- Correlations between Atterberg limits, free swell index, and UCS in relation to fly ash content were derived that can guide future researchers in predicting the behavior and performance of soils incorporating these specific fly ash types. The data representing the relationship between the enhancement ratio and fly ash percentages was found to be a strong fit with the derived formulas, indicated by high coefficient of determination (R^2) values such as 0.9829 and 0.9978 for liquid limit, 0.9916 and 0.9921 for plastic limit, 0.9932 and 0.978 for plasticity index, 0.9996 and 0.9991 for free swell index, and 0.9994 and 0.9867 for unconfined compressive strength for class F and class C, respectively. However, in the case of the California Bearing Ratio (CBR), more extensive research is necessary to accumulate sufficient data for developing a new predictive formula for CBR values in soils stabilized with these types of fly ash.

6 Recommendations

The recommendations for this research are the followings:

- The derived formulas were based on a rough correlation by estimating the average enhancement ratio with respect to the fly ash percentages and thus the trend of each geotechnical parameter may change depending on the properties of the expansive clayey soil and the chemical composition of the fly ash used in any investigation. However, these correlations are valuable because they provide a systematic way for future researchers to predict how the addition of specific types of fly ash will affect the behavior and performance of expansive soils.
- It has been acknowledged that class C fly ash exhibits better performance than class F in soil stabilization, yet it is expensive and may not be readily accessible in all geographic areas. Therefore, the choice between class F and class C fly ash should be made based on their availability and cost, specific project requirements, and desired engineering properties, as their chemical compositions and performance characteristics differ.

7 Future research studies

There is potential for future research studies:

- Future research could empirically validate the correlations identified in this study by testing them in real-world scenarios or controlled experimental settings.
- Longitudinal studies could be conducted to assess whether these predicted correlations remain consistent over time.
- AI-driven data analytics and machine learning models could be leveraged to refine and enhance the accuracy of predictive correlations.

These studies will enhance prediction accuracy, optimize stabilization methods, and ensure reliable field applications of fly ash in expansive soils.

Statement for conflict of interest

All authors declare that they have no conflicts of interest.

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