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Review

Geotechnical Characteristics of Fine-Grained Soils Stabilized with Fly Ash, a Review

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Abstract: Fly ash is a waste material obtained from burning of coal in thermal power plants. Coal consumption is still very high and is expected to remain above 38% globally. Therefore, large volumes of fly ash are produced every year that need to be managed as waste. Improper disposal of fly ash can lead to surface water and ground water pollution and adversely affect human health and environment. The use of fly ash as an agent to stabilize soil has recently become popular in geotechnical engineering due to its many benefits such as being eco-friendly and cost-effective, and improving the geotechnical characteristics of the soil. This paper presents a review of the geotechnical properties of fly ash-stabilized fine-grained soils. Several features of fly ash, including classification, physical, geotechnical, chemical, and mineralogical properties, health concerns, disposal, availability, and cost are analyzed. The effects of fly ash in improving a wide range of mechanical properties of soils including unconfined compressive strength, shear strength, CBR value, consolidation and/or swelling characteristics, and permeability are reviewed in detail. It is shown that fly ash can be a substitute material for use in soil stabilization, leading to substantial economic and environmental benefits.

Keywords: coal fly ash; fine-grained soils; soil mechanics tests; field applications; geotechnical properties

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1. Introduction

Fine-grained soils such as clay or silt typically show low mechanical strength and significant volume variation under loading [1–3]. The low strength of fine-grained soils causes more damage to civil engineering structures in comparison with natural hazards, such as floods and earthquakes [2]. In many countries, damages to structures constructed on soft soils amount to billions of dollars [1,4,5]. Thus, it is important to apply appropriate soil stabilization method to prevent the damages and achieve the desired engineering properties of the soil, such as compressibility, durability, plasticity, and permeability [6]. In general, soil stabilization methods can be classified as physical, mechanical, and chemical [1,7,8]. However, depending on the soil type and application, some of the methods could be expensive or ineffective. Therefore, there is a need to investigate new methods to improve the strength and reduce swelling and/or settlement characteristics of problematic soils [7]. Chemical stabilization is commonly used to improve the behavior of clay soils by modifying the physicochemical properties of clay soil for permanent stabilization [9,10]. The chemical reaction provides a strong bond network in soil structure, leading to more durable, stronger, and higher quality soil compared to unstabilized soil [8,11]. Using chemical binders in soil stabilization is also preferable owing to the ease of adaptability [12]. Based on soil type and chemistry, a single binder or two binders can be added to stabilize soil [13].

Common chemical stabilizers can be classified into three groups. These are traditional stabilizers (lime and cement), by-product stabilizers (cement kiln dust, lime kiln dust, other forms of lime by-product, fly ash); and non-traditional stabilizers (potassium compounds, polymers, sulfonated oils, etc.) [9]. Lime and cement are the two most widely used chemical binders in soil stabilization [3,6,11,14–18]. Lime has pozzolanic reactions which require water and some species such as Si and Ca which are generally dissolved from soil, while cement has hydraulic reactions which only require water [11]. However, the production of these binders has a negative impact on the environment in terms of CO_2 emissions as they have high embodied energy and high cost [6]. For example, producing 1 ton of cement releases approximately 1 ton of carbon dioxide [19,20–24]. Therefore, the utilization of fly ash as an alternative cementitious agent for soil stabilization is encouraged due to its pozzolanic characteristics, cost-effectiveness, environmental sustainability, and ease of adaptability. The use of fly ash offers many benefits as summarized below:

- Disposal of fly ash could lead to the pollution of air, surface water, and groundwater. This is because, the heavy metals in fly ash can leach to the surface soil, deep soil, and underground water. Hence, using fly ash can avoid environmental pollution [25–29].
- A large amount of fly ash is disposed to landfills or placed in storage [30–32], thus the disposal/storage cost of fly ash increases every year. The disposal space and disposal cost of fly ash can be minimized by increasing the use of fly ash in industry [26].
- Utilization of some expensive natural resources can be reduced by replacing them with by-products [30].
- The use of fly ash by-products instead of the use of Portland cement in geotechnical applications can be a solution to reduce the CO_2 emissions caused by cement production.
- Fly ash-stabilized soil can be used as an effective material in geotechnical applications due to its enhanced geotechnical characteristics [33–36].

