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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Numerical Investigation of Clayey Slopes Stabilised with Fly Ash-Based Materials

Uçucu Kül Bazlı Malzemelerle Güçlendirilen Killi Şevlerin Sayısal Analizi

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Abstract

This study investigates the potential use of Class C fly ash, Class F fly ash, and alkali-activated Class F fly ash to improve the slope stability of clay embankments through 3D numerical modelling with PLAXIS. Laboratory-based input parameters, derived from previous experimental work by the author, were used to define the geotechnical behaviour of the soils in the simulations. Results demonstrate that clay slopes stabilised with alkali-activated Class F fly ash provides the most effective improvement, with significant increases in factor of safety and reductions in plastic strain zones. Although Class C fly ash moderately improved soil stiffness, it was not fully effective in mitigating deformation. Class F fly ash exhibited similar behaviour to the control sample due to its limited reactivity; however, its performance improved significantly following alkali activation. These findings suggest that, especially in regions where granular fill material is scarce, the slope stability of locally found clay soils can be effectively improved using alkali-activated fly ash. This approach not only enhances slope performance but also contributes to more sustainable geotechnical practices by reducing the consumption of natural resources and lowering overall construction costs.

Keywords: *Slope Stability, Plaxis 3D, Fly Ash Stabilisation, Alkali Activation, Clay*

Öz

Bu çalışma, kilden oluşan şev dolgularının stabilitesini artırmak amacıyla, C sınıfı uçucu kül, F sınıfı uçucu kül ve alkali aktivatör ile aktive edilmiş F sınıfı uçucu kül kullanım potansiyelini, PLAXIS yazılımı ile gerçekleştirilen 3 boyutlu sayısal modelleme aracılığıyla incelemektedir. Sayısal analizlerde kullanılan geoteknik parametreler, yazar tarafından daha önce yürütülen laboratuvar deneylerinden elde edilmiştir. Elde edilen sonuçlar, alkali aktivatörle stabilize edilmiş F sınıfı uçucu külün, güvenlik katsayısında belirgin artışlar ve plastik şekil değiştirme bölgelerinde azalmalar sağlayarak en etkili iyileştirmeyi sağladığını ortaya koymaktadır. C sınıfı uçucu kül, zemin rijitliğini belirli ölçüde artırsa da deformasyonu azaltma konusunda tam anlamıyla etkili olamamıştır. F sınıfı uçucu kül ise düşük reaktivitesi nedeniyle kontrol numunesine benzer bir davranış sergilemiş; ancak alkali aktivasyon sonrası performansında önemli iyileşmeler gözlenmiştir. Bu bulgular, özellikle granüler dolgu malzemesinin kısıtlı olduğu bölgelerde, yerel kil zeminlerin alkali aktivatör ile işlenmiş uçucu kül kullanılarak etkin şekilde iyileştirilebileceğini göstermektedir. Bu yaklaşım, yalnızca şev performansını artırmakla kalmayıp, aynı zamanda doğal kaynak tüketimini azaltarak ve inşaat maliyetlerini düşürerek daha sürdürülebilir geoteknik uygulamalara katkı sağlamaktadır.

Anahtar Kelimeler: *Şev Stabilitesi, Plaxis 3D, Uçucu Kül ile Zemin Iyileştirmesi, Alkali Aktivasyon, Kil*

1. Introduction

Untreated soil embankments can pose significant risks, including pavement damage, settlement, and slope failures [1]. Therefore, ensuring the stability of embankment slopes is essential to prevent such geotechnical hazards. Slopes constructed on fine-grained soils, particularly clayey soils, may exhibit initial stability shortly after construction [2]. However, the shear strength of these soils often decreases over time, eventually approaching the fully softened strength as defined by Skempton [3].

To improve the long-term stability of soil slopes, various ground improvement techniques have been applied, generally classified as mechanical or chemical stabilisation. Mechanical stabilisation includes methods such as mechanically stabilised earth systems, retaining structures, soil nailing, and the use of geosynthetic reinforcements, often in combination with materials such as concrete, gabions, or rock fills. Chemical stabilisation, on the other hand, involves the incorporation of chemical additives to enhance the shear strength of the soil, thereby increasing its resistance to gravitational forces [2]. In addition to technical effectiveness, the economic feasibility and environmental impact of these methods are also critical considerations in modern engineering practice.

