An overview of how fly ash affects the stability and geotechnical characteristics of soil.

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Abstract

Fly ash, a waste material from power plants is difficult to get rid of and causes environmental issues. One way to tackle this problem is by using fly ash to improve the stability of soil. Soil stability means making the soil stronger and better for construction by improving its properties like water content, strength, flexibility, and density. Many studies have looked into how adding fly ash affects soil stability. This report reviews some of those studies to understand how fly ash changes the characteristics of soil, especially when mixed with clay.

Overall, the studies show that fly ash helps improve soil stability, especially by increasing the California Bearing Ratio (CBR) values (a measure of soil strength), improving how water flows through the soil, and reducing the chances of the soil swelling or shrinking. This is because of the size and shape of the fly ash particles, as well as how long the soil is treated. Over time, the soil becomes less likely to expand. Since fly ash doesn't break down, the improvements in the soil's behaviour are long-lasting.

Introduction

A significant issue facing the entire world is the decline in building construction sites, particularly in the highly populous nations of eastern and southeast Asia (Brockerhoff and Nations, 1998; Faisal Noaman et al., 2022; Ravallion et al., 2007).

The population growth has led to a rise in the need for electrical energy. The coal-burning electric power thermal plant then generates millions of tons of waste products, including ground granulated blast furnace ash (FA) and fly ash (FA). GGBFS for furnace slag (Hassan et al., 2020a, 2019a). The elimination and Recycling these waste materials has grown to be a significant financial and environmental problem (Hassan et al., 2020a, 2020b). To discover a solution, researchers have carried out a number of in-depth examinations.Hassan et al. (2020c, 2020b, 2019b) have addressed this issue. A few of these Studies concentrated on using fly ash to increase the soil's capacity, which is generated in thermal power plants as trash (Ozdemir, 2016; Ram and Masto (2014); S and others (2014)). The strength of the soil is a key factor in construction, which has led researchers to explore ways to improve soil by mixing it with other materials like fly ash (FA) or lime. These additives, which come from industrial activities, can make the soil stronger and more stable. There are different ways to stabilize soil: mechanical, hydraulic, physical, and chemical methods. Many studies have shown that mixing soil with waste materials like fly ash and lime improves the soil's strength and stability.Fly ash is a waste product mainly created when coal is burned in power plants to produce electricity. It contains various chemicals and minerals, including aluminum, silicon, iron oxides, and some unburned carbon. The properties of fly ash can vary depending on the type of coal used and the methods applied in the power plants.

SOIL STABILIZATION:

In the soil stabilization process, the properties of the soil are improved to make it perform better for construction. This includes improving things like the soil's density, water content, plasticity, and strength. These changes help temporarily strengthen the ground.

Soil stabilization can be used for many different types of soil, from clays that expand and shrink to more grainy soils. The main benefits of this process are that it makes the soil stronger, less plastic, lowers its ability to absorb water, and can reduce the thickness of roads or pavements built on it. For soils that expand and contract, stabilization helps control these changes and improves their strength. In geotechnical engineering, these types of soils are often called swelling or shrink-swell soils.

PROPERTIES OF FLYASH

Fly ash is a versatile material that can be used in many applications, such as making cement, bricks, blocks, and tiles. It's also very useful for construction projects like building embankments, reclaiming low-lying areas, filling underground or open mines, and even improving agriculture and restoring damaged land.

Because fly ash reacts well with lime, it works great as a binding material for cement. Its geotechnical properties also make it a good alternative to soil, and the right mix of silica, alumina, and iron oxide makes it suitable for applications that involve heating (sintering). Fly ash is safe to use because it contains very low levels of harmful metals or chemicals, and its physical and chemical properties are similar to regular soil.

PHYSICAL PROPERTIES OF FLY ASH:

Fly ash is a fine powder made up mostly of round, spherical particles, though some ashes may have irregular or angular shapes. The size of the particles depends on where the fly ash comes from, and it can be finer or coarser compared to Portland cement particles. Some particles are solid, while the larger ones may be hollow spheres that contain many smaller particles inside.

Influence of fly ash on the volumetric change of clay soil

This section looks at how adding fly ash (FA) affects the amount of swelling or shrinking in soil and aims to find the best way and the right amount of FA to improve the soil. Many studies and experiments have been done to understand how soil behaves when mixed with FA, and the following parts go into detail about these findings.

BENEFITS OF SOIL STABILIZATION:

Benefits of Soil Stabilization process can include:

- Higher resistance (R) values
- Reduction in plasticity
- Lower permeability
- Reduction of pavement thickness
- Aids compaction

Effect of Fly Ash on the secondary consolidation of clay soil

Saha and Pal (2012) studied how adding fly ash (FA) affects the compressibility of clay soil by layering the materials in different ways: (Soil - FA - Soil) and (FA - Soil - FA). They compared these layered samples with plain soil samples (Soil - Soil - Soil) and plain fly ash samples (FA - FA - FA). Their goal was to see how the order of the layer's influences soil behaviour. They found that plain soil compressed more than plain FA. The (FA - Soil - FA) samples had compression levels similar to plain FA. The time it took to go from the first phase of settling to the second phase of compression was shorter in the (Soil - FA - Soil) samples than in the others.