Based on the above considerations, there is a need for collecting evidence on the suitability of fly ash-stabilized soil techniques for fostering its application. The main objective of this article is to review the geotechnical properties of fine-grained soil stabilized with fly ash. The article includes three main parts: Section 2 is dedicated to a review of classification, physical, geotechnical, chemical, and mineralogical properties, health concerns, disposal, availability, and cost of fly ash, Section 3 is focused on the consistency limits, compaction, California bearing ratio, unconfined compressive strength, shear strength, swelling, and consolidation characteristics of fly ash-stabilized fine-grained soils, and Section 4 is highlighted practical aspects of fly ash use in geotechnical applications.

2. Coal Fly Ash

Coal fly ash is one of the waste materials obtained from burning of coal in thermal power plants [37]. The World-Wide Coal Combustion Products Network (WWCCPN) gives the global definition of fly ash as generated from a coal-fired power station, collected by electrostatic precipitators. In some countries, it is called pulverized fuel ash (PFA). In general, fly ash represents 85% of the total ash. Other ash types are furnace bottom ash (FBA) and hollow ash particles [38].

2.1. Classification of Fly Ash

Fly ash classification systems are different in the USA, China, India, Russia, Canada, Europe, Australia, and Japan, thus, fly ash has no universal classification system [39]. Kelly [39] proposed a global fly ash classification system considering the classification schemes of eight countries and building an intermediate classification system. Based on the literature, it appears that, generally, the preferred standard is that of the American Society for Testing Materials [40]. According to the ASTM C618 [40] fly ash can be categorized as class C fly ash or class F fly ash. When fly ash includes more than 70 wt% $SiO_2 + Al_2O_3 + Fe_2O_3$ and is low in lime (less than 10% CaO), it is categorized as class F fly ash, whereas if it includes between 50 wt% and 70 wt% $SiO_2 + Al_2O_3 + Fe_2O_3$ and is high in lime (more than 20% CaO), it is categorized as class C fly ash [40].

There are essentially four types/ranks of coal: lignites, sub-bituminous, bituminous, and anthracite [41]. Class C fly ash is produced from burning of low-rank (lignites or sub-bituminous) coals. The calcium content of class C fly ash varies between 20% and 40%, therefore it is also called high calcium fly ash. On the other hand, class F fly ash is produced from high-rank bituminous coals or anthracites. The calcium content of class F fly ash varies between 1% and 10% and it is also called low calcium fly ash [30].

The main difference between class C and class F fly ash is the different contents of calcium and silica-alumina-iron in the fly ash. Another difference is that class C fly ash generally has more alkalinity than class F fly ash due to the higher content of combined sodium, potassium, and sulfates [30]. In addition, class C fly ash has both cementitious and pozzolanic properties. Due to the self-cementing properties of class C fly ash, it gets stiff in the presence of water. Conversely, class F fly ash has only pozzolanic properties. Due to the low CaO content of class F fly ash, activators such as hydrated lime or quick lime mixed with water are needed to enhance its cementitious properties [41].

2.2. Properties of Fly Ash

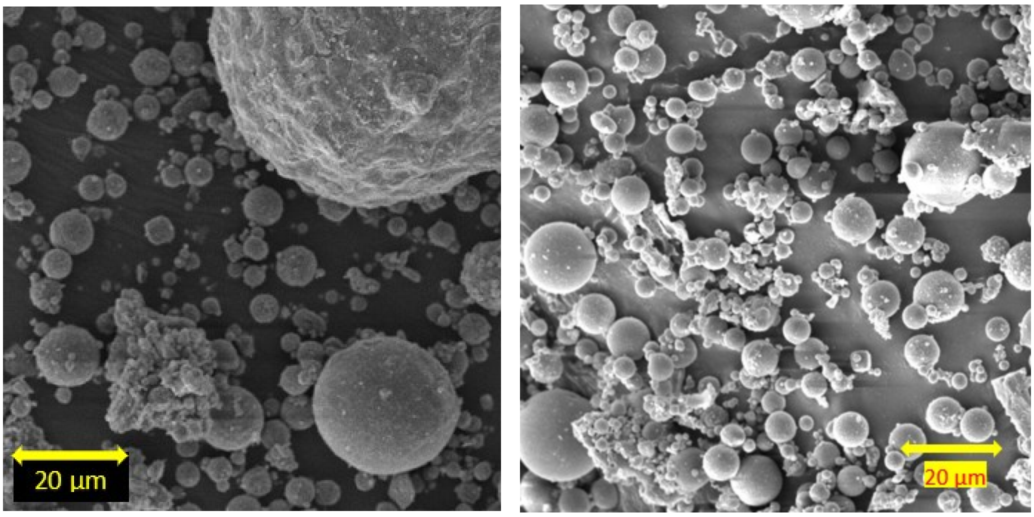
The properties of fly ash show a variety depending on the coal quality or source, combustion process, and degree of weathering [25,26,41–43]. Some properties of fly ash are summarized below.