Recently, there has been a growing shift towards more cost-effective and environmentally sustainable alternatives to traditional stabilisation techniques. Cement, for instance, remains one of the most commonly used chemical stabilisers in soil improvement. However, cement production is responsible for nearly 8% of global greenhouse gas emissions [4]. This level of emissions is anticipated to grow further due to the increasing demand for construction worldwide [5]. Consequently, identifying sustainable alternatives for cement has become increasingly urgent to mitigate CO_2 emissions and support the transition to greener engineering practices [6].

Fly ash, a by-product generated from coal combustion in thermal power plants, has emerged as a promising alternative to cement in soil stabilisation [7]. Researchers have highlighted its pozzolanic properties, ease of application, and cost-effectiveness as key advantages [8]. According to ASTM C618 [9] standards, fly ash is classified into Class C and Class F. Class C fly ash contains 20-40% calcium oxide (CaO) and exhibits both cementitious and

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pozzolanic properties. In contrast, Class F fly ash, with less than 12% CaO, is primarily pozzolanic. Furthermore, the combined content of SiO_2, Al_2O_3, and Fe_2O_3 in Class C fly ash typically ranges between 50% and 70%, whereas in Class F fly ash it usually exceeds 70% [9]. Due to its lower self-cementing capacity, Class F fly ash often requires additional activation agents to enhance its performance [10]. The lower chemical reactivity of Class F fly ash compared to Class C is not solely due to its low CaO content, but also influenced by factors such as lower alkali content and, in some cases, a lower proportion of the glassy (amorphous) phase. The origin of the coal and combustion conditions play a crucial role in determining these characteristics. Class C fly ash is typically derived from younger lignite or sub-bituminous coal, which burns at lower temperatures and cools more rapidly, conditions that favour the formation of a higher glass phase content. In contrast, Class F fly ash is usually produced from bituminous coal or anthracites, which tend to combust at higher temperatures and cool more slowly [7, 10]. These conditions may result in a lower proportion of amorphous phases and a higher degree of crystallinity in some cases, thereby limiting its inherent pozzolanic reactivity. As a result, external activation, typically through alkali solutions or thermal treatment, is often required to improve the binding efficiency of Class F fly ash in soil applications. Moreover, as an aluminosilicate-rich industrial residue, Class F fly ash is widely used as a precursor for synthesising geopolymers. Its high content of reactive silica and alumina in amorphous form significantly contributes to its suitability for geopolymerisation [11]. When activated with alkaline solutions, Class F fly ash can produce geopolymeric binders capable of substantially improving soil strength and durability. Several studies have demonstrated the potential of alkali-activated fly ash in stabilising soils, with the efficiency depending on factors such as activator concentration, curing conditions, and fly ash dosage [12-14].

A considerable body of laboratory-based research has confirmed that both Class C and Class F fly ash, -especially when alkali-activated- can improve soil properties such as plasticity, swelling behaviour, compaction, and strength parameters [10,11,15-21]. While Class C fly ash generally provides rapid strength gain due to its cementitious nature, Class F fly ash typically requires higher content or activation to achieve comparable results.

Despite extensive laboratory studies demonstrating the effectiveness of fly ash and alkali-activated fly ash in soil stabilisation, numerical studies assessing their performance in slope stability applications remain scarce. In particular, the integration of these materials into slope stability modelling frameworks is still limited in the literature. Although several recent studies have employed numerical simulations to assess the use of recycled and waste materials in embankment construction [2,4,22], studies specifically focusing on Class C, Class F, and alkali-activated fly ash are still lacking.

