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Review Article

Geotechnical Properties of Fly Ash Blended Expansive Soil: A Review

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Abstract

Fly ash, an industrial byproduct, is used as both a building material and a soil stabilizer due to its pozzolanic properties. Moreover, it is challenging to extrapolate the results based on an inadequate amount of laboratory data because of the non-homogeneous character of the soil and the diversity in the chemical properties of fly ash. This review article fills in the gaps by providing an overview of the existing data related to the geotechnical characteristics of expansive soil stabilized with fly ash. The chemical composition of fly ash is provided in terms of oxides of various elements to help identify the kinds produced in different nations. Additionally, information about the physical and geotechnical characteristics of fly ash blended expansive soil is provided in order to comprehend the influence of the fly ash's chemical composition and the expansive soil's fines percentage. While the geotechnical property comprises Atterberg's limit, compaction, UCS, shear strength, free swelling index, CBR, and consolidation, the physical property includes specific gravity and durability. Shear modulus, damping ratio, and Poisson's ratio are used to describe the dynamic properties of the modified expansive soil. The published data in this field and the research gap will be identified by the researchers with the aid of this article.

Keywords: Fly Ash; Expansive Soil; Chemical Property; Geotechnical Property.

1. Introduction

Any civil engineering structure is supported by the subgrade soil, which may be a natural soil layer or maybe a layer of compacted stabilized soil. The function of the subgrade is to receive the load from the superstructure and distribute it into the soil mass. The poor subgrade with expansive soil reduces the life of the structure and sometimes causes ultimate failure due to the large volume change during sessional variation. During the dry session, the shrinkage of the expansive soil causes a loss of mechanical properties due to the development of cracks. A direct correlation between crack development and the rate of evaporation has been reported by previous researchers [1], and the development of cracks can be controlled by some additives, such as biochar [2]. The development of the crack can initiate at the top surface as well as at the bottom, near the interface of different layers of soil. However, the crack at the top can propagate easily [3]. Also, owing to the alternate change of moisture in the soil, alternate swelling and shrinkage take place, which causes the development of cracks and heaves in the soil, resulting in the ultimate failure of the structure followed by economic loss. Several methodologies have been developed for the dewatering of clay through geosynthetic [4], preloading [5], electrokinetic [6], and chemical additives [7]. However, dewatering clay soil is always difficult due to its low permeability.

On the other hand, fly ash is a fine residue produced during coal combustion to generate electricity [8] and stored in ash ponds due to its low utilization rate. An estimation shows the annual generation of 600–800 MT of fly ash globally

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[9], to which the USA and Europe contribute approximately 10%, whereas India and China contribute around 18% [10, 11]. The generation and utilization rates of fly ash in different countries are depicted in Figure 1 [12]. Further, storage of fly ash poses an environmental problem owing to its chemistry, and spilling of fly ash poses a serious environmental problem, as reported at Kingston Fossil Plant in December 2008 [13]. The current practice of disposing of fly ash is landfill and monofil [14]. However, due to its pozzolanic nature, it can be used for the stabilization of soil [15].

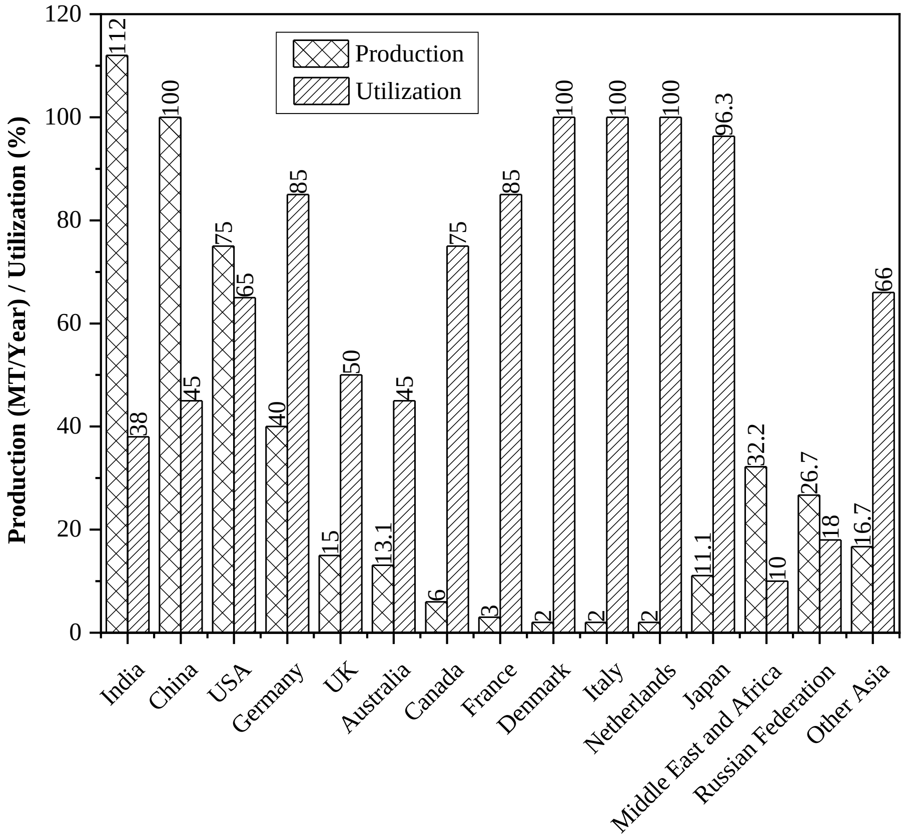

Figure 1. Production and utilization rate of fly ash [12]

Owing to fly ash's pozzolanic qualities, numerous studies have stabilized various soil types using fly ash either by itself or in combination with other industrial waste. Given that the expansive soil contains clay elements and is therefore regarded as problematic soil, a number of studies have attempted to address the issues by utilizing additions. Fly ash is plentiful because of its low utilization rate, and it has been utilized by numerous researchers to enhance the geotechnical characteristics of expansive soil. The effectiveness of a geopolymer based on sugarcane bagasse ash on the swell-shrinkage property of highly compressible organic clay soil with a 62.40% clay content was reported by Khandelwal et al. [16]. According to Kishor & Singh [17], fly ash and liquid alkali activators ($Na_2SiO_3.9H_2O$ and NaOH) work well together to improve the expansive soil's geotechnical properties, which contain 50.7% clay.

According to Wang et al. [18], fly ash activated with NaOH is a useful tool for enhancing the mechanical characteristics of modified expansive soil that has a 55% free swelling index. In their investigation of the impact of sludge pond ash on clay, Pesarakloo et al. [19] found that while ash's cementing activity causes the UCS to rise, increasing ash lowers the maximum dry density. In order to stabilize expansive soil on-site, Jamsawang et al. [20] used a shallow mixing technique with bottom ash, which reduces the free swelling index because it doesn't expand. Sengul et al. [21] investigated the properties of clay using fly ash and polypropylene fiber, whereas Pan et al. [22] investigated the properties of fly ash-stabilized clay with salinity and curing time. Many forms of ash have been used in a number of research projects on expanding soil alteration. However, the findings cannot be applied to all types of ash and expanding soil because of the inconsistent characteristics of these materials. Therefore, it is necessary to gather the findings published by many studies for diverse ash types and expansive soil. This review study presents a detailed comparison of the physical, geotechnical, and dynamic features of expanded soil modified with fly ash that have been reported by researchers. It will assist the researchers in comprehending the impact of various parameters on the properties of fly ash-stabilized expansive soil by compiling and comparing the results based on a number of parameters, including the percentage of fly ash in the soil, the chemical composition of fly ash, the fly ash particle size, the percentage of fine in the expansive soil, and other parameters (discussed in separate sections).

2. Research Methodology

For this review paper, several articles related to soil stabilization using fly ash, which have been published in reputed journals, have been studied. Previously published data has been collected and presented in this paper in terms of graphs. In some articles, the data was available in tabulated form, whereas in others, it was in graphical form, and the data was extracted from the graph. A comparison has also been made among the data available in previously published research. Initially, a comparison between the chemical properties of fly ash from different countries presented by different researchers has been made. Further, a graph for the average percentage with a standard deviation of different chemicals present in the fly ash has also been plotted and presented in this paper, along with a graph showing the variation of the lime index of Class F and Class C fly ash along with the expansive soil. Later, published results related to the impact of fly ash on the geotechnical behaviors of expansive soil were presented and compared for different percentages of additives. The flow diagram depicting the gathering and selection of the published research articles is shown in Figure 2.

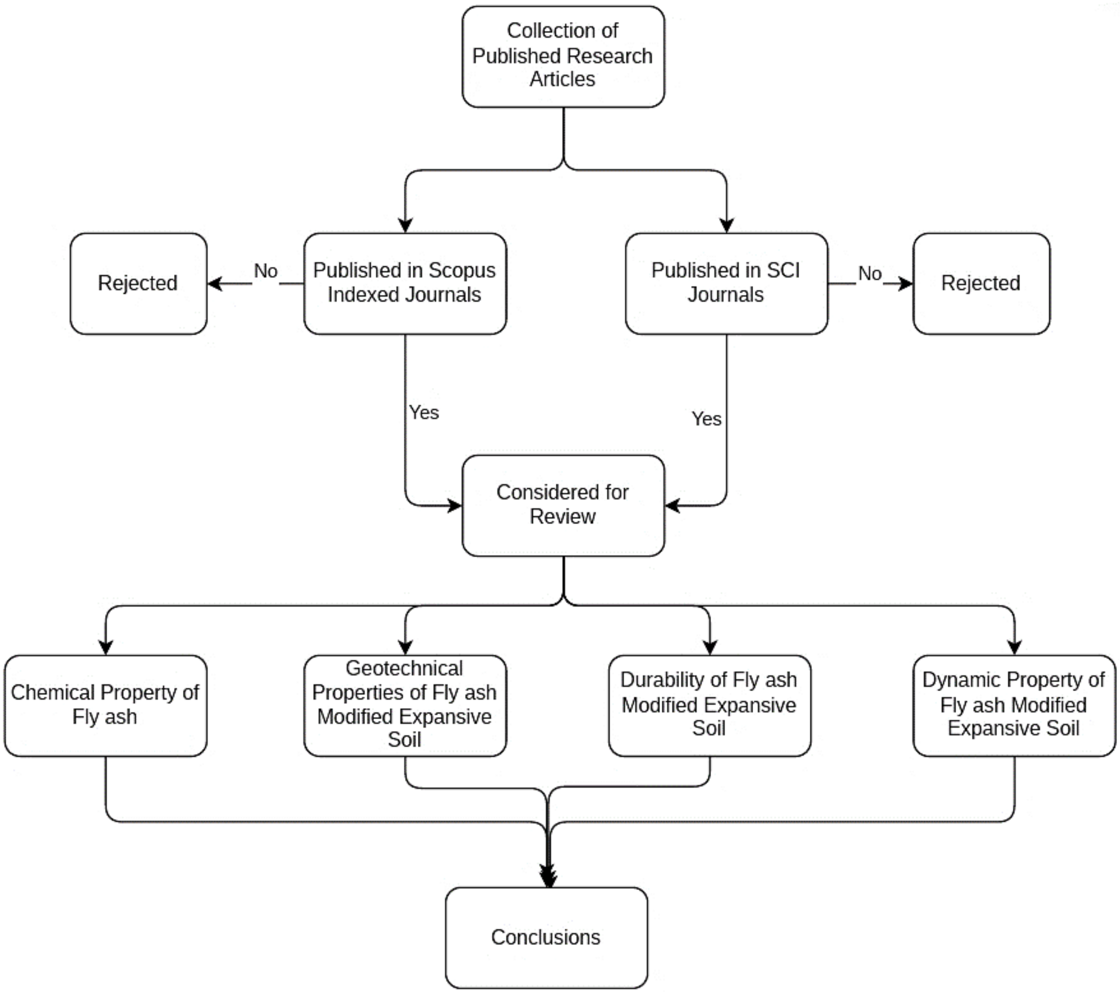

Figure 2. Flow diagram depicting the gathering and selection of the published articles

3. Chemical Property

Fly ash is one of the most complex minerals, with around 316 individual minerals and 188 mineral groups [23]. But the main component of all fly ash types is SiO_2, which is joined in Class F fly ash by Al_2O_3 and Fe_2O_3, and in Class C fly ash by CaO (>15%). Comparing Class F fly ash to Class C fly ash, it was found that the percentage of Al_2O_3 and Fe_2O_3 is higher. The percentage of different minerals in the fly ash reported by different researchers has been shown in Table 1. Significant differences have been noted in the chemical composition of fly ash from various nations. Additionally, Figure 3 displays the standard deviation of each chemical's average value from the average proportion of the various chemicals contained in the fly ash. It is observed from Figure 3 that SiO_2 and CaO vary in a wide range as compared to Al_2O_3 and Fe_2O_3, whereas another chemical such as MgO, K_2O, Na_2O, SO_3, TiO_2, MnO, P_2O_5 varies in a very narrow range. However, loss on ignition (LOI) also shows a considerable range of variation for fly ash from different countries. In Table 1, the sum percentage of (SiO_2 + Al_2O_3 +Fe_2O_3) has also been presented, which can be used to classify the fly ash as Class F or Class C. According to ASTM [24], fly ash is categorized as Class F if it includes more than 70% (SiO_2 + Al_2O_3 + Fe_2O_3), and Class C if it contains 50% to 70% (SiO_2 + Al_2O_3 + Fe_2O_3).