2.2.1. Physical and Geotechnical Properties

Fly ash consists of fine particles, generally spherical in shape (Figure 1), hollow [25,44], and amorphous (glassy) structure in nature [30,41]. In some cases, fly ash particles can be observed in irregular shapes. This indicates that coal melted under low temperature between 850–900 °C [42]. Depending on the amount of unburned carbon and iron in the ash, the color of the fly ash may vary from orange to red, brown, or from gray to black [41,45]. A higher unburned carbon content is generally responsible for a gray to black color, while iron content is correlated with brown color. Lighter colors in fly ash are associated with high lime concentration [46]. The sizes of fly ash particles vary, ranging from sand to clays [25], and are normally between 0.5 and 400 μm, with an average size of between 12 and 80 μm [47]. Martin et al. [48] indicated that fly ash is usually classified as fine-grained and often found in silt sized. Moghal [43] argued that if the fly ash particles are deposited further from discharge unit, more than 50% of the particles fall into the silt-sized range; on the other hand, a relatively higher size range (typically sand size) is found close to deposit areas. The specific gravity of fly ash could vary from 1.6 to 3.1 and is often around 2 [43]. This variety might be due to several factors like gradation, chemical composition, and particle shape of fly ash [41]. The specific gravity values of fly ash are generally lower than fine-grained soils which lead to a lower dry density in fly ash-stabilized soils. Prakash and Sridharan [49] argued that lower specific gravity or a decrease in dry density can be advantageous when fly ash is used as embankment material, backfill material in retaining wall applications, and construction fill materials on weak soils.

Based on compaction tests, maximum dry density (MDD) of fly ash could vary from 1.01 to 1.78 g/cm^3. MDD values of 'silt and clay', and 'sand' are between 1.28 and 1.92 g/cm^3 and 1.68 and 2.08 g/cm^3, respectively. Hence, it can be said that, in general, MDD values of fly ash are slightly lower than silt and clay and are significantly lower than sand. Optimum moisture content (OMC) of fly ash varies from 11 to 53%. OMCs of sand, silt, and clay vary from 6 to 10%, 11 to 15%, and 13 to 21%, respectively. Therefore, OMC of fly ash may include the ranges of fine-grained soils.

Fly ash is usually non-plastic (NP), meaning that there is no swelling potential when used in geotechnical applications. The specific surface area of fly ash could vary from 170 to 1000 m^2/kg [30]. Schure et al. [50] conducted a series of tests to analyze the surface area of fly ash. They suggested that the surface area is affected by particle size. Based on the results, the surface area decreased with the increase in particle size.



(**a**) (**b**)

Figure 1. Scanning electron microscopy (SEM) images of (**a**) class C fly ash and (**b**) class F fly ash at 20 µm [51].

The permeability of fly ash is affected by internal pore structure, pozzolanic activity, particle size distribution, and degree of compaction achieved. The coefficient of permeability of compacted pure fly ash can range from 10^{-6} to 10^{-9} m/s [41]. The values match the range exhibited by silty sand to silty clay soils [52].The permeability of class C fly ash was observed to be lower than that of class F fly ash [53]. This could be due to the fact that class C fly ash has interfacial cementitious nature due to its high Ca content which leads to lower permeability than class F fly ash [54]. The angle of shearing resistance of fly ash usually ranges from 26° to 42° [43]. These values are comparable with the angle of shearing resistance of silt (26° to 45°) and sand (27° to 45°) [41]. The observed wide range in angle of shearing resistance might be due to the effects of different coal sources and boiler firing temperatures on the surface morphological characteristics of fly ash [43].

2.2.2. Chemical Properties

The main chemical elements composing fly ash are Si, Al, Ca, Fe, and Mg (that form about 95–99% of total components), while the minor components of fly ash are titanium (Ti), sodium (Na), potassium (K), and sulfur (S) (about 0.5–3.5%) [26].