In view of this, the present study aims to contribute to the growing body of sustainable geotechnical research by numerically assessing the slope stability of embankments constructed with Class C fly ash, Class F fly ash, and alkali-activated Class F fly ash. Given the increasing emphasis on environmentally friendly stabilisation practices, the PLAXIS 3D finite element software is employed to model and analyse the behaviour of stabilised and unstabilised embankment slopes under gravity loading conditions. The analysis focuses on key parameters such as overall slope stability, factor of safety (FoS), and plastic strain patterns. The strength reduction method is used to identify critical failure mechanisms and determine corresponding FoS values. By incorporating laboratory-derived compaction and triaxial test data into the numerical models, this study establishes a realistic framework for evaluating the mechanical behaviour of stabilised and unstabilised soils. The outcome of this study is expected to support the adoption of Class C, Class F, and alkali-activated fly ash in embankment stabilisation, presenting a technically viable, cost-effective, and environmentally sustainable alternative to conventional methods.

2. Materials and Methods

2.1. Materials

In this study, kaolinite clay was used as the base soil, which had previously been characterised in detail according to British Standards (BS) [23,24] by Turan et al. [10], as summarised in Table 1. The stabilisation of the clay was carried out using Class C fly ash, Class F fly ash, and alkali-activated fly ash at proportions of 15% and 25% by the dry weight of the soil. For alkali activation, the alkali content ratios were set to silica modulus (SM) (SiO_2/Na_2O) of 1.25 and alkali dosages (M+) (Na_2O/fly ash) of 12%. These values provided the most comparable improvements in strength according to UCS results from earlier studies [10,11,25]. The UCS tests were repeated three times for each mixture to ensure result reliability, and the average values guided the selection of the 15% and 25% additive contents. Therefore, detailed consolidated-undrained (CU) triaxial tests were conducted on samples stabilised with 15% and 25% fly ash and alkali-activated fly ash, and the input parameters derived from these tests, comprising cohesion, angle of shearing resistance, and unit weight, were used in the slope stability analysis (Table 2).

Table 1. Index and compaction properties of the kaolinite clay.

Clay properties	Value	Standard
Liquid limit (LL)	49%	BS 1377-2 [23]
Plastic limit (PL)	25%	
Plasticity index (PI)	24%	
Classification (BS)	CI	
Maximum dry unit weight (γ_{dmax})	15.2 kN/m^3	BS 1377-4 [24]
Optimum moisture content (w_{opt})	21%	
Specific gravity (Gs)	2.6	BS 1377-2 [23]

2.2. Method

The slope model was developed using PLAXIS 3D, a widely utilised finite element software in geotechnical engineering. Unlike most previous studies in the literature, which commonly employ two-dimensional slope models, this study constructed a full three-dimensional (3D) slope model. The side view of the three-dimensional slope model is presented in Figure 1.

During the meshing process, solid elements were generated using the fine mesh option. This selection was made to minimise numerical convergence errors and to avoid potential inaccuracies associated with overly coarse elements. Particular attention was given to ensuring that the boundary conditions realistically represented actual field constraints. Accordingly, the 80-metre base of the slope was fixed in the vertical direction, whereas the top surface was left free to deform vertically [26].

The analyses focused only on vertical loading conditions, including gravity loading, plastic deformation analysis, and the calculation of the FoS. No additional environmental effects, such as rainfall infiltration or variations in groundwater level, were considered. This simplified modelling approach was adopted to evaluate the fundamental performance of waste-based stabilisers -Class C fly ash, Class F fly ash, and alkali-activated fly ash- under dry slope stability conditions.

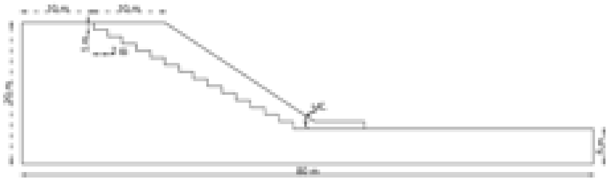


Figure 1. Side view of the slope model geometry.

The staircase-like structure and the inclined surface shown in Figure 1 together represent the complete geometry of the modelled slope. In the initial phase of the study, the entire slope was analysed under the assumption that it consisted solely of the control sample. Reinforcement using waste materials was then carried out by removing the inclined surface and replacing it with soil samples stabilised with various reinforcement agents. This procedure is illustrated in more detail in Figure 2. In this figure, the area highlighted in turquoise represents the control sample, while the green-shaded region indicates the portion where the original soil was excavated and substituted with stabilised soil specimens incorporating waste-based materials. This modification enabled the evaluation of the influence of the stabilising agents on slope performance under dry conditions.