Table 1. Minerals present in fly ash presented by different researchers

Percentage of minerals (%)													Country	Reference
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	TiO_2	MnO	P_2O_5	LOI	$SiO_2 + Al_2O_3 + Fe_2O$		
50.62	25.15	3.62	0.062	0.209	-	-	0.016	-	-	-	3.81	79.39	India	[25]
35.8	14.5	11.5	23.2	0.83	1.74	0.2	-	-	0.02	-	-	61.8	USA	[26]
55	11	-	5	-	-	-	-	-	-	-	-	66	USA	[27]
36.1	19.5	5.74	26.2	4.9	0.47	1.64	1.46	-	0.03	1.1	0.19	61.34	USA	[28]
46.1	22.7	20.8	1.84	0.85	2.41	0.49	0.32	-	0.03	0.21	1.88	89.6	USA	[28]
47.4	25.5	5.7	14.8	2.7	-	-	2.8	-	-	-	-	78.6	Turkey	[29]
57.5	33	4.8	0.5	0.2	0.4	0.2	-	1.4	-	-	1.5	95.3	India	[30]
36.5	41	4.5	9	3.8	0.4	0.4	-	1.4	-	-	3.5	82	India	[30]
53.12	29.58	5.32	2.82	0.73	1.2	0.34	0.25	1.05	0.04	0.17	5.38	88.02	China	[31]
54.8	22.3	5.1	9.8	-	-	-	0.6	-	-	-	-	82.2	USA	[32]
63	19.7	4.9	7.4	1.6	-	-	0.1	-	-	-	-	87.6	USA	[32]
75.39	22.26	0.51	0.17	-	-	-	-	-	-	-	-	98.16	India	[33]
52.55	24.12	-	2.65	0.57	0.96	-	-	-	-	0.72	18.18	76.67	India	[34]
59.83	30.48	-	1.74	0.86	-	-	-	6.91	-	-	0.85	90.31	India	[35]
43	9.32	2.64	41	1.9	-	-	0.83	-	-	-	1.07	54.96	Turkey	[36]
64.3	27.45	2.65	0.85	0.47	1.03	0.07	-	1.77	-	-	-	94.4	India	[37]
62.09	23.8	8.55	-	1.17	-	-	-	-	-	-	-	94.44	India	[38]
36.7	18.6	7	25	5.5	0.5	1.8	1.5	-	-	-	-	62.3	USA	[39]
54.8	22.3	5.1	9.8	-	-	-	0.6	-	-	-	-	82.2	USA	[40]
63	19.7	4.9	7.4	1.6	-	-	0.1	-	-	-	-	87.6	USA	[40]
-	-	-	25.8	-	-	-	1.48	-	-	-	-	61.7	USA	[41]
34.52	28.87	4.94	16.45	3.04	-	-	-	-	-	-	-	68.33	India	[42]
44.18	22.13	4.85	18.98	1.01	1.52	0.45	3.96	0.98	-	-	1.19	71.16	Turkey	[43]
58.62	19.44	10.18	2.18	1.66	1.5	0.19	0.36	1.11	-	-	1.1	88.24	Turkey	[43]
52.03	32.31	5.8	7	1.2	1.2	0.2	-	-	-	-	-	90.14	Sri Lanka	[44]
66.4	20.18	5.28	0.88	0.6	1.44	0.076	-	1.54	0.065	0.36	4	91.86	India	[45]
55.69	26.33	6.9	3.43	0.62	0.98	-	0.45	-	-	-	5.6	88.92	India	[46]
41.53	27.51	10.38	14.52	0.99	0.71	0.96	0.57	1.9	0.16	0.5	0.27	79.42	Australia	[47]
60.98	24.47	6.7	4.9	0.68	-	-	0.52	0.1	-	-	1.86	92.15	Japan	[48]
29.41	14.66	13.71	25.55	5.86	2.8	5.91	-	-	-	-	2.1	57.78	China	[49]
54.4	28.6	3.2	1.6	1.4	1.7	0.3	-	1.8	-	-	-	86.2	India	[50]

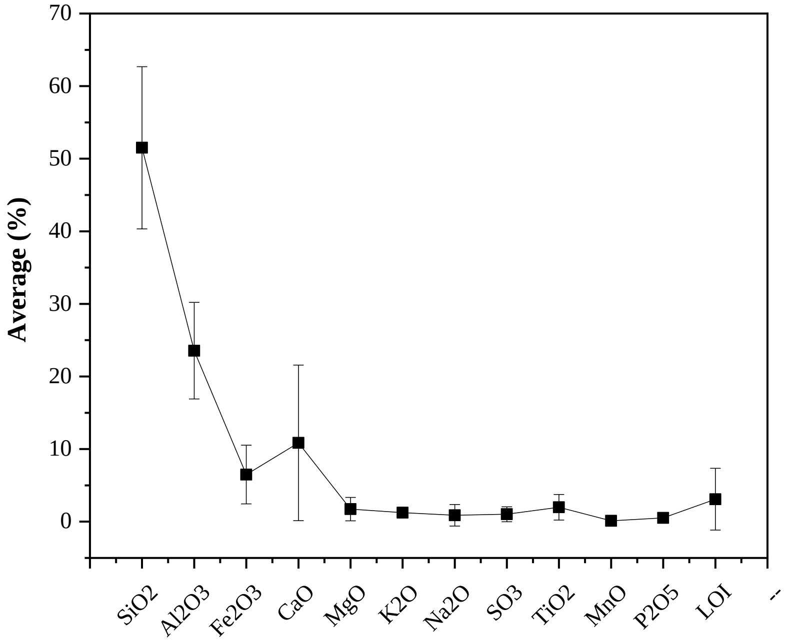

Figure 3. Average percentage with standard deviation of mineral composition of fly ash

Based on the calcium-sulfur ratio, the fly ash can also be categorized as acidic (pH = 1.2 to 7), moderate alkaline (pH = 8 to 9), or strongly alkaline (pH = 11 to 13) [51]. The Class F fly ash with low CaO has high reserve acidity with a low lime index, which resists the change in pH value. Figure 4 shows the plot between the percentage of CaO and lime index for fly ash and expansive soil, which shows that the lime index increases with the increase in CaO percentage. Additionally, it is noted that the Class F fly ash and expansive soil have a lime index of less than 0.2, indicating their resistance to pH value changes.

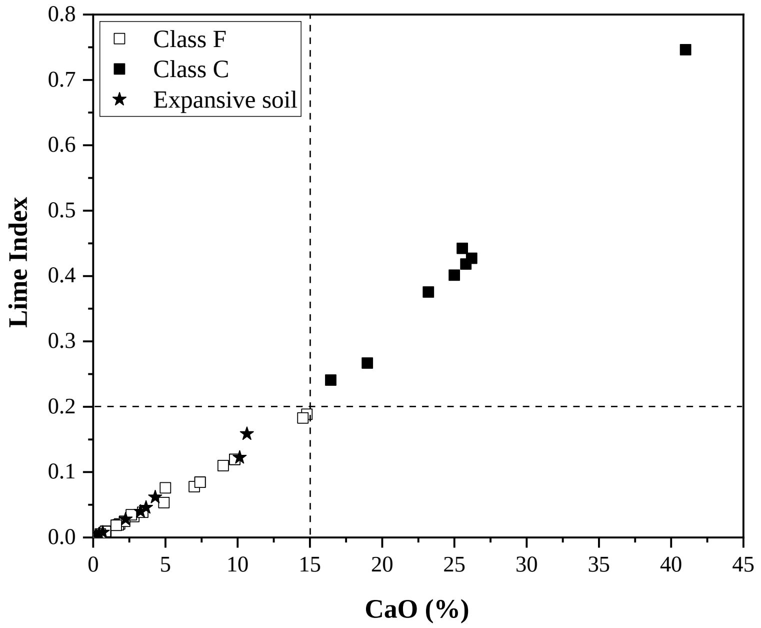

Figure 4. Variation of the lime index with CaO percentage

4. Geotechnical Properties

4.1. Specific Gravity

A significant factor influencing the soil's maximum dry unit weight is its specific gravity. The maximum dry unit weight drops in tandem with a reduction in the soil's specific gravity. A decline in strength could result from the soil's maximum dry unit weight dropping. However, because fly ash cements soil, a drop in the maximum dry unit weight could not result in a reduction in strength in fly ash blended soil. Numerous scholars have looked into how fly ash affects the specific gravity of expanding soil mixed with varying fly ash percentages (Figure 5).

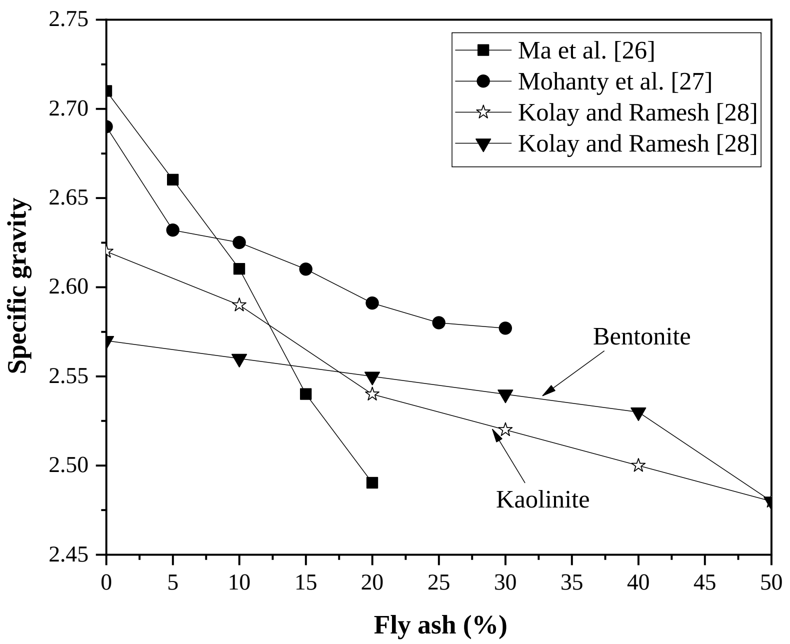

Figure 5. Specific gravity of expansive soil blended with fly ash

It was found that when the percentage of fly ash in the blended expansive soil increases, so does its specific gravity. In their study, Ma et al. [52] examined the effects of 5%, 10%, 15%, and 20% fly ash on the specific gravity of a soil-fly ash mixture. They discovered that the specific gravity of the combination decreased linearly, going from 2.71 for 0% fly ash to 2.49 for 20% fly ash. The specific gravity of the mixture decreased from 2.69 to 2.57 for 0% and 30% fly ash, respectively, according to Mohanty et al. [25]; however, the rate of change was minimal after 25% fly ash. Fly ash and expanding soil have somewhat different specific gravities, which could account for the minute variation. The specific gravity of the Kaolinite-fly ash mixture and the Bentonite-fly ash mixture was examined by Kolay & Rames [26] in relation to the fly ash content. At 50% fly ash content in the mixture, the specific gravities of Bentonite and Kaolinite dropped to 2.48 and 2.57, respectively. The specific gravity of the fly ash is lower than that of the expanding soil, which is the only reason for the specific gravity drop [26].

4.2. Atterberg's Limit

The impact of fly ash percentage on the plastic and liquid limits of fly ash blended expansive soil, as described by earlier studies, is depicted in Figure 6. Fly ash was shown to significantly reduce the plasticity index by up to 10% in expansive soil with a clay percentage of 65%, according to research by Puppala et al. [27]. When fly ash content increases from 5% to 20%, Ma et al. [52] found that the plastic limit shows a decreasing trend while the liquid limit and plasticity index show a decreasing trend. Other researchers have also documented a similar trend in the plasticity index and liquid limit for fly ash contents ranging from 8% to 24% in soil containing 30% clay [53]. Similar results were previously observed by Mahedi et al. [28] and Phanikumar & Sharma [54] for expansive soil with 5%, 10%, 15%, and 20% fly ash.