Phanikumar and Sharma (2007) looked at how FA affects the shrinking and swelling of expansive clay. They found that mixing 20% FA with the clay improved the second phase of settling (secondary consolidation) compared to untreated clay. Also, both the first and second phases of settling happened faster with the FA-treated clay. For construction, this means that while the total settling of a building on FA-treated clay might not reduce, it happens more quickly. Pal and Ghosh (2014) confirmed these results by experimenting with different percentages of FA (10–50%) mixed with clay soil.

Saha and Pal (2012) studied how mixing fly ash (FA) with clay affects how much the soil compresses. They tested different layers of soil and FA: (Soil - FA - Soil) and (FA - Soil - FA), comparing them to plain soil (Soil - Soil - Soil) and plain FA (FA - FA - FA). Their goal was to see if the order of layers changes the soil's behaviour. They found that plain soil compressed more than plain FA, and the (FA - Soil - FA) samples had compression levels like plain FA. The (Soil - FA - Soil) samples settled faster between the two stages of compression than the others.

Phanikumar and Sharma (2007) studied how FA affects clay that expands and shrinks. They found that mixing 20% FA with clay improved the second stage of settling (secondary consolidation) compared to untreated clay. Both stages of settling also happened faster with FA-treated clay. In construction, this means that while a building on FA-treated clay may not settle less, it will settle more quickly. Pal and Ghosh (2014) supported these findings by testing different amounts of FA (10-50%) mixed with clay.

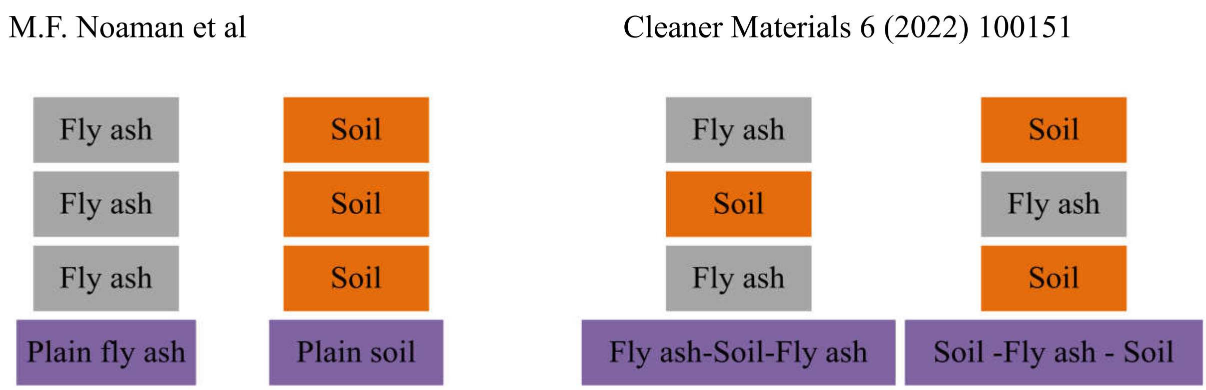

Fig. 1. Saha and Pal test models (Saha and Pal, 2012).

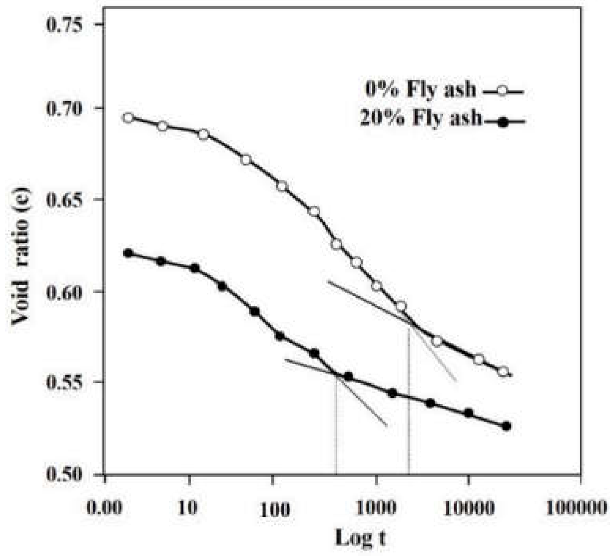

Fig. 2. Effect of FA on secondary consolidation (Phanikumar and Sharma, 2007)