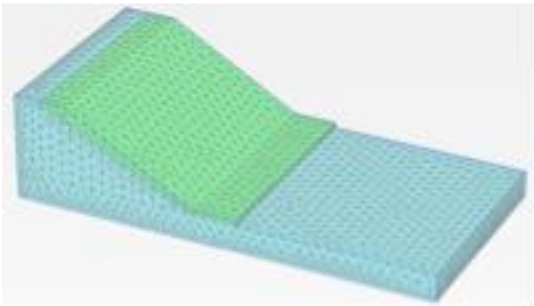


Figure 2. 3D meshed geometry of the slope model with highlighted control (turquoise) and reinforced (green) zones.

The development of the slope model incorporated essential input parameters of the fill materials, including shear strength characteristics -cohesion and angle of shearing resistance- as well as compaction properties such as maximum dry unit weight. These values were adopted from previous experimental work by Turan et al. [10,11] and Turan [25], where standard Proctor and consolidated undrained (CU) triaxial tests were conducted on soils stabilised with Class C fly ash, Class F fly ash, and alkali-activated fly ash (Class F+AA) at 28 days curing time. The reason for selecting 28-day test data is that, although 1-day and 7-day results can provide an early indication of initial stability, the 28-day results offer a more comprehensive assessment of the stabilisation performance. By this time, the majority of the chemical reactions have reached completion, making the data more representative of long-term behaviour. A summary of the input parameters used in the numerical analyses is presented in Table 2.

Table 2. Laboratory-derived geotechnical parameters of Class C, Class F, and alkali-activated fly ash stabilised soils for PLAXIS 3D numerical modelling [10,11,25].

Sample designations	Dry unit weight (γd) (kN/m3)	Effective cohesion (c′) (kPa)	Effective angle of shearing resistance (φ′) (°)
Control sample	15.2	19.0	18.4
15% class C	14.5	86.6	22.5
25% class C	14.3	99.1	24.0
15% class F	14.2	11.1	22.3
25% class F	13.9	15.1	22.4
15% class F+AA	14.6	183.3	22.6
25% class F+AA	14.5	388.6	29.0

3. Results and Discussion

3.1. Slope behaviour and deformation contours under FoS analysis

The effects of varying proportions of fly ash (Class C and Class F) and alkali-activated fly ash additives on the slope stability of stabilised soils were assessed through FoS analyses and deformation contour evaluations conducted using PLAXIS 3D software. The FoS-iteration curves presented in Figure 3 clearly demonstrate the influence of each mixture on slope behaviour. Furthermore, Figures 4(a–h) show the variations in deformation contours for both the control sample and the stabilised soils within the context of the FoS analysis, while the corresponding FoS values are presented in Table 3. Specifically, Figures 4(b–h) provide side-view outputs derived from PLAXIS 3D simulations, enabling clearer observation of the contour patterns. These side views were extracted from the mid-section of the three-dimensional models, with Figure 4(a) presenting the control sample as a representative reference.

Table 3. FoS values of the control sample and soils stabilised with Class C fly ash, Class F fly ash, and alkali-activated Class F fly ash.

Sample designations	FoS values
Control sample	1.44
15% class C	1.71
25% class C	1.76
15% class F	1.43
25% class F	1.45
15% class F+AA	1.85
25% class F+AA	2.14

In the control sample with no additives, the obtained FoS remained at approximately 1.44. This value is one of the lowest recorded among all analysed samples, indicating that the slope is at a critical safety threshold. According to various standards, an FoS below 1.50 is considered critical, particularly in scenarios requiring a high level of protection for human life, property, and the environment [4]. In this context, the use of the control sample alone may lead to slope failures and related stability issues over time. Leroy et al. [27] also emphasised that when the slope is in a critical FoS condition, the likelihood of landslides becomes significantly high due to both internal and external triggering factors. An examination of the deformation contours further reveals that, in the control sample, a limited but deep-seated deformation occurred, especially near the toe of the slope, indicating a dominant rotational failure mechanism (Figure 4b). In the mixture containing 15% Class C fly ash, the FoS increased to approximately 1.71. This improvement is directly proportional to the enhancement in cohesion and angle of shearing resistance.