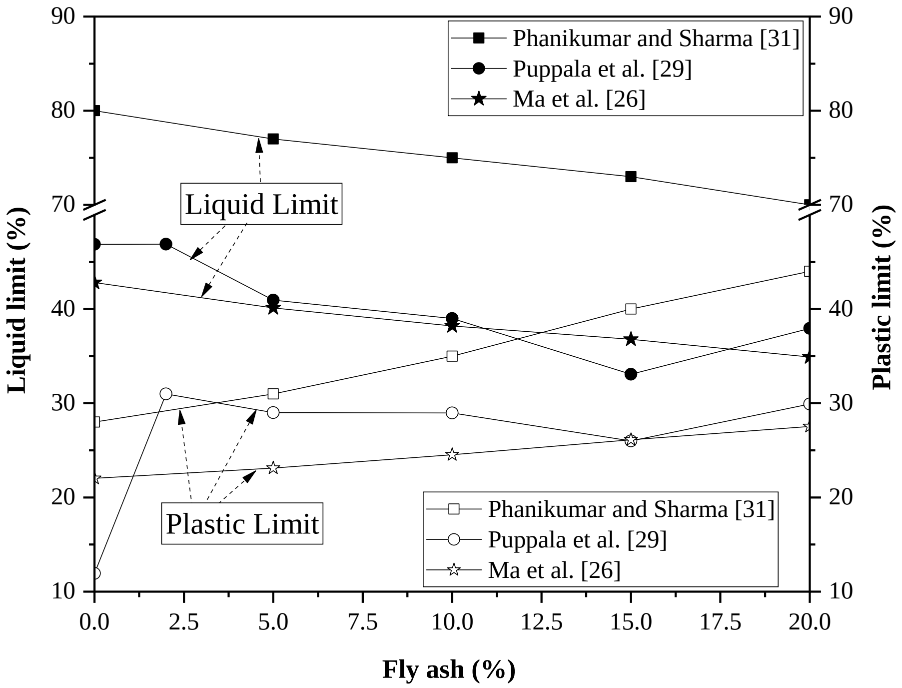

Figure 6. Change in liquid limit and plastic limit with fly ash

Mohanty et al. [25] studied the expansive soil with 40% clay content and observed an increasing trend in plastic limit and shrinkage limit from 5% to 30% fly ash, whereas, liquid limit and plasticity index was observed to have a decreasing trend for a similar variation of fly ash. Nalbantoglu [29] studied the impact of 15% and 25% fly ash with 14.8% CaO and reported a sharp drop in plasticity index up to a fly ash content of 15%, whereas for higher percentages, the rate of change decreased. Fly ash's impact on the expansive soil's shrinkage limit is depicted in Figure 7.

Mir and Sridharan [30] examined the impact of two distinct fly ash types on the expansive soil property (liquid limit 84%) and found that the shrinkage limit rose as fly ash content increased up to a maximum value and then began to decline. But according to Sharma et al. [55], the shrinkage limit continuously decreased as fly ash content increased by up to 25%. According to the findings, the ideal amount of fly ash with a liquid restriction of 40% is 40%, which results in a shrinkage limit of 54.6%, whereas the ideal percentage of fly ash with a liquid limit of 50% is 20%, giving a shrinkage limit of 47.5%. The impact of fly ash on the linear shrinkage of two distinct types of expansive soil with fine contents of 91.6% and 70% was investigated by Kolay & Ramesh [26]. In both soils, it is seen that the liner shrinkage value drops when fly ash content rises (Figure 8). In contrast to soil containing 70% fine, soil containing 91.6% fine exhibits a greater rate of decline in linear shrinkage value; nevertheless, at higher fly ash percentages (>50%), the linear shrinkage values appear to converge (Figure 8).

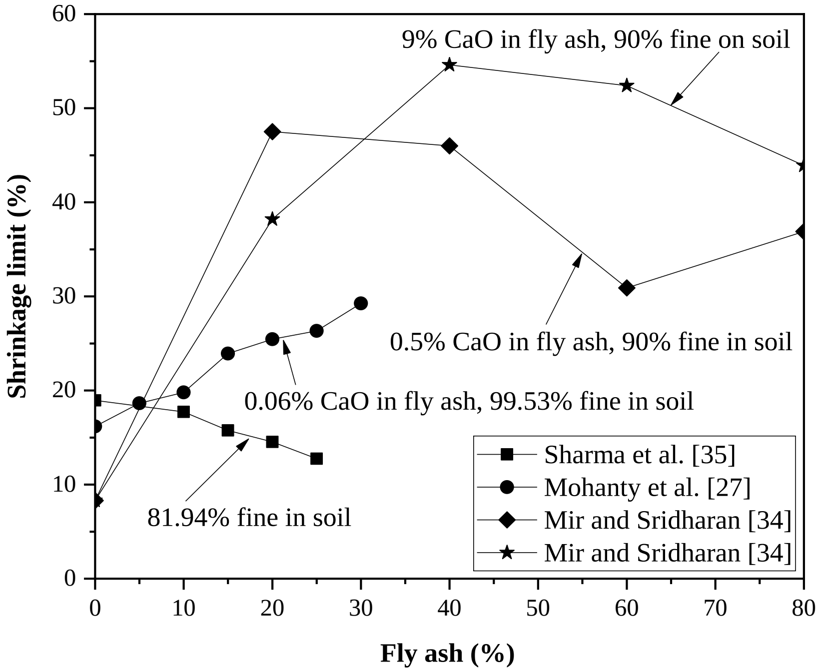

Figure 7. Change in shrinkage limit with fly ash

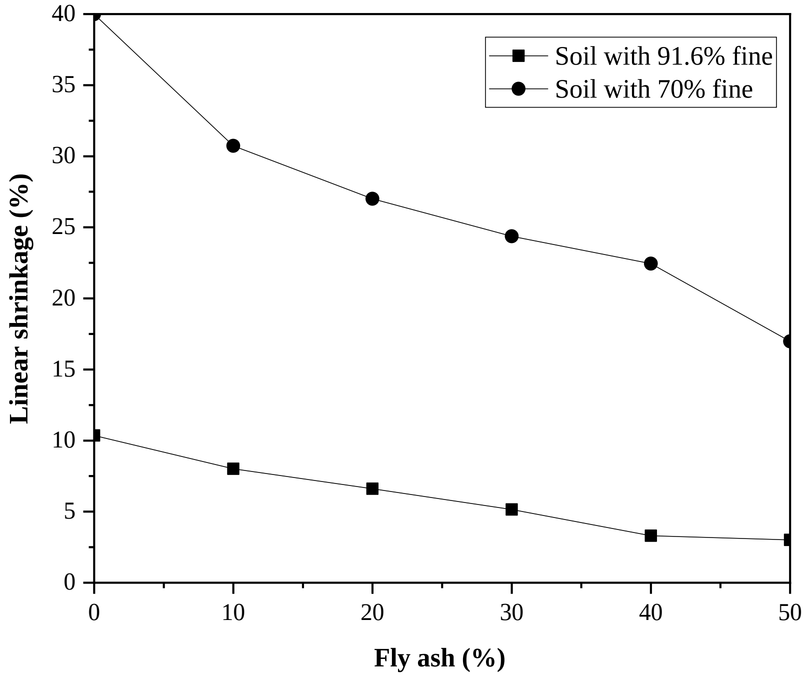

Figure 8. Change in linear shrinkage with fly ash

4.3. Swelling Pressure and Free Swelling Index

Soil with significant free swelling is deemed undesirable for civil engineering structures. The free swelling index measures the increase in soil volume when it comes into contact with water. This type of soil is unsuitable for civil engineering construction, so it must be modified in order to lower the swelling pressure and release swelling prior to construction. Numerous investigators have endeavored to regulate the soil's free swelling and swelling pressure through the application of fly ash treatment. Different researchers have documented variations in swelling pressure and differential free swelling, respectively, which are depicted in Figures 9 and 10.

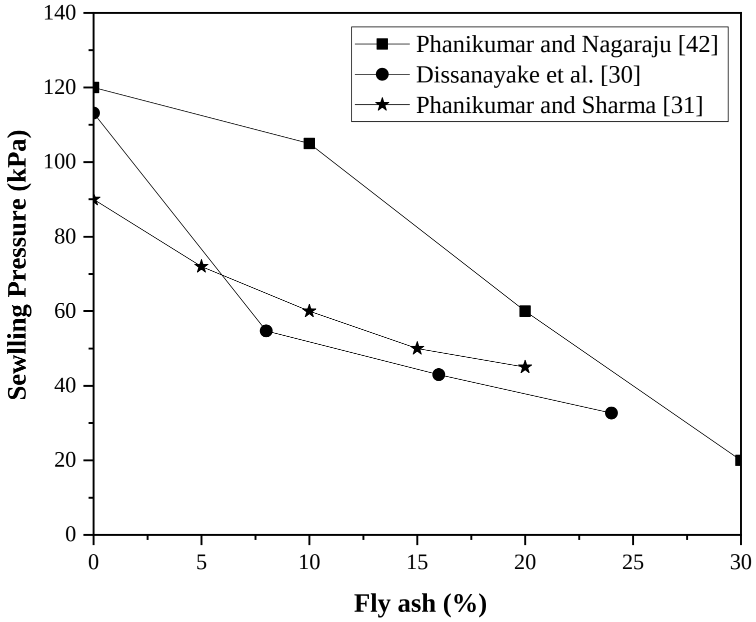

Figure 9. Variation of swelling pressure with fly ash

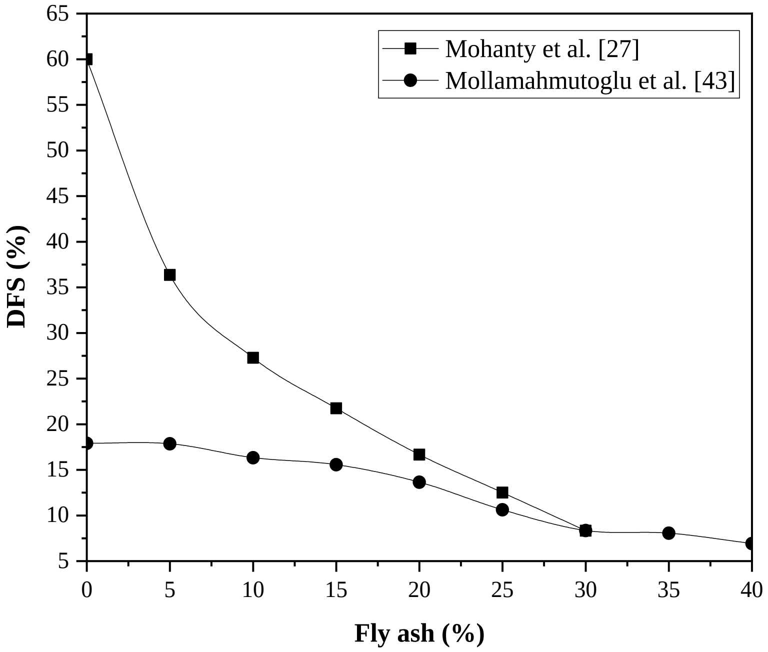

Figure 10. Variation of differential free swelling with fly ash

Puppala et al. [27] have studied the impact on the soil (Arlington Clay) containing 65% fine and observed a nonlinear decreasing trend in the free swelling index (FSI) with a rise in the fly ash till 10%, after which there is no significant impact on the FSI. Phanikumar & Sharma [56] reported a considerable fall in FSI of the soil containing 84% fine to 20% fly ash, which follows a similar trend as reported by another researcher [57]. Similar results for free swelling index and swelling pressure have been reported by Zha et al. [31] for the soil containing 97.6% fine and blended with 6%, 9%, 12%, and 15% fly ash. A sharp decrease in the free swelling at 5% fly ash was observed by Mohanty et al. [25]; however, after 5% fly ash, the free swelling follows a linearly decreasing trend with a combatively lower rate. It has been noted that fly ash content significantly influences the swelling pressure, which falls as the percentage of fly ash rises [32, 33, 53, 54]. Other researchers [34, 35] have also presented a similar trend in swelling pressure. Mollamahmutoglu et al. [36] also reported a decrease in swelling potential from 5% to 40% fly ash content along with the wetting-drying impact. There is no impact of wetting-drying on swelling potential up to 2 cycles for any percentage of fly ash. Meanwhile, for the 3rd cycle, the swelling potential increased and again became constant up to the 5th cycle. However, the result after five cycles has not been reported by the authors. Kolay & Ramesh [26] came to the conclusion that the percentage of fine in the expansive soil determines the swelling pressure of fly ash-stabilized soil and that the percentage of fly ash decreases significantly in soil with a larger percentage of fine. The presence of multivalent cations provided by the fly ash, which speeds up the flocculation of the clay by cation exchange and lowers the specific surface area, is what causes the drop in FSI and swelling pressure of the soil-fly ash mixture [58].