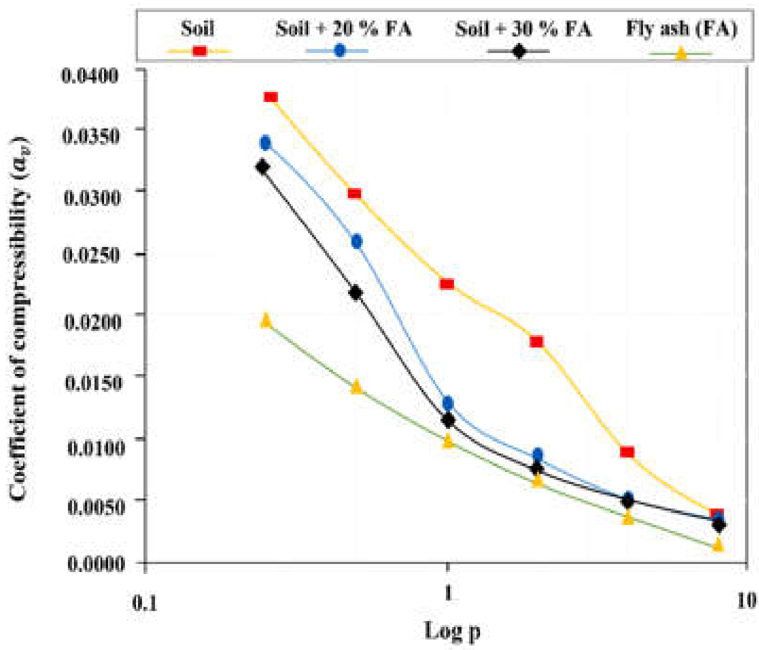

Fig. 3. Effect of FA on the coefficient of compressibility (Saha and Pal, 2012).

PROPERTIES OF SOIL FOR ADDITION OF FLYASH

Table 1: Data Obtained from Experimental Conducted

S.NO	Flyash Added(%)	Liquid Limit(%)	Plastic Limit(%)	Maximum Dry Density	Average Optimum Moisture Content(%)	Specific Gravity	Unconfined Compressive Test(kg/cm^2)
1.	0	21.42%	20.65%	1.81	7%	2.73%	0.395
2.	5	15.38%	17.29%	1.73	7%	2.47%	0.418
3.	10	21.8%	12.46%	1.63	7%	2.03%	0.452
4.	15	24.3%	11.32%	1.59	7%	2.21%	0.905
5.	20	31.2%	11.20%	1.60	7%	2.21%	0.498

Table 1: Different Dosage of fly Ash (S. ANDAVAN , MOHAMED HASSAAN.M)

Amiralian et al. (2012) investigated the influence of FA additions on the swelling and compressibility behaviours of sand soil. Nine samples were prepared for the experimental work, and the percentages of FA added into the soil were from 2.5 % to 20 %, with a 2.5 % increase in the FA percentage. The experimental results indicated that the existence of FA mixed with soil could improve the compressibility behaviour and swelling properties of soil. It was found that the initial void ratio e0 of each mixture decreased with an increase in the percentage of FA, as shown in Table 2. While the sand soil stability at 17.5 % of FA was more effective than other fly ash contents. Whilst Saha and Pal (2012) observed that the behaviour of compressibility of pure clayey soil improved with the addition of 20 % and 30 % of fly ash, respectively. The percentage of improvement beyond 30 % is slight and does not represent the size of the increase in the proportion of fly ash.

FA contents (%)	C_c	C_s	e_0
0	0.0498	0.0398	0.523
2.5	0.0489	0.0212	0.490
5.0	0.0398	0.0205	0.465
7.5	0.0365	0.0192	0.439
10	0.0357	0.0186	0.416
12.5	0.0340	0.0172	0.389
15	0.0282	0.0146	0.361
17.5	0.0265	0.0119	0.340
20	0.0265	0.0139	0.319

Table 2 Values of initial void ratio, compression index (Amiralian et al., 2012).

This finding was observed through the study of the influence of the FA content on the compressibility parameters of clay soil**. Fig. 3 and Table 3** show the development of compressibility parameters with the utilisation of four specimens (soil), (soil – fly ash – soil), (fly ash – soil – fly ash) and (fly ash).

Description of case	Log p	a_v at log p	C_c at log p	m_v at log p	Dial gauge reading versus square root of time equal 20 *sec*
Soil	1	0.028	0.07	0.025	230
FA	1	0.005	0.03	0.006	154
Soil - FA – Soil	1	0.016	0.05	0.015	165
FA - Soil – FA	1	0.014	0.047	0.009	147

Table 3 Values of av, Cc, mv and dial gauge reading (Saha and Pal, 2012)

Effect of fly ash on the settlement of soil

Using laboratory oedometer studies, Saha and Pal (2012) examined the impact of FA on clay soil settling behaviour. On the other hand, FA specimens had a settling value of 0.19 mm. The findings indicated that the module (Soil-FA-Soil) had decreased by 0.30 mm and 0.26 mm in the FA-Soil-FA module. These findings might be explained by the molecular structures that developed in the samples, and then reduce the amount of soil settlement brought on by the upper and lower layers or the middle layer. Figure 5 illustrates the connection between applied settlement and the pressure logarithm (log p) for every instance. But Karim According to et al. (2020a,b,c), the ultimate consolidation settlement of 20% fly ash is the ideal amount of clay soil, which yields a final 0.638 mm of consolidation settling, however above this proportion there was a little rise.