In a study examining the effects of nano-material-induced improvements in soil microstructure on slope stability, Shwan [28] demonstrated through numerical analyses that increases in both cohesion and angle of shearing resistance led to a significant rise in FoS. Similarly, the experimental results presented in the methodology section were consistent with the numerical findings obtained in this study, thereby supporting model validation and reinforcing the reliability of the adopted approach. However, despite the increase in FoS, the deformation distribution remained uncontrolled, and the slip surface was clearly observed (Figure 4c). When the additive ratio was increased to 25%, the FoS rose slightly further to approximately 1.76. Nonetheless, the trend of the FoS curve and the deformation contours were found to be similar to those obtained with the soil stabilised using 15% Class C fly ash (Figure 4d). Compared to the control sample, the soils stabilised with 15% and 25% Class C fly ash exhibited increased stiffness. This indicates that the performance improvements resulting from the hydration and pozzolanic properties of Class C fly ash were not only supported by chemical and experimental evidence, but also validated through numerical analyses conducted in this study. However, it was also observed that these mixtures still could not fully prevent the spread of deformation. In a similar study, Rajak et al. [29] conducted numerical analyses using the FLAC software and reported that increasing the fly ash content significantly improved the FoS of slopes. This trend continued consistently up to a fly ash content of 30%, beyond which a slight decline in FoS values was observed. Accordingly, an optimal fly ash content of 30% was recommended for improving slope stability.

In the mixtures containing Class F fly ash, the FoS obtained with a 15% additive content remained approximately 1.43, comparable to that of the control sample (Figure 4e). This outcome indicates that low-reactivity Class F fly ash does not significantly contribute to slope stability. When the dosage was increased to 25%, the FoS rose slightly to around 1.45; however, no notable difference was observed between the two mixtures in terms of deformation contour patterns (Figure 4f). The limited performance of Class F fly ash is attributed to its low calcium content, which prevents it from effectively participating in hydration reactions. As a result, it provides only a limited binding effect through pozzolanic activity. Turan et al. [10] and Seyrek [19] have both emphasised that Class F fly ash alone exhibits insufficient reactivity and must be combined with suitable chemical activators to enhance its effectiveness. Accordingly, in the context of the present slope stability cases, it has been demonstrated that the additive failed to ensure adequate structural integrity and stiffness (Figures 4e-f).

The inclusion of Class F fly ash activated with an alkaline solution generated notably improved results at both replacement levels. In the mixture containing 15% alkali-activated Class F fly ash, the FoS increased to approximately 1.85 (Figures 3 and 4g). This demonstrates that alkali activation enhances the reactivity of Class F fly ash, thereby improving both cohesion and binding capacity. The deformation distribution in this case was significantly limited, and the slip surface was effectively controlled. The mixture with 25% alkali-activated fly ash achieved the highest FoS among all tested samples, reaching approximately 2.14 (Figure 4h), which corresponds to an increase of nearly 49% compared to the control sample. The curve rose steeply with iterations, and the deformation contours were confined to a very narrow zone. The absence of a clearly defined slip surface and the near-elimination of deformation indicate that this additive combination most effectively improved both strength and deformation control. Similarly, Munoz et al. [4] developed a stabilised soil mixture incorporating rice husk ash - whose chemical composition resembles that of Class F fly ash- along with Portland cement and a small amount of polypropylene fibre. Given that materials similar to Class F fly ash typically offer limited improvement when used alone, the addition of supplementary materials was employed to enhance soil performance. Slope stability analyses performed using the Slide2 software showed that this multi-component stabilisation system produced high FoS values [4]. Thus, a more environmentally friendly approach was achieved by minimising the use of conventional materials such as cement.

Overall, the results indicate that both the type and proportion of additives have a pronounced impact on slope stability. The best performance was achieved with the mixture containing 25% Class F fly ash activated by an alkaline solution, in which the factor of safety was maximised and deformations were effectively controlled. These findings highlight that additives with inherently low reactivity, such as Class F fly ash, can result in significant improvements in slope stability when chemically activated with alkali solutions.