4.4. Compaction Characteristics

The maximum dry unit weight of the expanded soil stabilized by fly ash diminishes as the fly ash content rises (Figure 11), as a result of the blended fly ash expanding soil's decreased specific gravity. As stated in references 26, 30, and 40, the ideal moisture content rises. When the optimal moisture level increased, Mohanty et al. [25] saw a steady drop in the maximum dry unit weight of up to 30% fly ash. Nevertheless, there is a very small change in the maximum dry unit weight, whether fly ash is at 25% or 30%. This could be because the specific gravity of fly ash varies so little at these percentages. Additionally, a linear trend in the maximum dry unit weight drop with a rise in fly ash content was documented by Mollamahmutoglu et al. [36]. Zha and colleagues (2019) observed a decline in the ideal moisture content and maximum dry unit weight as the fly ash percentage increased. On the other hand, Phanikumar & Sharma [54] observed that when fly ash increased in expansive soil, the maximum dry unit weight increased and the optimal moisture content decreased. A constant drop in the ideal moisture content has been observed; however, Bose [34] reported an increase in maximum dry unit weight at 20% fly ash, but it declines at a larger percentage of fly ash. The impact of fly ash percentage and fly ash particle size on the compaction characteristics was examined by Murmu et al. [37]. In comparison to coarser particles (> 0.075 mm and < 0.425 mm), it is noted that expanding soil containing finer fly ash particles (< 0.075 mm) has a higher maximum dry unit weight. Fly ash has a relatively lower specific gravity, which could explain why the maximum dry unit weight decreases as the percentage of fly ash increases [59, 60]. The compacted soil-fly ash mixture's swelling and shrinking behavior is further reduced by the reduction in the maximum dry unit weight [61].

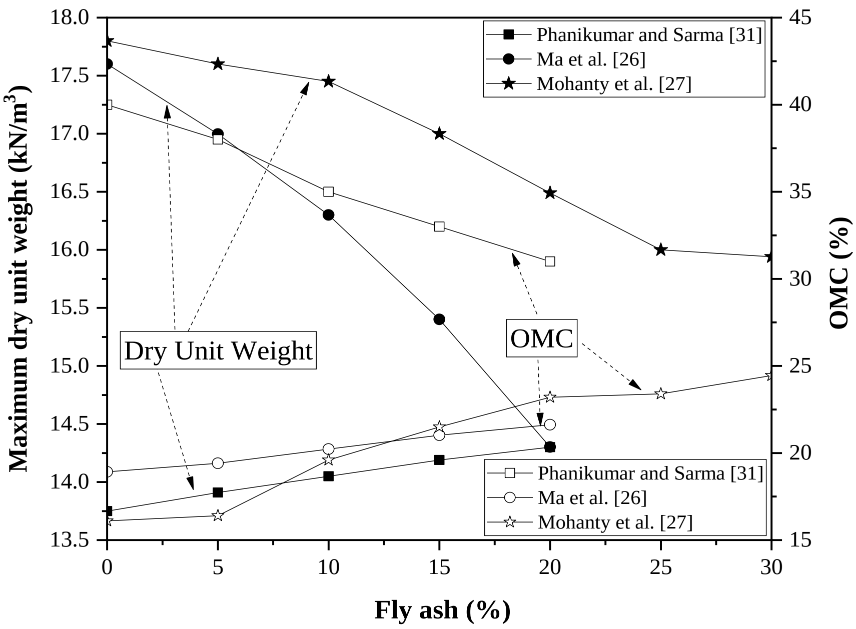

Figure 11. Variation in OMC and maximum dry unit weight with fly ash

4.5. Unconfined Compressive Strength (UCS)

The UCS is the strength of the soil when there is no confining pressure, and it gives the minimum strength of the soil under compressive load. Figure 12 depicts the change in UCS with the percentage of fly ash in expansive soil.

Puppala et al. [27] found a continuous increase in UCS for fly ash percentages of 5%, 10%, and 15%. However, the impact above 15% has not been reported. A similar effect has been observed by Phanikumar & Nagaraju [35] for fly ash percentages of 10%, 20%, and 30% and by Kumar et al. [62] for 5%, 10%, 15%, and 20% fly ash. Zha et al. [31] also reported similar results for 3%, 6%, 9%, 12%, and 15% fly ash blended expansive soil. Mahedi et al. [28] described the rising trend of UCS for 10%, 15%, and 20% fly ash, but the rate of gain in strength dropped with the curing time. Dissanayake [53] studied the same impact with 8%, 16%, and 24% fly ash and reported 16% as the optimum value for UCS of fly ash blended expansive soil, whereas Ma et al. [52] and Kumar & Hrika [57] reported 10% fly ash as an optimum quantity for UCS of fly ash blended expansive soil. Some researchers have reported 20% fly ash as an optimum percentage for UCS value [33, 34, 55]; however, the rate of rise in UCS is dependent on the property of the fly ash. The rise in the UCS may be caused by the cementing nature of the fly ash, but at a higher percentage, the unit weight of the mixture shows a higher impact on the UCS in comparison to the cementing nature of the fly ash. Mollamahmutoglu et al. [36] reported 35% fly ash with 41% CaO content as an optimum dose for expansive soil with 99.9% fine. In an investigation conducted by Rao & Subbarao [38], the optimum amount of fly ash was determined by stabilizing three distinct kinds of expansive soil with varying percentages of fly ash (5%–80%). The research demonstrated that mixing 5% fly ash in the expansive soil containing 52.67% fine gives the maximum UCS value, whereas for the expansive soil containing 64.48% fine, the optimum quantity is 15%, and for the expansive soil containing 74.75% fine, the optimum quantity is 20%. It is observed from the research that for maximum UCS value, the optimum quantity of fly ash increases with increasing fine content in the soil.

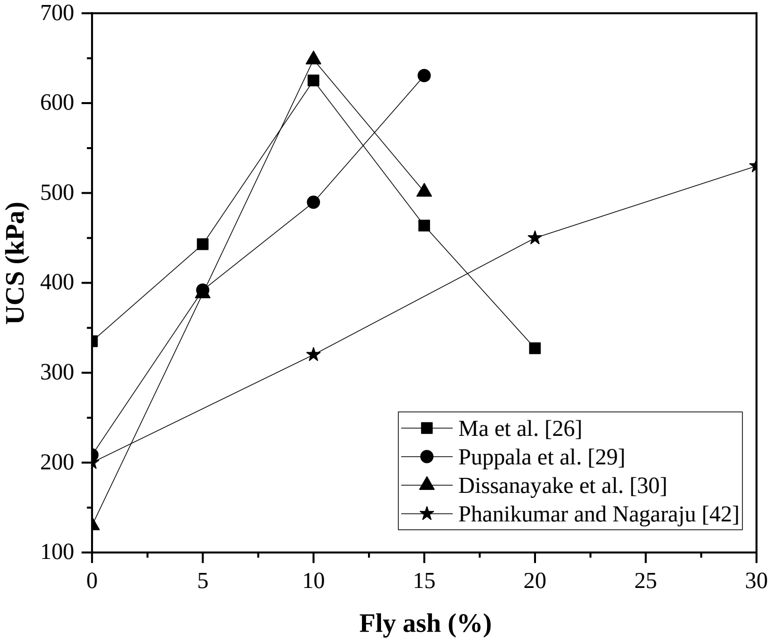

Figure 12. Unconfined compressive strength of modified expansive soil

4.6. Shear Strength

An essential characteristic of soil is its shear strength, which is primarily determined by the shear parameters cohesion and angle of internal friction. Figure 13 shows how fly ash affects the expanding soil's shear parameter. Noaman et al. [39] investigated the effect of fly ash on clay's shear strength, ranging from 5% to 50% with a 5% increment. The test was run with a strain rate of 1.25 mm/min with confining pressures of 50, 100, and 150 kPa. The findings indicated that the greatest values of cohesion (30 kPa) and internal friction angle (16.07^0) were obtained with 25% fly ash in the expansive soil; nevertheless, the rate of cohesion growth is larger than the angle of internal friction. Phanikumar & Sharma [54] examined the expansive soil's undrained shear strength at fly ash percentages of 5%, 10%, 15%, and 20%. They found that the undrained shear strength increased as fly ash percentage increased. Additionally, Figure 14 illustrates how the elastic modulus of blended expansive soil containing varying proportions of fly ash changes under various confining pressures. Up to 25% fly ash, the elastic modulus (Figure 14) increases; beyond that, no discernible effect was seen for any confining pressure (50, 100, or 150 kPa) [39].

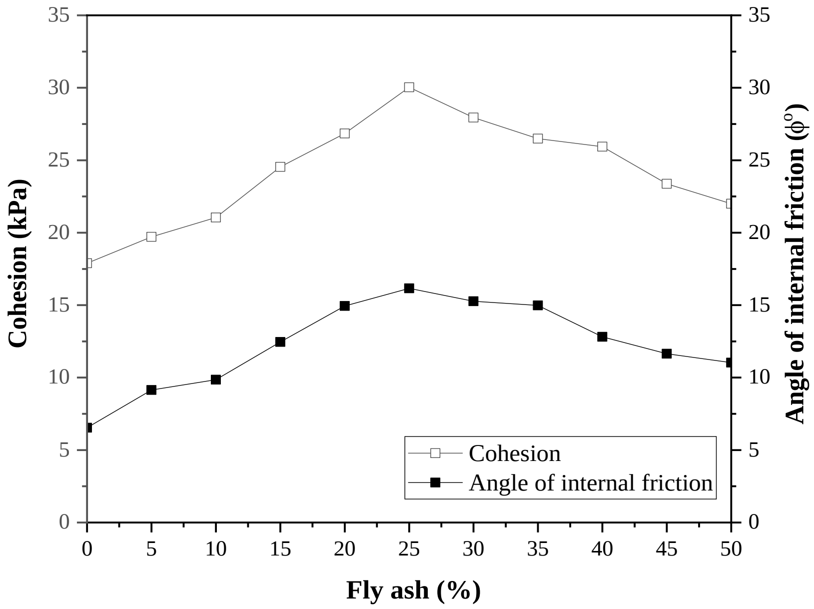

Figure 13. Shear parameter variation with fly ash percentage

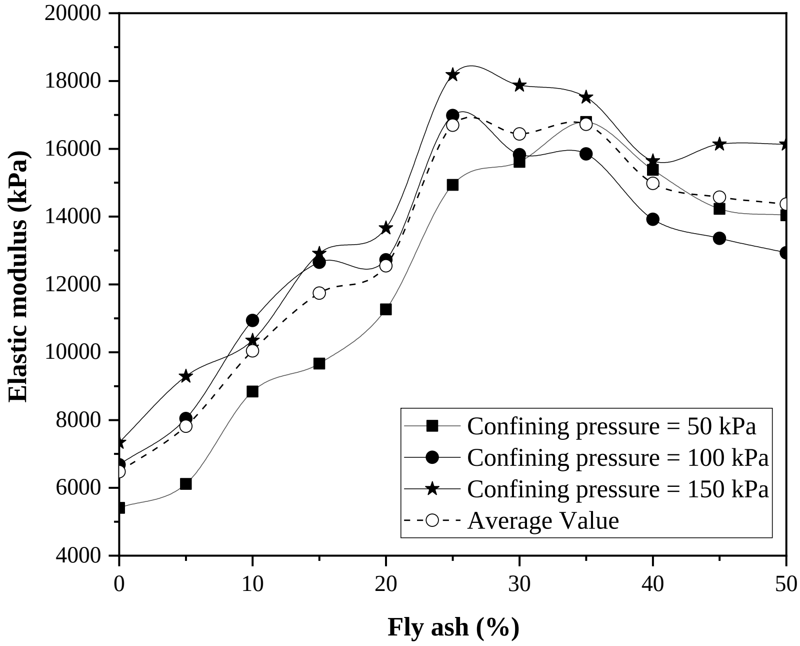

Figure 14. Variation of elastic modulus with fly ash content

4.7. California Bearing Ratio (CBR)

CBR is the measure of resistance of soil towards penetration and is frequently used in road embankments. Numerous investigators have examined the impact of fly ash on the CBR of swelling soil; Figure 15 displays the findings of those earlier investigations.