However, **Hasnat et al. (2020)** found that with a 25% fly ash load, the lowest settlement values were 0.336 mm (saturated) and 0.183 mm (unsaturated). Although Rajabi et al. (2021) investigated the impact of nano-iron oxide on clay soil consolidation characteristics, the findings of consolidation tests indicate that reducing soil settlement may be achieved by adding nano-iron oxide up to an optimal level for the same stresses.
Even still, more settlement happens at the same stress as the additive percentage rises. This effect is explained by the interaction between nano-iron oxide and a clay soil combination.

In 2015, **Somnath Shil** examined mixed soil specimens with different FA percentages (20%, 30%), comparing the results with plain soil samples and simple FA samples. The highest settlement for plain soil samples is 0.45 mm, and for plain FA samples, it is 0.17 mm, as shown in Fig. 6, which also displays settlement values and log p. The settlement was 0.27 mm when 30% FA was added, and 0.28 mm when 20% FA was added. According to the test results, the fly ash additions may reduce soil settling (Behera et al., 2021). Karami et al. (2021) examined the impact of soil ,fly ash-lime enzyme on the development of subgrade bearing capacity, using 3-D numerical modelling to assess the improvement.

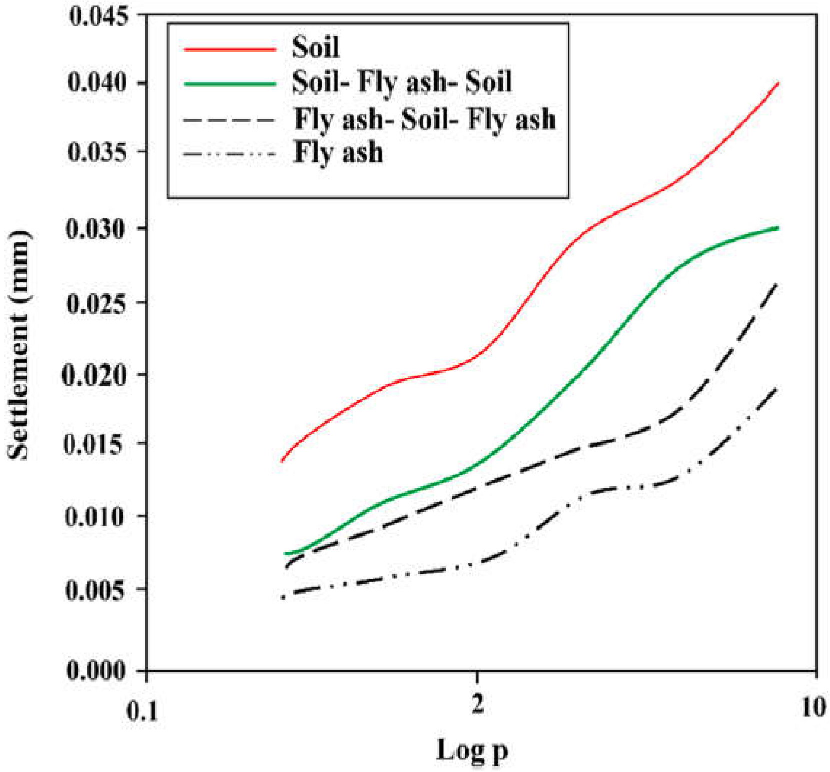

Fig. 4- Settlement values for various samples with and without FA (Saha and Pal, 2012).

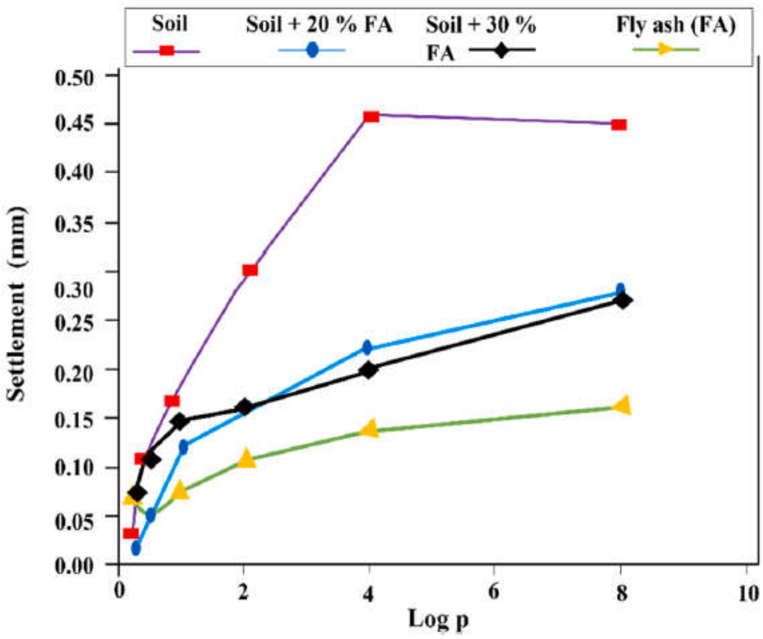

Fig.5- Influence of FA percentage on the settlement values (Somnath Shil, 2015).