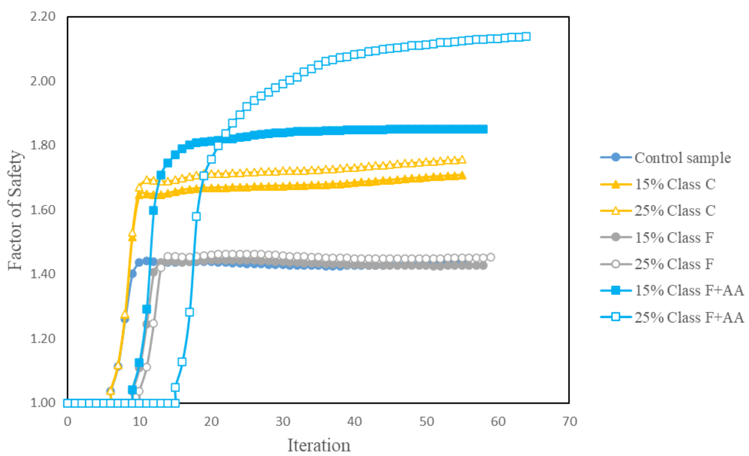
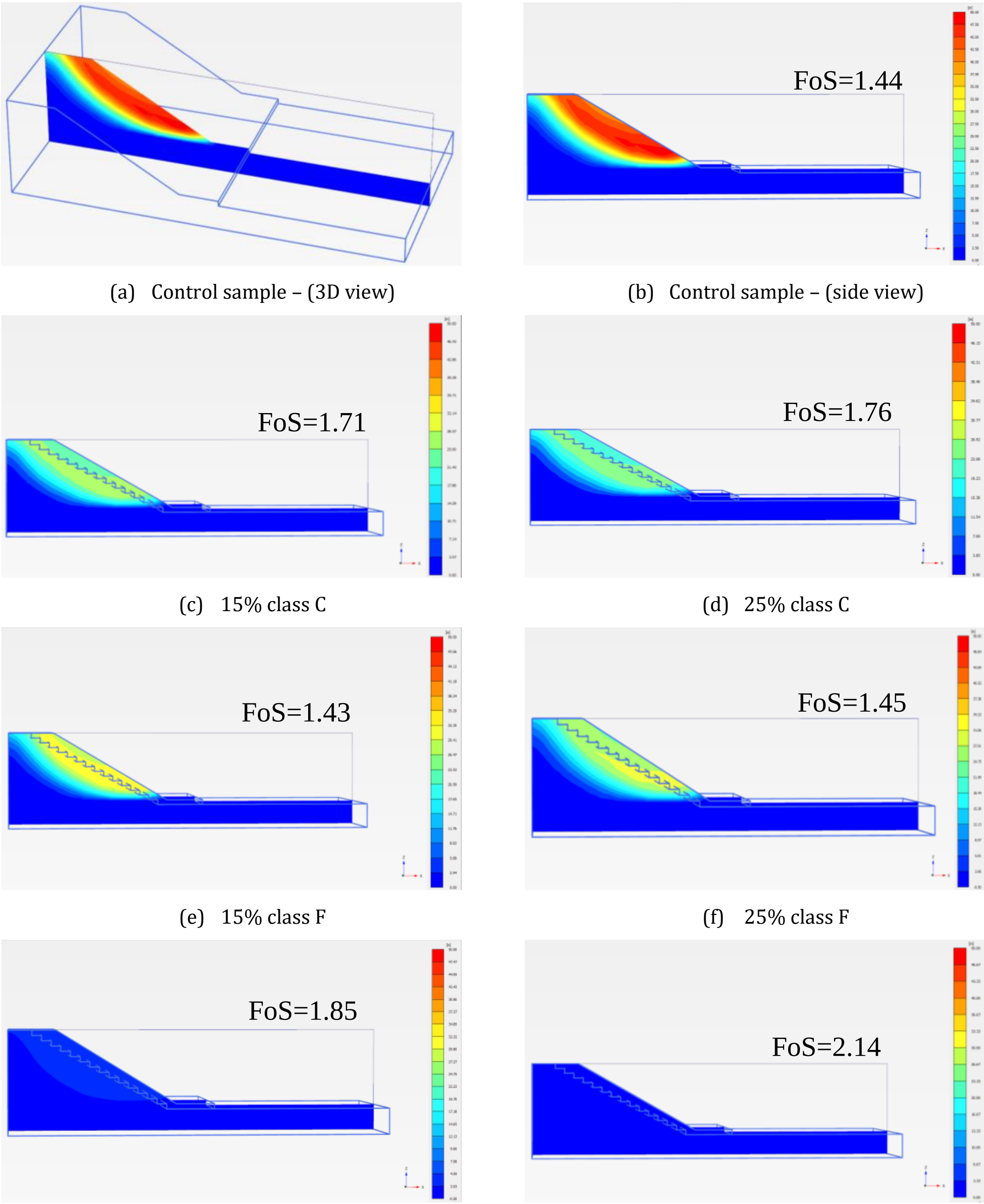