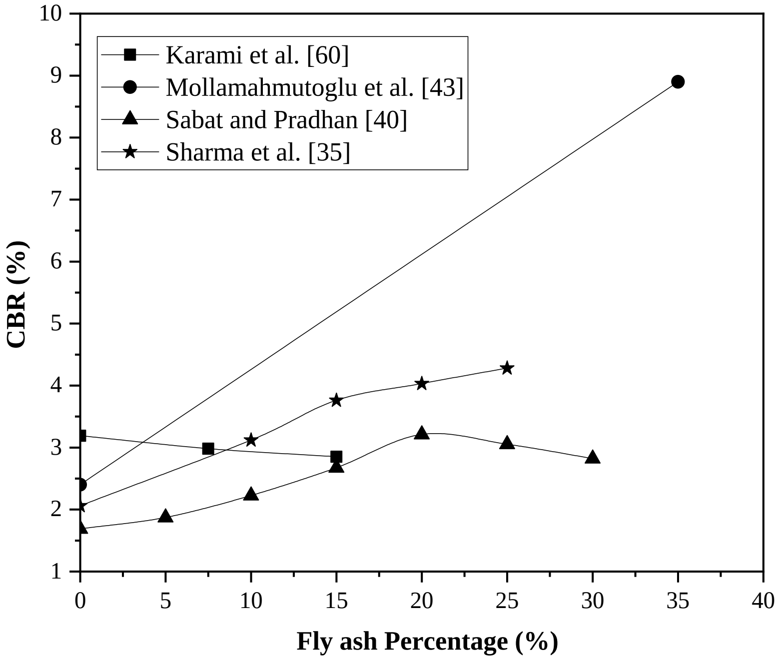

Figure 15. CBR of soil stabilized by fly ash

Mollamahmutoglu et al. [36] investigated the impact of fly ash with 41% CaO content on the CBR of soil containing 99.9% fine content. The result shows that 35% fly ash is an optimum percentage, with a soaked CBR value of 8.9% in comparison to 2.4% CBR of untreated soil. Similar results have been observed by Sabat and Pradhan [33] and Bose [34]; however, the optimum quantity is observed as 20%, which gives 3.5% and 1.96% soaked CBR values, respectively. Sharma et al. [55] investigated the fly ash (36.48% fine) effect on the CBR of the soil with an 81.94% fine content. It has been shown that the CBR value rises as the fly ash percentage rises; after adding 25% fly ash, the value rises from 2.06% to 4.28%.

4.8. Hydraulic Property

The hydraulic property of soil mainly refers to permeability and is a very important parameter when the soil is used in the hydraulic structure. Fly ash, which includes 15.5% coarse particles, improves the soil's coefficient of consolidation and permeability (k), according to research done by Mohanty et al. [25] on the permeability of blended expansive soil (Figure 16).

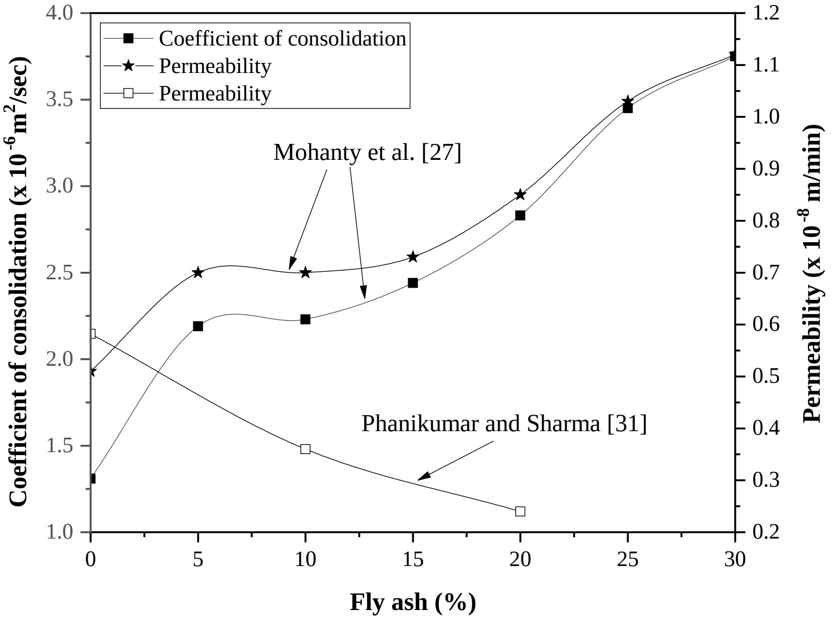

Figure 16. Variation in coefficient of consolidation and permeability with fly ash content

A higher proportion of coarse particles in the mixture could be the cause of the increased permeability. The permeability of the expansive soil mixed with 10% and 20% fly ash, on the other hand, was found to be reduced by Phanikumar & Sharma [54] in their permeability tests. As the author reports, the rise in the dry unit weight in this instance may be the cause of the decrease in permeability. Lin & colleagues [40] examined the soil-water characteristic curve (SWCC) of two distinct expansive soils (Hollywood and Heiden) stabilized with 9% fly ash in order to comprehend the features of unsaturated soil (Figure 17).

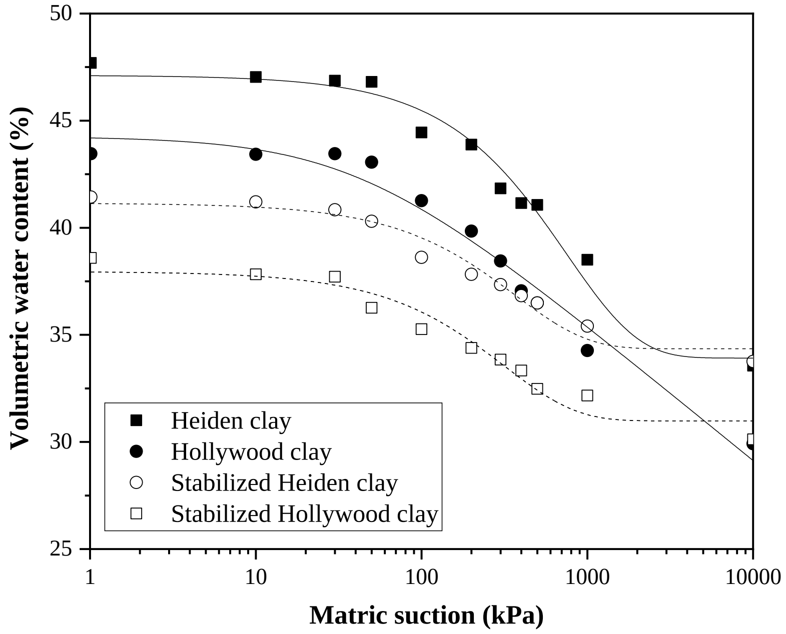

Figure 17. SWCC of un-stabilized clay and flay ash stabilized clay

The results show a 6%-7% decrease in the volumetric water content at 1kPa matric suction. However, the SWCC was found converging at the higher suction level. Puppala et al. [63] also studied the SWCC of fly ash stabilized swelling soil in the suction range of 0 kPa – 1000 kPa and observed that at any suction level, as the amount of fly ash in the soil increases, the volumetric water content falls.

4.9. Consolidation

The effects of 5%, 10%, 15%, 20%, 25%, and 30% fly ash (84.5% fine) on the consolidation behavior of soil with 99.53% fine content were investigated by Mohanty et al. [25]. The study shows that while the compression index (C_c) (Figure 19), coefficient of volume change (m_v) (Figure 18), and coefficient of compressibility (a_v) (Figure 18) all decrease with an increase in fly ash content up to 30%, the coefficient of consolidation (C_v) increases.

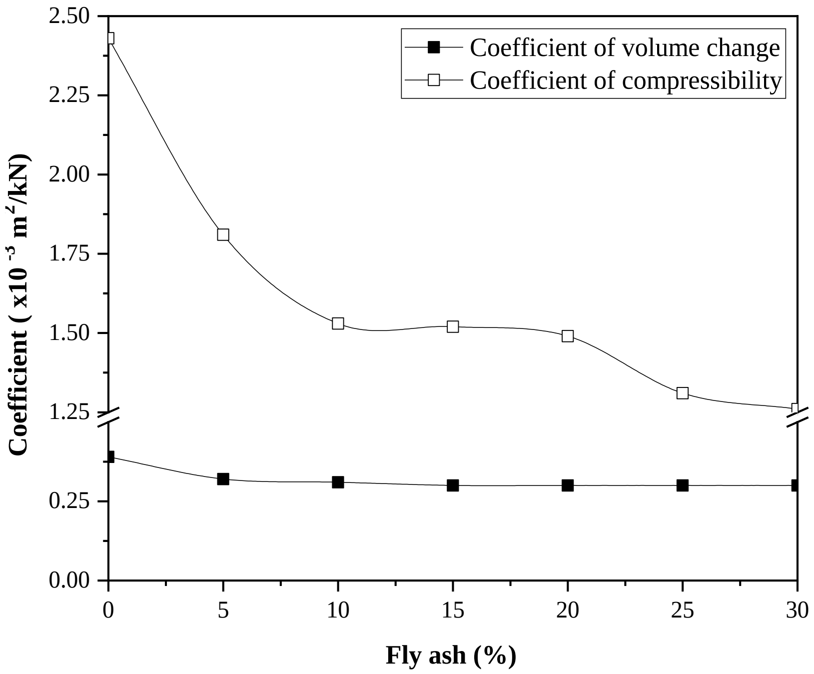

Figure 18. Variation of coefficient of volume change with fly ash

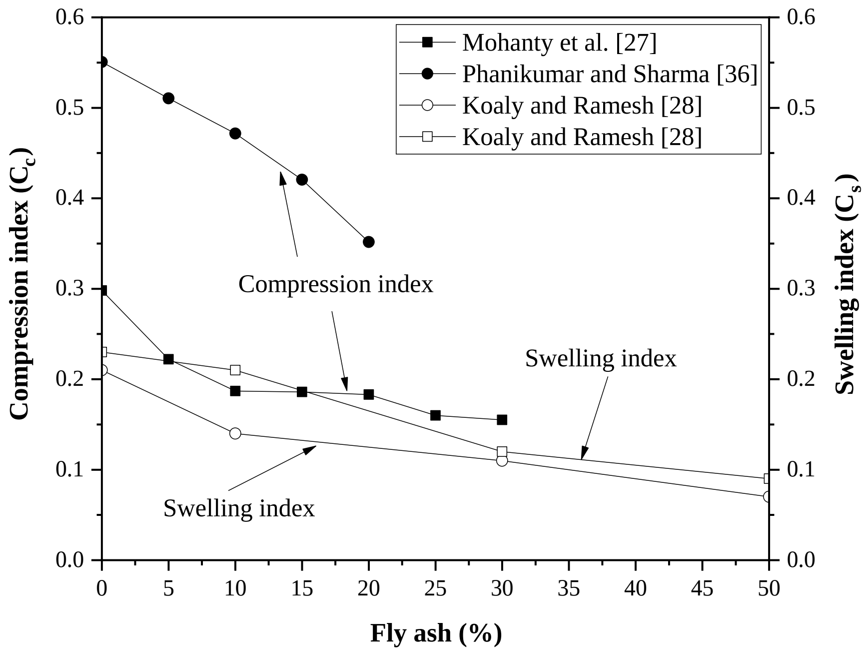

Figure 19. Change in swelling index and compressibility with fly ash

A similar result has been obtained by Phanikumar & Sharma [56] on soil with an FSI value of 250% for fly ash content of 5%, 10%, 15%, and 20%. However, the rate of change is higher than the result reported by Mohanty et al. [25]. Further, Phanikumar & Sharma [56] reported that for any normal stress, the void ratio decreases with rise in fly ash content (Figure 20).

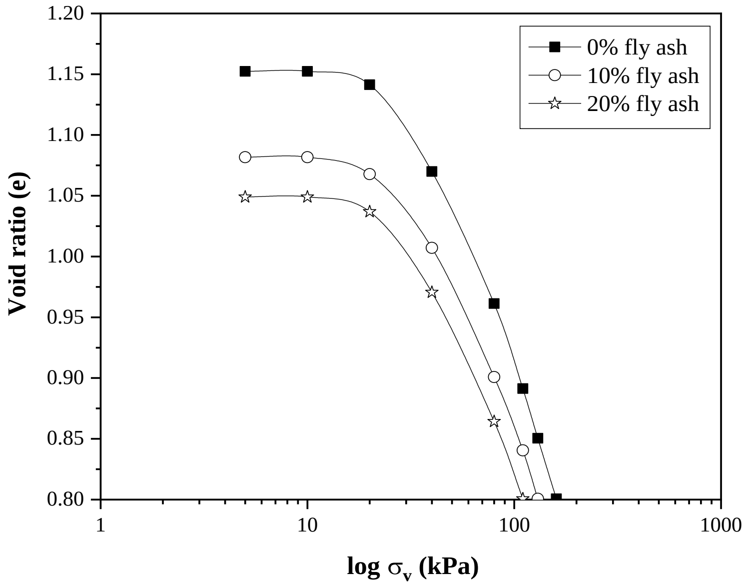

Figure 20. Consolidation curve for stabilized and un-stabilized soil

In two distinct types of soil with 91.6% and 70% fine content, Kolay & Ramesh [26] investigated the impact of fly ash on the compressive and swelling index. The compression index of soils with higher fine content is shown to decrease until it reaches 30% fly ash, at which point it begins to increase; in contrast, the index of soils with lower fine content increases until it reaches 30% fly ash, at which point it starts to decline. In addition, regardless of the soil's fine quality, the swelling index falls as fly ash content rises.