Effect of fly ash on swelling of soil

(Salim, 2021) examined the effects of the FA content on the expansive soil's FSI, swell potential, and swelling pressure in lab tests. These admixtures' effects were contrasted with those of organic soils. The results indicate that the percentage of edema and swell
As the proportion of bentonite increases, so does the pressure. The As fly ash levels rise, edema and swelling pressure fall. proportion. The ideal fly ash proportion was 5%, where the swell and there was a significant drop in swell pressure. Prabakar and associates (2004) examined three soil types with varying FA percentages ranging from 9 to 46% by the weight of dry earth.

The experimental results of swelling for different fly ash ratios were erratic and unpredictable. These findings may be represented by wave lines and might be explained by a non-uniform distribution of FA in soils during blending. When 80% FA is mixed with soil-C, the FSI values become zero. When 56.30 percent and 66.66% FA are added to the soils, respectively, the FSI values of the soil-A and soil-B values are zero. Swelling further decreases when the FA volume in the soil increases. This is brought on by FA's unexpansive qualities as well as the size and form of its particles, which support the idea that FA can enhance engineering features like cohesiveness and shear strength, which in turn increases bearing capacity and successfully regulates swelling behavior. Lin et al. (2013) used microscopic analysis to examine the microstructural alterations that take place in two kinds of expansive soils that are improved by FA class C.

The findings demonstrated that adding fly ash to stabilize the soil raises the UCS while lowering the plastic index (PI), clay percentage, swell pressure, and soil water content.

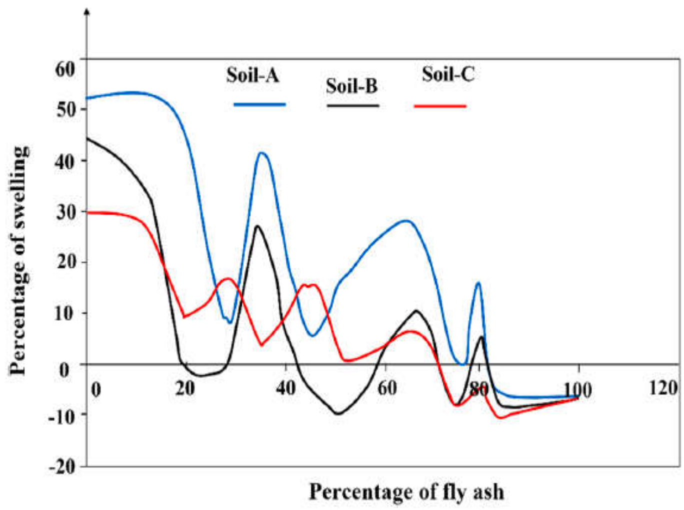

Fig. 6. Free swelling test values for soils mixed with a high percentage of FA (Prabakar et al., 2004).

Nalbantoħlu (2004) examined Tuzala's performance and Samples of Degirmenlik soil were taken 1.5 meters below the surface of the ground. Two stages of the experiment were carried out, compacted soil samples that were not combined and soil samples that had FA added different percentages. According to the findings, the Tuzla soil produces a 6.5% swelling rate, but the untreated Degirmenlik soil produces 19.6% Figure 9 illustrates how effective FA is at reducing the swell potential of soil samples from Degirmenlik. 15% FA addition The swell potential is reduced by 5% when the line thickness is increased and the colors are changed to bright and contrasted, while the same is reduced by 3.7% when the FA is 25%.

Additionally, the results demonstrated that, as shown in Fig. 7, the swell potential of Degirmenlik soil combined with 25% FA decreased to zero in the event of a 30-day curing interval.

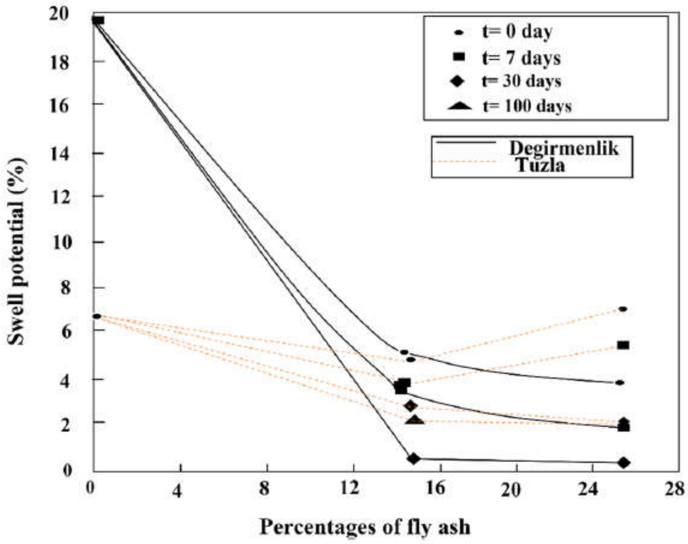

Fig. 7. Influence of FA on the swell potential [Nalbantoğlu (2004)].