Figure 3. Variation of the factor of safety with iterations for different stabiliser types and contents, as obtained from PLAXIS 3D analyses.



(a) Control sample – (3D view)

(b) Control sample – (side view)

(c) 15% class C

(d) 25% class C

(e) 15% class F

(f) 25% class F

(g) 15% class F+AA

(h) 25% class F+AA

Figure 4. Phase displacement contours obtained from slope stability analyses using PLAXIS 3D for different stabilised soil mixtures. Each panel (a-h) represents the corresponding mixture condition. The contours show deformation patterns under FoS conditions, with the respective FoS values indicated above each figure.

3.2. Strain behaviour under FoS analysis

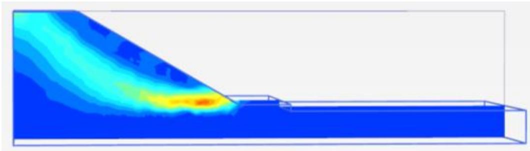
The primary strain (ε1) contours obtained under the FoS analysis are presented in Figures 5(a-g) to evaluate the effect of different types and proportions of additives on the deformation behaviour within the slope. These contours visually illustrate the location and depth of potential slip surfaces, as well as the degree of deformation.

The strain distribution of the control sample (Figure 5a) is predominantly localised around the toe of the slope, with deformation occurring near the surface. The deformation depth is shallow, and the strain is concentrated within a specific region. This indicates that the soil, characterised by low cohesion and internal friction angle, has undergone brittle rotational failure, suggesting that the elastic threshold has been exceeded.

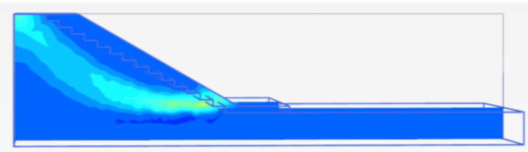
The strain behaviour of Class C fly ash mixtures shows that the 15% addition (Figure 5b) exhibits reduced deformation compared to the control sample. The strain contours remain concentrated near the toe of the slope, with a shallow and localised pattern of deformation. In the case of the 25% fly ash mixture (Figure 5c), the strain values are slightly lower and the distribution appears more uniform. However, overall, the difference between the 15% and 25% mixtures is not substantial, suggesting that both proportions result in only a partial improvement in deformation behaviour. This indicates that although Class C fly ash contributes to increased soil stiffness due to its hydration properties, its effectiveness can be considered moderate. Similarly, Hu et al. [30] investigated the improvement of weathered granite soil with fly ash using ABAQUS 2022 and compared the plastic zones of a 15% fly ash-stabilised soil with those of an untreated sample. They reported that the plastic zone was more confined in the stabilised soil. Accordingly, they observed that the improvement reduced the spread of deformation and enhanced slope stability.