5. Durability

A crucial characteristic of every geomaterial is durability, which expresses how easily a feature will hold up in the face of challenging environmental circumstances. In general, exposure to various conditions, such as the freeze-thaw cycle and alternate wet-dry cycle, causes the material to lose its strength. The effects of 5%, 10%, and 20% fly ash on the resilience of costly fly ash blended soil under wetting-drying and freeze-thaw cycles were investigated by Bin-Shafique et al. [41]. Research has been done on the impact of twelve cycles of freeze-thaw and wetting-drying on the plasticity index, vertical swelling, and unconfined compressive strength (UCS). Similar to the wet-dry cycle and freeze-thaw cycle, it was shown that the plasticity index (Figure 21) and vertical swelling (Figure 22) decrease with the amount of fly ash content. The wet-dry cycle using saline water, however, has a bigger effect. Also, for any proportion of fly ash, the wet-dry cycle has a greater impact as compared to the freeze-thaw cycle on the plasticity index (Figure 21), whereas the freeze-thaw cycle has a greater impact on vertical swelling (Figure 22). Further, the wet-dry and freeze-thaw cycles show the opposite impacts on the UCS (Figure 23). After wet-dry cycles, the UCS value is found to be higher than that of the un-stabilized soil, whereas, after the freeze-thaw cycle, the UCS decreased below the value obtained for un-stabilized soil.

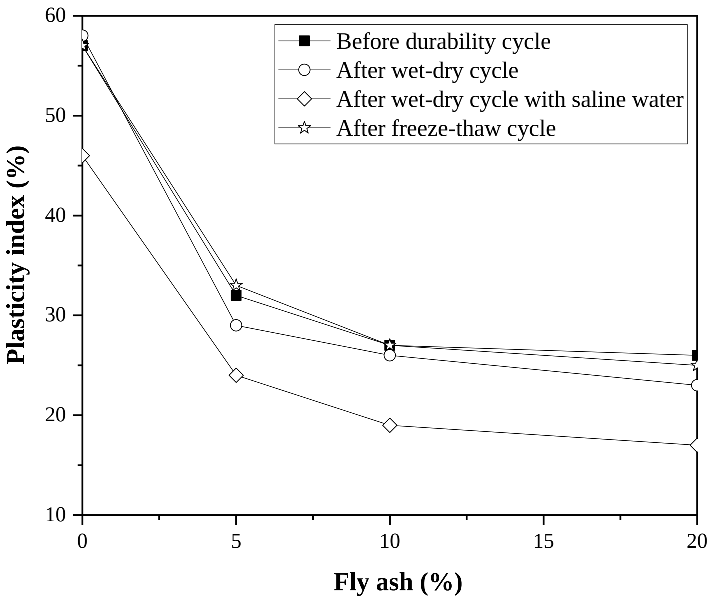

Figure 21. Plasticity index variation over a durability cycle with fly ash content

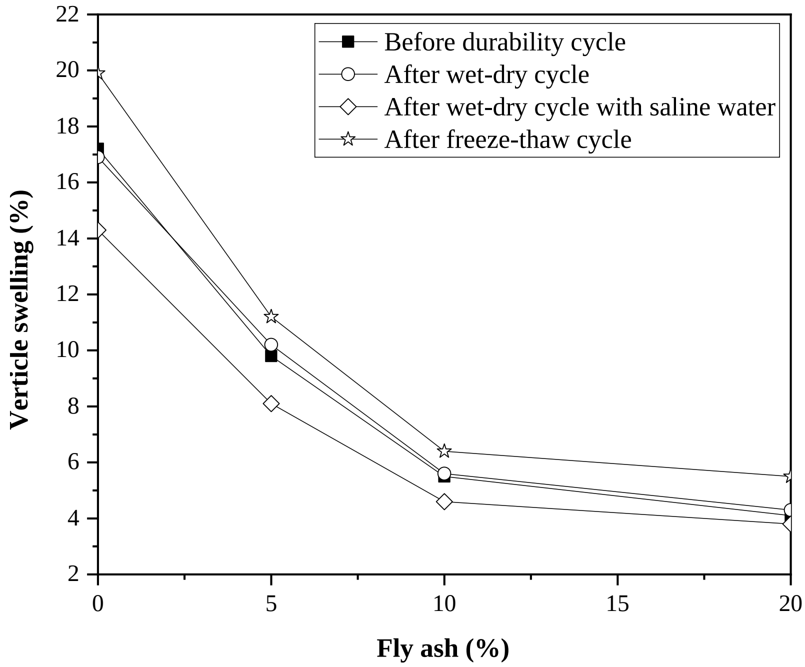

Figure 22. Vertical swelling variation with fly ash content following the durability cycle

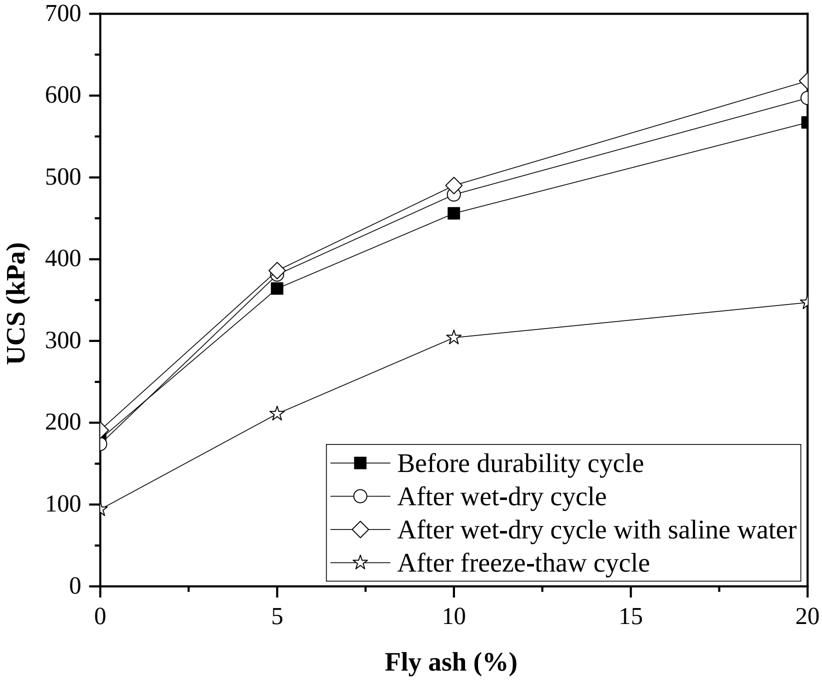

Figure 23. Variation of UCS with fly ash content after durability cycle

Further, Bin-Shafique et al. [42] studied the impact of the freeze-thaw cycle along with the drainage condition on the UCS, tensile strength, and vertical swelling of San Antonio Clay and Helotes Clay blended with fly ash (10% and 20%) under different drainage conditions. Figure 24 shows that the un-stabilized Helotes clay exhibits a greater loss in compressive strength than the un-stabilized San Antonio clay; yet, the fall in compressive strength diminishes as the fly ash percentage rises. Helotes clay may have lost more of its compressive strength because of its higher initial water content, which expands as the ground freezes and causes fractures to form and the clay to weaken. However, the trend is opposite in the case of tensile strength, which shows a higher fall loss in the tensile strength of San Antonio clay as compared to Helotes clay (Figure 25). Further, it was observed that clay with a poor drainage system loses more strength (both compressive and tensile) after the freeze-thaw cycle than clay with a good drainage system.

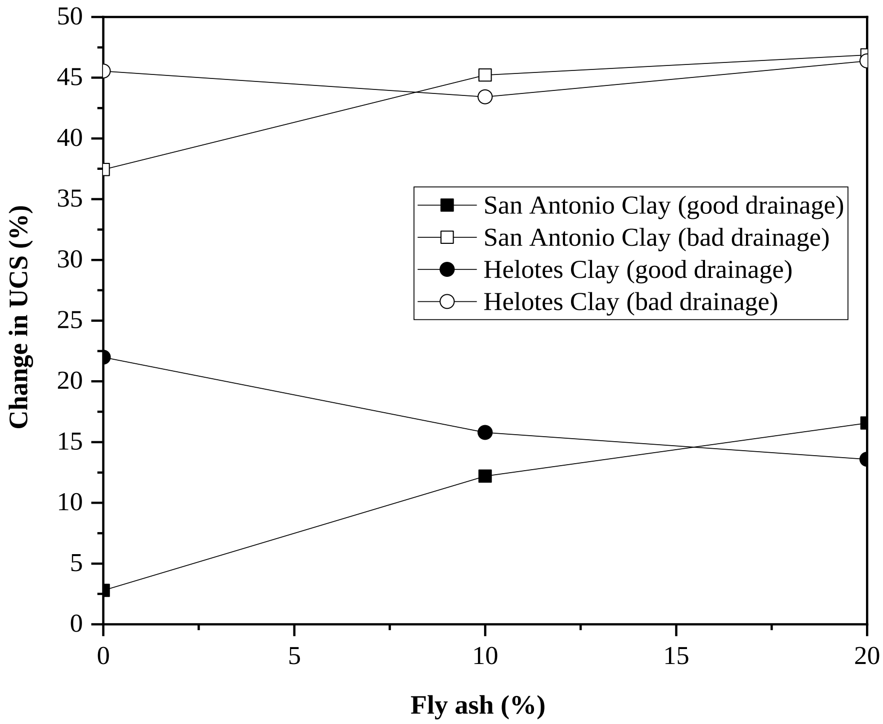

Figure 24. Percentage change in UCS with fly ash content

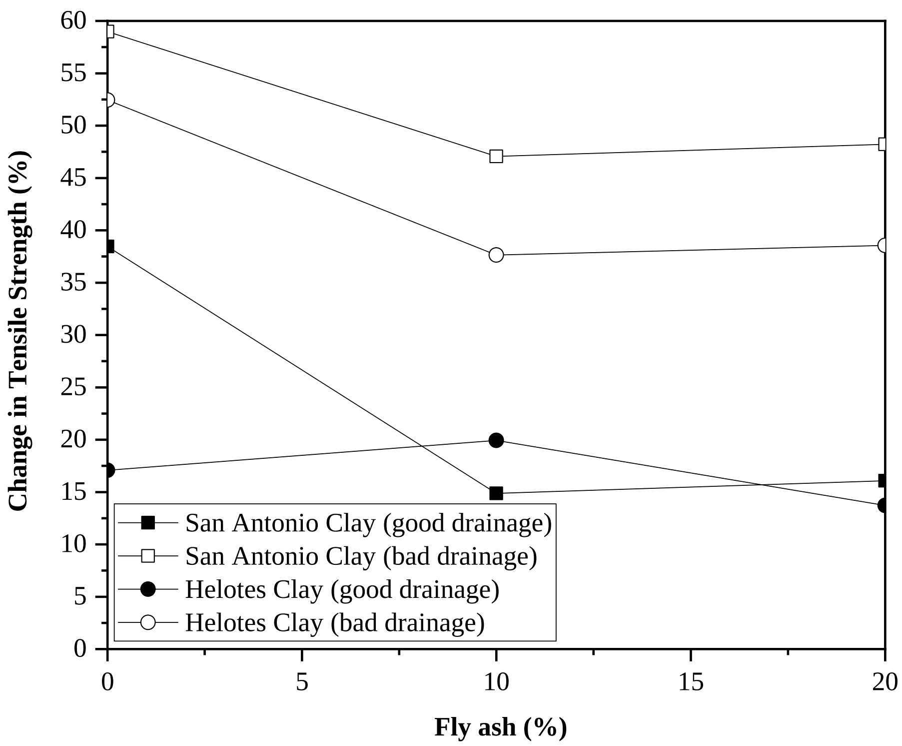

Figure 25. Percentage change in tensile strength with fly ash content

Due to the poor drainage system, the void will hold more water freezing, which will develop cracks in the soil and decrease its strength. However, the vertical swelling of the modified clay increases after freeze-thaw cycle and is higher in case of poor drainage conditions. Further, an increase in the vertical swelling has been observed (Figure 26) after the freeze-thaw cycle, which may be due to the combined effect of free swelling of clay minerals and freezing of the pore water [42].