Impact fly ash on compaction characteristics of soil

Phanikumar and Sharma (2007) looked at how FA affected the volume change of two different kinds of clay soils: expansive and nonexpansive. A range of FA ratios, including 0, 5, 10, 15, and 20% by dry soil weight, have been employed. The results demonstrated that raising the FA concentration might raise the maximum dry density and lower an OMC. The non-expansionary FA average dry weight rose by around 7% and its OMC dropped by roughly 15% at 20% of the FA ratio. Additionally, the compact curve steadily diminishes as the amount of FA increases. Typical Proctor compaction curves are displayed in Fig. 16 along with the average dry weight of the clay at different FA fractions and the variability of the OMC. Andavan and Pagadala came at the same conclusions (2020a).

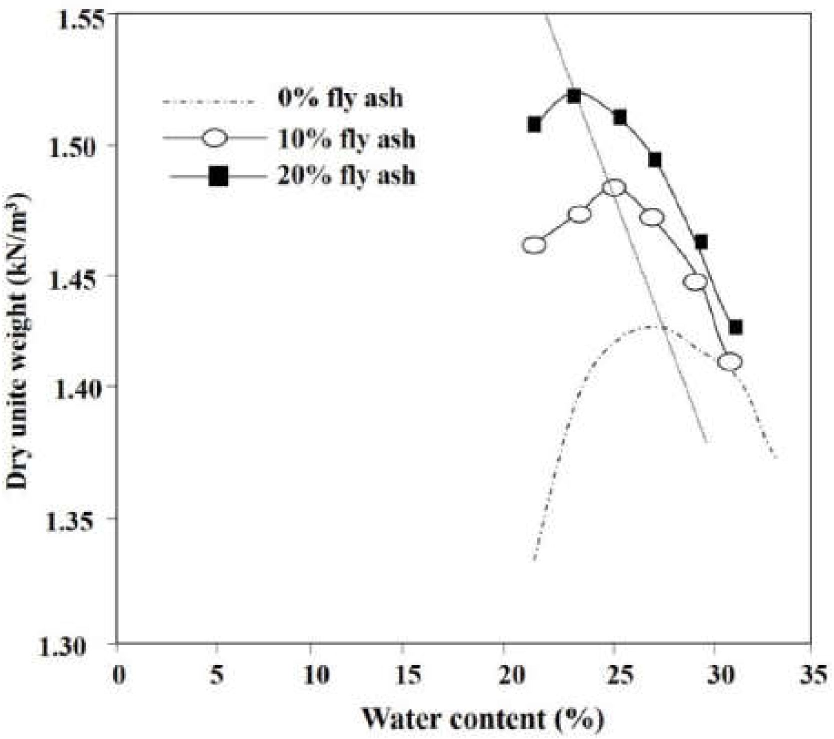

Fig. 8. Effect of FA on the dry unit weight and water content (Phanikumar and Sharma, 2007).

The behavioural aspect of soils combined with FA was investigated by Prabakar et al. (2004) in order to enhance soil carrying capacity and provide engineering features. Three distinct soil types with FA concentrations ranging from 9% to 46% by soil weight have been taken into consideration. The purpose of the study was to evaluate FA's potential as a soil addition. The results shown that the dry density decreases as WC increases. The dry density of soil falls with any proportion of FA addition. The maximum dry density for soil without FA ranges from 1.775 to 1.760 g/cm3, whereas the maximum dry density for soil with 100% FA is the lowest. Table 4 presents the average density and moisture content of soils mixed with FA. Same results pointed out by Karim et al. (2020a,b,c) where fly ash increases plastic and liquid limitations, according to tests. Fly ash reduced specific gravity. Dry unit weight dropped due to less water.

FA	Soil-A		Soil-B		Soil-C	
	OMC %	γ dry g/cm^3	OMC %	γ dry g/cm^3	OMC %	γ dry g/cm^3
0 %	14.57	1.71	24.81	1.57	30.09	1.43
9 %	15.80	1.58	24.80	1.52	29.50	1.38
20 %	17.98	1.57	25.20	1.41	29.50	1.35
28.5 %	20.40	1.44	25.76	1.39	30.05	1.31
35.5 %	22.30	1.39	28.30	1.34	31.90	1.24
41.5 %	25.20	1.36	29.80	1.30	33.30	1.25
46 %	27.20	1.34	30.20	1.29	234.26	1.21
100 %	44.24	0.94	–	–	–	–

Table 5 Average density and moisture content of soils combined with FA (Prabakar et al., 2004).

Effect of fly ash on shear strength of soil

The extra-high-water content of the dredged clay and black cotton soil prevented its immediate reutilization in geotechnical applications. Therefore, dewatering is required before making any improvements. Because chemical flocculants have good flocculation, they are utilized to enhance the dewatering process (Xu et al., 2021; Yin et al., 2020). The speed at which cement, fly ash, and slag might be added to dredge sludge to increase its strength was investigated by Liu et al. in 2021. According to tests, the Shear strength increases and the water content of solidified sludge falls as fly ash and slag percentages rise, according to tests.