Fly ash also includes trace elements, such as arsenic (As), selenium (Se), boron (B), nickel (Ni), molybdenum (Mo), lead (Pb), zinc (Zn), and cadmium (Cd). Most of the trace elements in fly ash are in low concentration [25,47]. Some leaching and mobility research has been carried out to determine the possibility of eliminating the trace elements in fly ash, hence decreasing the environmental damage [42]. According to the United States Geological Survey (USGS) [55], several trace elements in fly ash are radioactive, such as uranium (U) and thorium (Th). However, these elements have less toxicity characteristics in comparison with other trace elements, such as arsenic and selenium in fly ash. Also, the amounts of radioactivity in fly ash are comparable with common soils or rocks based on the NORM (Naturally Occurring Radioactive Materials) [56]. For example, when fly ash is used in concrete, the radioactivity of fly ash is similar to conventional concrete or building materials such as red brick and granite [55]. Sas et al. [57] indicated that naturally occurring radionuclide (NOR) contents of fly ash are lower than red mud samples.

The pH value of fly ash varies from 1.2 to 12.5. According to the Ca/S molar ratio and pH value in ash, it can be categorized into 3 groups of strongly alkaline ash (pH 11 to 13), mildly alkaline ash (pH 8 to 9), and acidic ash [42]. Class F fly ash tends to be acidic while class C fly ash tends to be alkaline.

Cation exchange capacity is defined as the number of changeable cations needed to balance the charge deficit on the surface of soil. In general, higher specific surface area corresponds to higher CEC and thus higher surface activity and higher water absorption potential [58]. The cation exchange capacity of fly ash is low due to its non-plastic properties which also leads to low water absorption potential [43].

Pozzolans are siliceous or siliceous and aluminous materials that, when combined with water and calcium hydroxide, produce cementitious products [30]. Fly ash generally has pozzolanic properties. According to pozzolanic reactivity, fly ash can be categorized as self-pozzolanic, pozzolanic, and non-pozzolanic [43]. Fly ash is described as self-pozzolanic when it forms cementitious products and subsequently hardens over time in the presence of water and without binder addition. Conversely, fly ash that forms cementitious products when combined with binder is described as pozzolanic fly ash. When the fly ash is unable to form cementitious products despite the presence of binder, it can be described as non-pozzolanic [43]. Thus, it can be said that class C fly ash is self-pozzolanic, while class F fly ash is pozzolanic. The pozzolanic reactivity of fly ash relies on its reactive silica, free lime, iron, and carbon contents and its fineness [59]. Sivapullaiah et al. [59] carried out UCS tests on 3 different fly ashes, including different reactive silica and free lime contents, to analyze the effects of pozzolanic reactivity. It was confirmed that the highest strength was obtained with the fly ash that contained adequate reactive silica and free lime [59]. Also, fly ash with spherical particle sizes ranging between 2–25 μm, tends to be highly reactive, whereas irregular shape and coarser particles in fly ash show poor reactivity [43]. The engineering properties of fly ash enhance over time due to the pozzolanic reactions. The pozzolanic properties therefore help to reduce the secondary settlement and permeability, and increase the shear strength and CBR with time [49].

Class C fly ash has more than 20% CaO (high lime content) and between 50 wt% and 70 wt% SiO_2, Al_2O_3, and Fe_2O_3, whereas class F fly ash includes less than 10% CaO (low lime content) and higher than 70 wt% SiO_2, Al_2O_3, and Fe_2O_3 [40]. Seyrek [60] carried out Atterberg limits, compaction, swelling pressure, and UCS tests on soils stabilized with class C fly ash and class F fly ash. It was found that class C fly ash provided significant improvement with the curing due to its cementitious and pozzolanic properties. In terms of swelling reduction, 30% class F fly ash was found comparable to 10% class C fly ash. Turan et al. [51] conducted a series of tests to analyze the effects of class C and class F fly ash on the shear strength, consolidation, and microstructural behavior of clay. They argued that class C fly ash is more effective in improving the mechanical and microstructural properties of the soil compared to class F fly ash. This is because cementitious properties of class C fly ash are high due to the high CaO content. It was suggested that class C fly ash is a suitable stabilization agent and can be used effectively to improve the soil properties. On the other hand, class F fly ash was suggested to be used in conjunction with alkali activators or lime to obtain sufficient mechanical properties in soil. Ahmaruzzaman [30] indicated that although the physical properties of fly ash are the main factor for its suitability in geotechnical applications, chemical composition is also important. Stabilization of some base courses or subgrades may rely on the chemical reactions between lime and fly ash or high lime class C fly ash. In some cases, low calcium class F fly ash may give satisfactory results if sufficient time is available to develop the slow pozzolanic reactions [30].