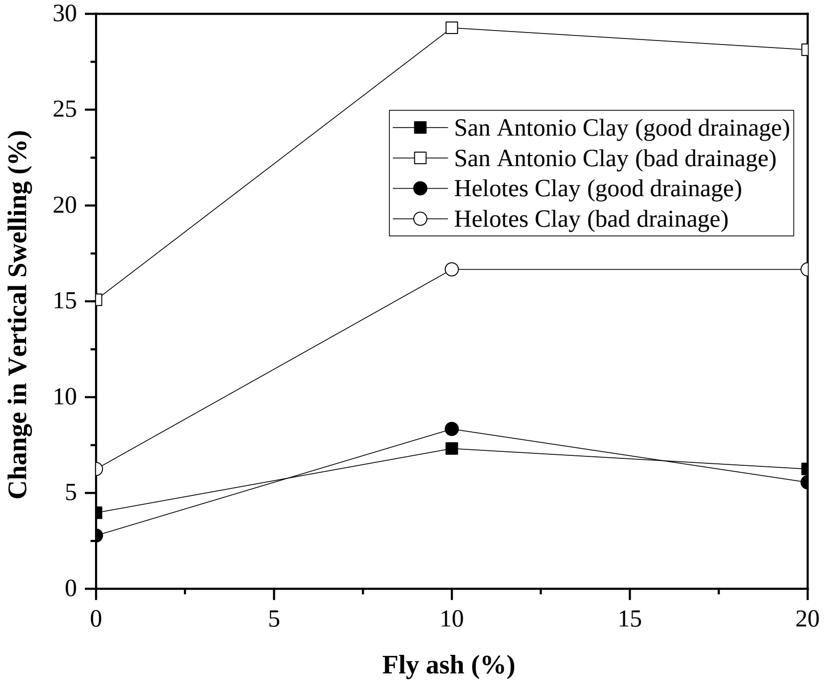

Figure 26. Percentage change in vertical swelling with fly ash content

6. Dynamic Property

Shear modulus, damping ratio, and Poisson's ratio are three key metrics used to study the dynamic property of soil. The dynamic characteristics of the swelling soil stabilized with 5%, 10%, 15%, and 20% fly ash were examined by Saride & Dutta [43]. While class C fly ash had a 52% fine content, the expanding soil employed for the study had a 70% fine content and a 40% clay component. Due to increased initial shear stiffness, it is shown that the normalized shear modulus degradation (G/G_{max}) of fly ash stabilized soil cured for 28 days increases with increasing fly ash content, regardless of the confining pressure (25 kPa, 100 kPa, and 200 kPa). It is discovered that fly ash has very little effect on the damping ratio, which further drops as confining pressure rises. Concurrently, as the fly ash percentage and confining pressure rise, Poisson's ratio falls. It is also noted that the curing period from 1 day to 28 days has no effect on the damping ratio, Poisson's ratio, or shear modulus degradation for any proportion of fly ash and confining pressure. Furthermore, regardless of the fly ash %, the maximum value of shear modulus rises with an increase in confining pressure (25 kPa to 200 kPa) at the small strain level (Figure 27). Conversely, as confining pressure increases from 25 kPa to 200 kPa, the minimum values of the damping ratio (Figure 28) and Poisson's ratio (Figure 28) fall.

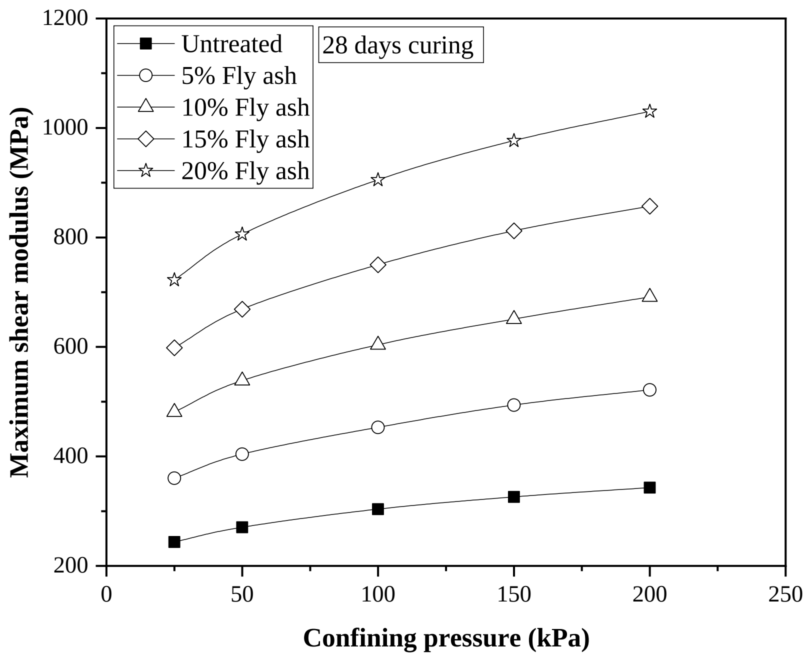

Figure 27. Maximum shear modulus variation with confining pressure

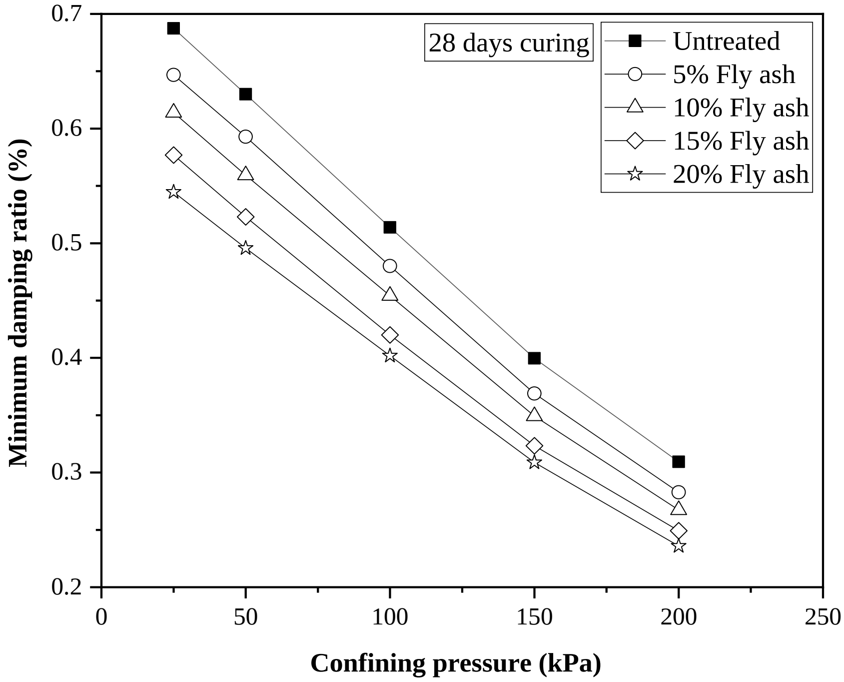

Figure 28. Change in minimum damping ratio in relation to confining pressure

7. Conclusions

Expansive soil is problematic soil with high volume change, which causes damage to civil engineering structures. On the other hand, fly ash is an industrial by-product generated from the thermal power industry and consists of pozzolanic activity to bind the soil particles together. This review article consists of results reported in several articles and a conclusion based on that research.

- The maximum dry unit weight of the mixture drops as the percentage of fly ash increases because the specific gravity falls. There has to be more research done in this area because not many researchers have observed an increase in the maximum dry unit weight. But the majority of researchers have reported a rise in UCS and CBR values up to an optimum quantity due to the cementing properties of the fly ash. However, the freeze-thaw cycle decreases the UCS, and the wet-dry cycle increases it. The UCS and tensile strength also depend on the drainage condition of the sample.
- While the plastic limit rises, the liquid limit falls as the mixture's fly ash percentage rises. The shrinkage limit, however, did not exhibit a regular trend; however, the linear shrinkage exhibits a declining tendency as the fly ash percentage increases.
- The durability test shows that the wet-dry cycle decreases the plasticity index, but the freeze-thaw cycle does not have any considerable impact on the plasticity index. Differential-free swelling and swelling pressure were reduced with a rise in fly ash. However, the vertical swelling decreases after wet-dry cycles in saline water but increases after the freeze-thaw cycle, and it also depends on the drainage condition of the sample.
- The addition of fly ash causes a decrease in the coefficient of volume change, the coefficient of compressibility, the compression index, and the swelling index, but at the same time, the coefficient of consolidation shows a non-linear irregular trend.
- SWCC shows that fly ash blended with swelling soil decreases its water-holding capacity. The shear parameters are found to be at their maximum at 25% fly ash, after which they start decreasing. However, the elastic modulus is found to be at its maximum in between 25%-30% fly ash in the mixture.
- The dynamic property of the fly ash blended swelling soil reveals that at any confining pressure, the addition of fly ash increases the maximum shear modulus, but at the same time, the maximum damping ratio and maximum Poisson's ratio decrease.
- Research on the SWCC, durability, and dynamic properties of fly ash blended swelling soil is found to be lacking, indicating a need for more in-depth studies in this area.

8. Declarations

8.1. Author Contributions

Conceptualization, S.A.; methodology, S.A. and N.A.A.; validation, S.A.; formal analysis, S.A.; investigation, S.A. and N.A.A.; resources, S.A. and N.A.A.; data curation, S.A. and N.A.A.; writing—original draft preparation, S.A.; writing—review and editing, S.A. and N.A.A.; supervision, S.A.; project administration, S.A. and N.A.A.; funding acquisition, N.A.A. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in the article.

8.3. Funding and Acknowledgements

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Tang, C. S., Wang, D. Y., Zhu, C., Zhou, Q. Y., Xu, S. K., & Shi, B. (2018). Characterizing drying-induced clayey soil desiccation cracking process using electrical resistivity method. Applied Clay Science, 152, 101–112. doi:10.1016/j.clay.2017.11.001.

[2] Yang, B., Xu, K., & Zhang, Z. (2020). Mitigating evaporation and desiccation cracks in soil with the sustainable material biochar. Soil Science Society of America Journal, 84(2), 461–471. doi:10.1002/saj2.20047.

[3] Zeng, H., Tang, C. S., Cheng, Q., Zhu, C., Yin, L. Y., & Shi, B. (2020). Drought-Induced Soil Desiccation Cracking Behavior With Consideration of Basal Friction and Layer Thickness. Water Resources Research, 56(7). doi:10.1029/2019WR026948.

[4] Liu, J., Lei, H., Zheng, G., Zhou, H., & Zhang, X. (2017). Laboratory model study of newly deposited dredger fills using improved multiple-vacuum preloading technique. Journal of Rock Mechanics and Geotechnical Engineering, 9(5), 924–935. doi:10.1016/j.jrmge.2017.03.003.

[5] Zornberg, J. G., Azevedo, M., Sikkema, M., & Odgers, B. (2017). Geosynthetics with enhanced lateral drainage capabilities in roadway systems. Transportation Geotechnics, 12, 85–100. doi:10.1016/j.trgeo.2017.08.008.

[6] Dizon, A., & Orazem, M. E. (2020). Advances and challenges of electrokinetic dewatering of clays and soils. Current Opinion in Electrochemistry, 22, 17–24. doi:10.1016/j.coelec.2020.03.002.

[7] Addai-Mensah, J. (2007). Enhanced flocculation and dewatering of clay mineral dispersions. Powder Technology, 179(1–2), 73–78. doi:10.1016/j.powtec.2006.11.008.

[8] Vu, D. H., Bui, H. B., Kalantar, B., Bui, X. N., Nguyen, D. A., Le, Q. T., Do, N. H., & Nguyen, H. (2019). Composition and morphology characteristics of magnetic fractions of coal fly ash wastes processed in high-temperature exposure in thermal power plants. Applied Sciences (Switzerland), 9(9). doi:10.3390/app9091964.

[9] Jayaranjan, M. L. D., van Hullebusch, E. D., & Annachhatre, A. P. (2014). Reuse options for coal fired power plant bottom ash and fly ash. Reviews in Environmental Science and Biotechnology, 13(4), 467–486. doi:10.1007/s11157-014-9336-4.

[10] Jana, A., Ghosh, M., Sinha, S., Jothiramajayam, M., Nag, A., & Mukherjee, A. (2017). Hazard identification of coal fly ash leachate using a battery of cyto-genotoxic and biochemical tests in Allium cepa. Archives of Agronomy and Soil Science, 63(10), 1443–1453. doi:10.1080/03650340.2017.1280730.

[11] Wang, N., Hao, L., Chen, J., Zhao, Q., & Xu, H. (2018). Adsorptive removal of organics from aqueous phase by acid-activated coal fly ash: preparation, adsorption, and Fenton regenerative valorization of "spent" adsorbent. Environmental Science and Pollution Research, 25(13), 12481–12490. doi:10.1007/s11356-018-1560-y.

[12] Gollakota, A. R. K., Volli, V., & Shu, C. M. (2019). Progressive utilisation prospects of coal fly ash: A review. Science of the Total Environment, 672, 951–989. doi:10.1016/j.scitotenv.2019.03.337.

[13] Bednar, A. J., Chappell, M. A., Seiter, J. M., Stanley, J. K., Averett, D. E., Jones, W. T., Pettway, B. A., Kennedy, A. J., Hendrix, S. H., & Steevens, J. A. (2010). Geochemical investigations of metals release from submerged coal fly ash using extended elutriate tests. Chemosphere, 81(11), 1393–1400. doi:10.1016/j.chemosphere.2010.09.026.

[14] Valeev, D., Kunilova, I., Alpatov, A., Mikhailova, A., Goldberg, M., & Kondratiev, A. (2019). Complex utilisation of ekibastuz brown coal fly ash: Iron & carbon separation and aluminium extraction. Journal of Cleaner Production, 218, 192–201. doi:10.1016/j.jclepro.2019.01.342.

[15] Sybertz, F. (1988). Pozzolanic activity of coal fly ash. Betonwerk und Fertigteil-Technik/ Concrete Plant Precast Technology, 54(1), 42–47.