Label No.	FA %	Cohesion (Kg/m^2)			ϕ (degree)		
		Soil-A	Soil-B	Soil-C	Soil-A	Soil-B	Soil-C
1	0	250×10^{-3}	185×10^{-3}	530×10^{-3}	30°15′	25°32′	17°10′
2	9.0	250×10^{-3}	208×10^{-3}	523×10^{-3}	31°36′	24°13′	20°26′
3	20.0	270×10^{-3}	300×10^{-3}	475×10^{-3}	33°1′	25°12′	21°58′
4	28.5	310×10^{-3}	300×10^{-3}	500×10^{-3}	35°56′	28°18′	23°15′
5	35.0	340×10^{-3}	330×10^{-3}	480×10^{-3}	34°12′	29°38′	26°17′
6	41.2	370×10^{-3}	370×10^{-3}	440×10^{-3}	32°6′	29°53′	27°22′
7	46.0	395×10^{-3}	380×10^{-3}	395×10^{-3}	28°38′	30°38′	27°56′
8	100.0	–	150×10^{-3}	–	–	29°21′	–

Table 6 Influence of FA content on cohesion and internal friction angle for different types of soils (Prabakar et al., 2004).

Effect of fly ash on the California bearing ratio (CBR)

The impact of lime and FA on soil CBR was investigated by Athanasopoulou (2014). Due to the pozzolanic nature of fly ash, Table 7's results showed that the highest CBR for S1 soil was caused by 12% lime content and 8% content for S2 soil. Particularly when there is a high FA or lime concentration, fly ash can decrease soil swelling and raise the OMC and CBR values. However, according to Sharma et al. (2012), 20% fly ash was the ideal quantity to increase clay soil stabilization. The CBR values of clay soil rose by around 5.7% for that percentage. As seen in Table 8, the use of FA has also improved the soil's geotechnical characteristics.

Additive	Additive amount (%)	Sample - (S_1)			Sample - (S_2)		
		γ_{dry} (kg/ m^3)	OMC %	CBR[a]	γ_{dry} (kg/ m^3)	OMC %	CBR[a]
FA	0	1.782	12.3	2.5	1.638	21.3	0.7
	4	1.779	14.6	4.9	1.622	22.4	3.6
	8	1.750	15.3	14.1	1.550	23.6	11.0
	12	1.680	16.0	16.0	1.492	24.7	13.8
	16	1.592	17.2	24.8	1.456	26.5	14.6
Lime	4	1.735	14.0	47.0	1.609	22.0	27.6
	8	1.705	15.1	60.0	1.529	22.4	62.5
	12	1.65	16.4	97.5	1.503	23.0	60.0

Table:7 CBR Values Variation with the amounts of Additive (Athanasopoulou, 2014).

To determine how adding FA might raise the CBR value, Edil et al. (2006) conducted an experimental investigation on soil–FA mixtures with varying FA levels (10–30%). The CBR of a soil-fly ash combination typically rises as the quantity of FA increases and falls as the water content rises. When 10% FA was added to the fine-grained soil, the CBR values rose by around 4%. CBR tests were conducted by Fauzi et al. (2010) using samples compacted at OMC and varying FA and BA (bottom ash) levels of 4%, 8%, and 12%.

For the tested specimens, the FA and BA stabilization greatly increased the CBR values. Although the results of adding marble dust (MD) to a clay-fly ash combination were somewhat comparable, Zorluer and Gucek (2014) found in their experimental investigation that adding MD and FA to clay soil raised the values of CBR following freeze-thaw (F-T). In general, specimens with a 10% MD + 20% FA combination exhibit a more notable and rapid improvement in strength.

The impact of varying FA percentages combined with the soil sample was investigated by Trivedi et al. (2013). The findings show that adding FA in even modest amounts has a significant impact on the soil. The CBR value rose from 5.64 percent to 20.53 percent with the inclusion of 20% FA. When compared to other percentages, it was found that soil with 20% FA produced the greatest results for soil stability.