2.2.3. Mineralogical Properties

Based on the XRD analysis, fly ash shows both crystalline and amorphous phases [61], however, the majority of fly ash shows amorphous (glassy) structure [26]. The crystalline phases of fly ash correspond to 5 to 50% of its mass [62].

The crystalline phases of class F fly ash include quartz, mullite, hematite, and magnetite while those of class C fly ash include quartz, lime, mullite, gehlenite, anhydrite, and cement minerals like C_3A and C_2S [43]. Although both types of fly ash include mullite, it is observed more in class F fly ash, and it is an inert mineral. Anhydrite in class C fly ash is obtained from the presence of O_2, SO_2, and CaO in the furnace, and it plays an important role in the production of ettringite. Also, lime in class C fly ash has a significant role in hydration reactions [62]. Some other mineral phases can also be observed in fly ash like albite, esperite, nepoutite, and tenorite [25].

Characterizing amorphous phases in fly ash is often difficult. However, a low Ca content in coal forms aluminosilicate glass, whereas high Ca content leads to calcium aluminosilicate glass. The calcium aluminosilicate glass is known as reactive amorphous phase in class C fly ash, and thus class C fly ash has higher reactivity than class F fly ash [62].

2.3. Health Concerns of Fly Ash

The inappropriate disposal of fly ash is an important concern due to the environmental threat [25,42,63]. Landfilling of fly ash could lead to surface water, air, and groundwater pollution due to the surface run off, wind transport, and leaching of its heavy metals to surface soil, underground water, and deep soil [26,27,47]. The disposal of fly ash in sea, ponds, or rivers can also damage aquatic life [26].

Based on the U.S Environmental Protection Agency (USEPA) risk assessment report, living near coal ash disposal areas may increase the risk of cancer [64]. Specifically, long-term exposure to coal fly ash dust can cause stomach cancer, lung cancer pleural abnormalities, and emphysema [43]. Borm [65] also stated that lung function impairment and respiratory symptoms can be observed with prolonged exposure to fly ash. However, when fly ash is used in geotechnical applications, the cementitious properties of fly ash with water or/and soil create a cemented matrix which does not allow the leaching of any metals due to the immobilization of fly ash in the matrix [41].

2.4. Disposal of Fly Ash

Fly ash generated in thermal power plants is traditionally disposed by using either wet disposal or dry disposal system [26,66]. In dry disposal system, fly ash is initially collected by electrostatic precipitation method, transferred on conveyors or trucks to the disposal site, and deposited there by building a dry embankment. In the wet disposal system, fly ash is first blended with water and thereafter transported as slurry via pipe and deposited in ash ponds close to power plants [26]. If these disposal methods are not managed well, they could cause serious environmental and health problems. Before 1970s in the United States, fly ash was commonly disposed of in unlined landfills or lagoons [67]. Disposal and management of fly ash was a significant problem in thermal power plants. Currently, waste minimization, recycling, and reuse programs are becoming popular that not only control hazardous fly ash wastes, but also offer guidelines for the safe disposal of fly ash. Sun et al. [68] proposed 3 different methods to handle fly ash waste: separation, solidification/stabilization, and thermal methods. The separation process aims to decrease the alkalis, heavy metals, salt, and chloride in fly ash and enhance the quality of fly ash. Alkali extraction, acid extraction, high temperature extraction, and biological extraction are mainly applied in this process. Solidification/stabilization is a popular method that uses a binder or additive to immobilize the hazardous heavy metals in fly ash before being disposed in landfills. Lastly, to dispose the fly ash safely, thermal methods are used which are divided into 3 categories: vitrification, sintering, and fusion [68].