[16] Khandelwal, A., Patel, K. K., & Singh, V. P. (2024). Volume Change Behavior of Amended Expansive Soil Using Sugarcane Bagasse Ash-Based Geopolymer. Journal of Materials in Civil Engineering, 36(4), 4024006. doi:10.1061/jmcee7.mteng-16294.

[17] Kishor, R., & Singh, V. P. (2023). Evaluation of Expansive Soil Amended with Fly Ash and Liquid Alkaline Activator. Transportation Infrastructure Geotechnology, 10(4), 685–706. doi:10.1007/s40515-022-00240-8.

[18] Wang, H., Liu, T., Yan, C., & Wang, J. (2023). Expansive Soil Stabilization Using Alkali-Activated Fly Ash. Processes, 11(5), 1550. doi:10.3390/pr11051550.

[19] Pesarakloo, V., Lajevardi, S. H., MolaAbasi, H., & Mirhosseini, S. M. (2024). Potential application of sludge pond ash as a novel additive for clay stabilization. Physics and Chemistry of the Earth, 133, 103534. doi:10.1016/j.pce.2023.103534.

[20] Jamsawang, P., Adulyamet, B., Voottipruex, P., Jongpradist, P., Likitlersuang, S., & Tantayopin, K. (2023). The free swell potential of expansive clays stabilized with the shallow bottom ash mixing method. Engineering Geology, 315, 107027. doi:10.1016/j.enggeo.2023.107027.

[21] Sengul, T., Akray, N., & Vitosoglu, Y. (2023). Investigating the effects of stabilization carried out using fly ash and polypropylene fiber on the properties of highway clay soils. Construction and Building Materials, 400, 132590. doi:10.1016/j.conbuildmat.2023.132590.

[22] Pan, L., Liu, H., Qiu, W., & Yin, J. (2023). Effects of Salinity and Curing Time on Compression Behavior of Fly Ash Stabilized Marine Clay. KSCE Journal of Civil Engineering, 27(10), 4141–4151. doi:10.1007/s12205-023-1674-8.

[23] Bhatt, A., Priyadarshini, S., Acharath Mohanakrishnan, A., Abri, A., Sattler, M., & Techapaphawit, S. (2019). Physical, chemical, and geotechnical properties of coal fly ash: A global review. Case Studies in Construction Materials, 11. doi:10.1016/j.cscm.2019.e00263.

[24] ASTM C618-19. (2022). Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. ASTM International, Pennsylvania, United States. doi:10.1520/C0618-19.

[25] Mohanty, S. K., Pradhan, P. K., & Mohanty, C. R. (2016). Consolidation and Drainage Characteristics of Expansive Soil Stabilized with Fly Ash and Dolochar. Geotechnical and Geological Engineering, 34(5), 1435–1451. doi:10.1007/s10706-016-0053-3.

[26] Kolay, P. K., & Ramesh, K. C. (2016). Reduction of Expansive Index, Swelling and Compression Behavior of Kaolinite and Bentonite Clay with Sand and Class C Fly Ash. Geotechnical and Geological Engineering, 34(1), 87–101. doi:10.1007/s10706-015-9930-4.

[27] Puppala, A., Hoyos, L., Viyanant, C., & Musenda, C. (2001). Fiber and Fly Ash Stabilization Methods to Treat Soft Expansive Soils. Soft Ground Technology, 136-145. doi:10.1061/40552(301)11.

[28] Mahedi, M., Cetin, B., & White, D. J. (2020). Cement, Lime, and Fly Ashes in Stabilizing Expansive Soils: Performance Evaluation and Comparison. Journal of Materials in Civil Engineering, 32(7), 04020177. doi:10.1061/(asce)mt.1943-5533.0003260.

[29] Nalbantoğlu, Z. (2004). Effectiveness of class C fly ash as an expansive soil stabilizer. Construction and Building Materials, 18(6), 377–381. doi:10.1016/j.conbuildmat.2004.03.011.

[30] Mir, B. A., & Sridharan, A. (2013). Physical and Compaction Behaviour of Clay Soil-Fly Ash Mixtures. Geotechnical and Geological Engineering, 31(4), 1059–1072. doi:10.1007/s10706-013-9632-8.

[31] Zha, F., Liu, S., Du, Y., & Cui, K. (2008). Behavior of expansive soils stabilized with fly ash. Natural Hazards, 47(3), 509–523. doi:10.1007/s11069-008-9236-4.

[32] Punthutaecha, K., Puppala, A. J., Vanapalli, S. K., & Inyang, H. (2006). Volume Change Behaviors of Expansive Soils Stabilized with Recycled Ashes and Fibers. Journal of Materials in Civil Engineering, 18(2), 295–306. doi:10.1061/(asce)0899-1561(2006)18:2(295).

[33] Sabat, A. K., & Pradhan, A. (2014). Fiber reinforced-fly ash stabilized expansive soil mixes as subgrade material in flexible pavement. Electronic Journal of Geotechnical Engineering, 19, 5757-5770.

[34] Bose, B. (2012). Geo engineering properties of expansive soil stabilized with fly ash. Electronic Journal of Geotechnical Engineering, 17(1), 1339-1353.

[35] Phanikumar, B. R., & Nagaraju, T. V. (2018). Effect of Fly Ash and Rice Husk Ash on Index and Engineering Properties of Expansive Clays. Geotechnical and Geological Engineering, 36(6), 3425–3436. doi:10.1007/s10706-018-0544-5.

[36] Mollamahmutoğlu, M., Yılmaz, Y., & Güngör, A. G. (2009). Effect of a class C fly ash on the geotechnical properties of an expansive soil. International Journal of Engineering Research and Development, 1, 1-6.

[37] Murmu, A. L., Jain, A., & Patel, A. (2019). Mechanical Properties of Alkali Activated Fly Ash Geopolymer Stabilized Expansive Clay. KSCE Journal of Civil Engineering, 23(9), 3875–3888. doi:10.1007/s12205-019-2251-z.

[38] Rao, K. M., & Subbarao, G. V. R. (2012). Optimum fly ash for mechanical stabilization of expansive soils using 2 2 factorial experimental design. Natural Hazards, 60(2), 703–713. doi:10.1007/s11069-011-0040-1.

[39] Faisal Noaman, M., Khan, M. A., Ali, K., & Jamal, A. (2023). Effect of fly ash on the shear strength of clay soil. Materials Today: Proceedings. doi:10.1016/j.matpr.2023.02.069.

[40] Lin, B., Cerato, A. B., Andrew, S. M., & Madden, M. E. E. (2013). Effect of fly ash on the behavior of expansive soils: Microscopic analysis. Environmental and Engineering Geoscience, 19(1), 85–94. doi:10.2113/gseegeosci.19.1.85.

[41] Bin-Shafique, S., Rahman, K., Yaykiran, M., & Azfar, I. (2010). The long-term performance of two fly ash stabilized fine-grained soil subbases. Resources, Conservation and Recycling, 54(10), 666–672. doi:10.1016/j.resconrec.2009.11.007.

[42] Bin-Shafique, S., Rahman, K., & Azfar, I. (2011). The Effect of Freezing-Thawing Cycles on Performance of Fly Ash Stabilized Expansive Soil Subbases. Geo-Frontiers Congress, 697–706. doi:10.1061/41165(397)72.

[43] Saride, S., & Dutta, T. T. (2016). Effect of Fly-Ash Stabilization on Stiffness Modulus Degradation of Expansive Clays. Journal of Materials in Civil Engineering, 28(12). doi:10.1061/(asce)mt.1943-5533.0001678.

[44] Çokça, E. (2001). Use of Class C Fly Ashes for the Stabilizationof an Expansive Soil. Journal of Geotechnical and Geoenvironmental Engineering, 127(7), 568–573. doi:10.1061/(asce)1090-0241(2001)127:7(568).

[45] Darikandeh, F. (2018). Expansive soil stabilised by calcium carbide residue-fly ash columns. Proceedings of the Institution of Civil Engineers: Ground Improvement, 171(1), 49–58. doi:10.1680/jgrim.17.00033.

[46] Gupta, C., & Sharma, R. K. (2014). Influence of marble dust, fly ash and beas sand on sub grade characteristics of expansive soil. Journal of Mechanical and Civil Engineering, 13, 13-18.

[47] Karami, H., Pooni, J., Robert, D., Costa, S., Li, J., & Setunge, S. (2021). Use of secondary additives in fly ash-based soil stabilization for soft subgrades. Transportation Geotechnics, 29, 100585. doi:10.1016/j.trgeo.2021.100585.

[48] Li, M., Fang, C., Kawasaki, S., & Achal, V. (2018). Fly ash incorporated with biocement to improve strength of expansive soil. Scientific Reports, 8(1), 2565. doi:10.1038/s41598-018-20921-0.

[49] Mohamed, A. A. M. S., Yuan, J., Al-Ajamee, M., Dong, Y., Ren, Y., & Hakuzweyezu, T. (2023). Improvement of expansive soil characteristics stabilized with sawdust ash, high calcium fly ash and cement. Case Studies in Construction Materials, 18. doi:10.1016/j.cscm.2023.e01894.

[50] Sharma, A. K., & Sivapullaiah, P. V. (2016). Swelling behaviour of expansive soil treated with fly ash–GGBS based binder. Geomechanics and Geoengineering, 12(3), 191–200. doi:10.1080/17486025.2016.1215548.

[51] Kolbe, J. L., Lee, L. S., Jafvert, C. T., & Muraka, I. P. (2011). Use of alkaline coal ash for reclamation of a former strip mine. Worl of Coal Ash (WOCA) Conference, 9-12 May, Denver, United States.

[52] Ma, Q. Y., Cao, Z. M., & Yuan, P. (2018). Experimental Research on Microstructure and Physical-Mechanical Properties of Expansive Soil Stabilized with Fly Ash, Sand, and Basalt Fiber. Advances in Materials Science and Engineering, 9125127. doi:10.1155/2018/9125127.

[53] Dissanayake, T. B. C. H., Senanayake, S. M. C. U., & Nasvi, M. C. M. (2017). Comparison of the Stabilization Behavior of Fly Ash and Bottom Ash Treated Expansive Soil. Engineer: Journal of the Institution of Engineers, Sri Lanka, 50(1), 11. doi:10.4038/engineer.v50i1.7240.

[54] Phani Kumar, B. R., & Sharma, R. S. (2004). Effect of Fly Ash on Engineering Properties of Expansive Soils. Journal of Geotechnical and Geoenvironmental Engineering, 130(7), 764–767. doi:10.1061/(asce)1090-0241(2004)130:7(764).

[55] Sharma, N. K., Swain, S. K., & Sahoo, U. C. (2012). Stabilization of a Clayey Soil with Fly Ash and Lime: A Micro Level Investigation. Geotechnical and Geological Engineering, 30(5), 1197–1205. doi:10.1007/s10706-012-9532-3.

[56] Phanikumar, B. R., & Sharma, R. S. (2007). Volume Change Behavior of Fly Ash-Stabilized Clays. Journal of Materials in Civil Engineering, 19(1), 67–74. doi:10.1061/(asce)0899-1561(2007)19:1(67).

[57] Kumar, P. G., & Harika, S. (2020). Stabilization of expansive subgrade soil by using fly ash. Materials Today: Proceedings, 45, 6558–6562. doi:10.1016/j.matpr.2020.11.469.

[58] Mitchell, J. K., & Soga, K. (2005). Fundamentals of soil behavior. John Wiley & Sons, Hoboken, United States.

[59] Lees, G., Abdelkader, M. O., & Hamdani, S. K. (1982). Effect of the Clay Fraction on Some Mechanical Properties of Lime-Soil Mixtures. Highway Engineer, 29(11), 2–9. doi:10.1016/0148-9062(84)91148-3.

[60] Bell, F. G. (1996). Lime stabilization of clay minerals and soils. Engineering Geology, 42(4), 223–237. doi:10.1016/0013-7952(96)00028-2.

[61] Du, Y., Li, S., & Hayashi, S. (1999). Swelling-shrinkage properties and soil improvement of compacted expansive soil, Ning-Liang Highway, China. Engineering Geology, 53(3–4), 351–358. doi:10.1016/S0013-7952(98)00086-6.

[62] Kumar, A., Walia, B. S., & Bajaj, A. (2007). Influence of Fly Ash, Lime, and Polyester Fibers on Compaction and Strength Properties of Expansive Soil. Journal of Materials in Civil Engineering, 19(3), 242–248. doi:10.1061/(asce)0899-1561(2007)19:3(242).

[63] Puppala, A. J., Punthutaecha, K., & Vanapalli, S. K. (2006). Soil-Water Characteristic Curves of Stabilized Expansive Soils. Journal of Geotechnical and Geoenvironmental Engineering, 132(6), 736–751. doi:10.1061/(asce)1090-0241(2006)132:6(736).