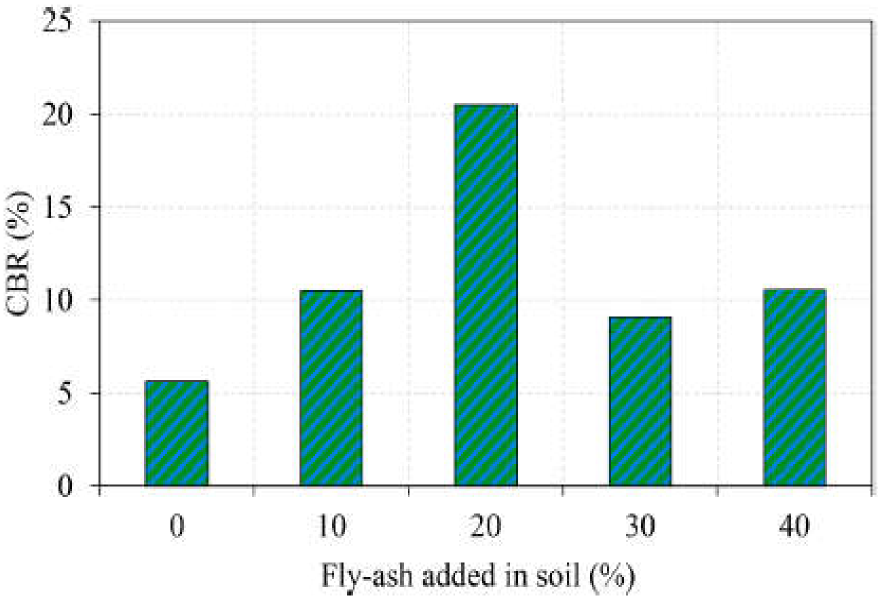

Fig. 9. Effect of fly ash on soil CBR values (Trivedi et al., 2013).

Effect of fly ash on soil permeability

According to Majumder and Saha's (2016) investigation on the impact of fly ash on soil parameters, the microscopic features of the soil mixtures may also play a role in the increased permeability as the addition of FA alters the inter-particle void ratio. Moreover, silt particles are about the same size, which leads to a stronger inter-particle vacuum and a significantly bigger inter-particle void. According to Lekha et al. (2015), the amount of FA supplied is just one of several elements influencing the soil's characteristics.

However, as Fig. 27 illustrates, the treated soil with FA had an increase in the fundamental geotechnical properties in terms of permeability. In terms of soil stability, the curing time was equally significant. After being treated with lime and fly ash, clay shows a greater decrease in coefficient of permeability than sand, according to test results by Islam et al. (2021). The permeability of the clayey soil treated with fly ash and lime decreases by up to 68–95% and 58%, respectively, during the course of a 14-day response time.

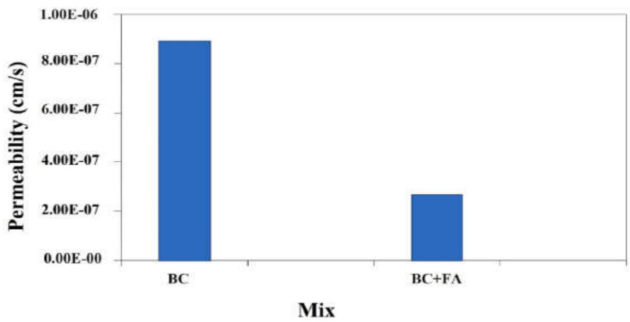

Fig. 10. Coefficient of permeability values (Lekha et al., 2015).

According to Debnath and Mittal (2019), when the quantities of cement and FA rise, the permeability coefficient falls. The minimal permeability was 9.01 × 10-8 cm/sec when 9% cement and 15% FA were applied as percentages. In order to reduce building costs, it is also advised to add 15% FA to 7% of cement. According to a research by Anupam et al. (2012), the addition of FA in varying amounts, i.e., 0–16% by dry weight of clayey soil (CL), alters permeability properties.

As the curing period rose, so did the permeability of the cured specimen. The FA may be effectively applied to soil to increase permeability and, therefore, sub-grade layer drainage. Lu et al. (2022) investigated the mechanical and hydraulic characteristics of four distinct soil combinations using a battery of experiments, including permeability tests. The combination consists of soil and cement, cement and fly ash, cement and sisal fiber, and cement and fly ash and sisal fiber. Each batch contained 10% by weight of additives. The findings show that while the addition of fly ash enhanced the permeability of the cemented soil, the addition of sisal fiber decreased it.

Conclusions

- Compared to untreated soil clay, secondary consolidation occurs earlier when fly ash is mixed with the soil clay. This implies that in engineering applications, the consolidation settling beneath the structures is not only reduced but also accomplished in a shorter amount of time.
- The characteristics of soil consolidation are improved when clay soil is treated with FA waste products. The pozzolanic activity of the FA is responsible for this enhancement in the soil's compressibility behavior.
- Due to the higher calcium concentration in class C raw fly ash material, which gives it superior cementitious qualities, fly ash class C had a greater impact on the soil stability characteristics than class F.
- In very compacted soil, a mixture of soil and fly ash frequently decreases the cohesiveness factor and increases the angle of internal friction. The qualities of fly ash and the makeup of the soil may be the source of the increase in soil cohesiveness.
- When the amount of fine sand and fly ash in the soil increased from 0% to 25%, respectively, the free swelling index dropped by 29% and 50.32% and the swelling potential by 80.4% and 32.7% to expansive clay soil.
  Swelling pressure dropped by 84.6% as the mixture's fine sand concentration rose from 0% to 25%, while fly ash content had no impact.
- When FA is added at a weight percentage of 16%, the CBR value is ten times the beginning value, and the result is not as excellent as when free lime is used. The increase in CBR in relation to the FA quantity could result from the FA's pozzolanic activity.
- By altering the inter-particle void ratio, adding FA to soil raises its permeability. It was shown that there is a clear correlation between the treatment time and the rise in permeability value, and that the permeability coefficient falls as the amount of fly ash increases.

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