In the mixtures containing Class F fly ash, only limited improvements in strain behaviour were observed as the additive content increased. The 15% and 25% mixtures (Figures 5d and 5e) exhibited similar patterns, with deformation concentrated near the surface and within a confined area, and strain levels remaining comparable to those of the control sample. In both cases, the enhancement in strain response was minimal. These results suggest that due to the low reactivity of Class F fly ash, its binding effect is weak, and increasing its content has a limited impact on slope stability.

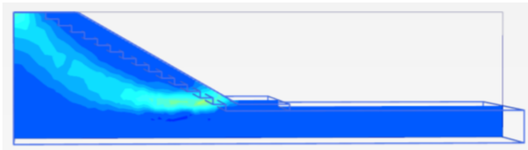
The mixtures incorporating Class F fly ash activated with an alkali solution produced the most favourable strain behaviour. At 15% content (Figure 5f), the deformation zone narrowed, strain values decreased, and only minimal strain contours were observed, suggesting that deformation was nearly eliminated. In the 25% mixture (Figure 5g), strain levels reached their lowest, and potential slip surfaces were significantly suppressed. The plastic strain in this case was approximately 96.6% lower compared to the control sample, indicating a substantial reduction in deformation. Overall, the results demonstrate that both the magnitude and spread of deformation were effectively controlled, making this additive system the most efficient solution for enhancing slope stability.



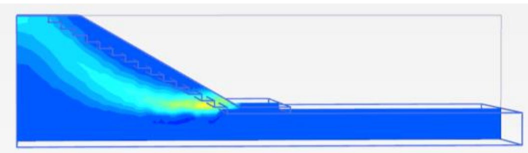
(a) Control sample



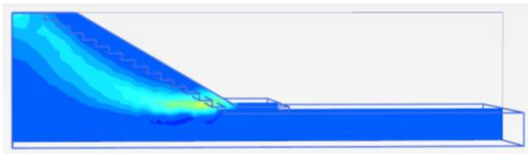
(b) 15% class C



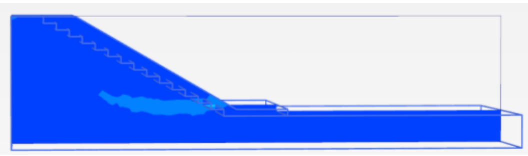
(c) 25% class C



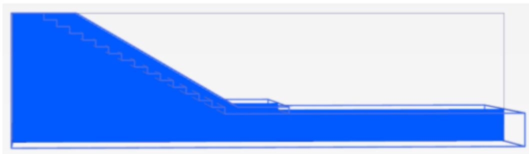
(d) 15% class F



(e) 25% class F



(f) 15% class F+AA



(g) 25% class F+AA

Figure 5. Strain behaviour under FoS analysis for different soil mixtures in slope stability assessment. Each panel (a-g) represents the corresponding mixture condition.

4. Conclusions

This study investigated the slope stability performance of kaolinite clay embankments stabilised with Class C fly ash, Class F fly ash, and alkali-activated Class F fly ash using PLAXIS 3D finite element analysis supported by laboratory test data. The key findings can be summarised as follows:

• Numerical simulations validated by laboratory-derived input parameters confirmed that alkali-activated Class F fly ash provided the most effective stabilisation, significantly increasing the FoS and reducing plastic strain zones within the slope.

• While Class C fly ash improved the stiffness and strength of the soil due to its cementitious and pozzolanic properties, its effectiveness was moderate, and it could not fully prevent the spread of deformation.

• Class F fly ash alone demonstrated limited reactivity and low binding capacity, yielding only marginal improvements in both safety and deformation behaviour. However, when chemically activated with an alkali solution, its performance improved markedly.

• Among all mixtures, the embankment stabilised with 25% alkali-activated Class F fly ash achieved the best results, with a nearly 50% increase in the FoS and a significant reduction in the extent of plastic deformation.

Overall, the findings suggest that in the absence of sufficient granular material for fill construction, stable embankments can be achieved by stabilising locally available clay soils using alkali-activated fly ash. This approach not only improves slope stability but also contributes to more sustainable geotechnical practice by reducing the consumption of natural resources and lowering overall construction costs.

Ethics committee approval and conflict of interest statement

This article does not require ethics committee approval. This article has no conflicts of interest with any individual or institution.

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