2.5. Availability of Fly Ash

Coal remains the most consumed fossil fuel for electric power production, even though local policies or international agreements make a change towards alternative energy sources, such as renewable and nuclear. Coal provides about 40% of electrical power production globally [69]. The coal demand is expected to grow in India, Southeast Asia, and several other countries in Asia, whereas a decline in coal demand is expected in Europe, the United States, and China in the future. Globally, a small increase is expected in coal demand in the next decade. However, over 38% of coal consumption is still predicted in a global perspective [69]. On the other hand, according to Sifton and Arato [70], the coal fired power plants are expected to be closed and therefore coal ash production will be stopped in developed countries in the next 50 years. However, there will still be huge amounts of impounded and landfilled coal ash. For example, the United Kingdom Quality Ash Association (UKQAA) indicated that about 100 million tonnes of landfilled fly ash in the UK will be a ‘pozzolanic’ reserve in the future [71]. In the United States, approximately 2 billion tonnes of coal ash material will be stored in the next decades [70]. Moreover, the production of coal ash is estimated to increase in developing countries. For example, India has the largest resource of energy with approximately 211 billion tonnes of coal reserves [24] and there is no significant alternative energy source like coal resources in India [26]. Therefore, coal consumption in India is expected to increase from 407 to 833 million tonnes of oil equivalent (mtoe) between 2015 and 2035 [41].

The production (Million metric tonnes (Mt)), utilization (Mt), and utilization rate (%) of coal combustion products (CCPs) in different countries are shown in Table 1 [38]. It is seen that China, India, the USA, and Europe were the largest CCPs producing countries. The worldwide production and utilization rates were over 1.2 billion tonnes (nearly doubling over the previous 5 years) and 63.9% yearly, respectively [38]. However, the utilization rates vary from country to country because of the different environmental regulations, market situations, and market education.

Table 1. Annual production and utilization of CCPs [38].

Country	CCPs Production (Mt)	CCPs Utilization (Mt)	Utilization Rate (%)
USA	107.4	60.1	56
China	565	396	70.1
Korea	10.3	8.8	85.4
India	197	132	67.1
Japan	12.3	12.3	99.3
Other Asian countries	18.2	12.3	67.6
Europe (EU15)	40.3	38	94.3
Middle East & Africa	32.2	3.4	10.6
Israel	1.1	1	90.9
Canada	4.8	2.6	54.2
Russia	21.3	5.8	27.2
Australia	12.3	5.4	43.5

2.6. Cost of Fly Ash

According to Ahmaruzzaman [30], fly ash is sometimes available free of charge at power plants in India. On the other hand, there is a marketed commodity of fly ash in many countries such as the UK and Europe, because of the growing demand for fly ash. However, fly ash is significantly less expensive than Portland cement [72]. Therefore, the costs of fly ash are mainly based on transportation, laying, and rolling costs. If the transportation distance is short, a significant amount could be saved in construction costs. It is recommended that fly ash should not be transported more than about 100–200 km [42]. Kumar and Patil [73] investigated the cost of fly ash utilization in road construction. They indicated that the cost of fly ash is directly related to the transportation distance and the cost of resources replaced by fly ash. When the fly ash was evaluated for use in flexible or rigid pavements of road construction for 0 km transportation distance and 1.5 m of embankment height, the cost saving was found to be about 31%. It was indicated that the utilization of soil was about 1324 kg/m^3 and 1264 kg/m^3 in flexible and rigid pavements for 1.5 m height conventional embankment, respectively. On the other hand, utilization of fly ash was about 556 kg/m^3 and 509 kg/m^3, in this way, soil savings were about 877 kg/m^3 and 747 kg/m^3 in flexible and rigid pavements, for the same height fly ash-based embankment. Other resource savings such as stone aggregate and stone chips were also considered. Based on this, the estimated total cost of conventional road construction was 120.5 Rs (Indian rupee) per m^3, whereas the cost of fly ash-based road construction was estimated as 83.5 Rs/m^3. It was estimated that the fly ash-based road construction can be cost-effective when the transportation distance is less than 60 and 90 km for flexible and rigid pavements, respectively. It was also argued that utilization of fly ash in road construction can lead to significant savings in disposal land and ash pond areas. A cost comparison of 3 stabilization methods was conducted based on 4181 m^2 [74]. In the first method, the soil was stabilized in situ at 0.30 m depth with the addition of 10% class C fly ash. Considering the fly ash and rolling costs, the estimated total cost was $33.750. In the second method, excavation to a 0.15 m depth was applied, followed by placing geogrid with 0.15 m of roadstone. Excavation, geogrid placement, and roadstone compaction costed a total of $41.771 to stabilize the 4181 m^2. The third method was also applied as excavation to a 0.30 m depth and filling the excavated depth with compacted roadstone. The estimated total cost was $59.360 [74]. Based on the above cost analysis, it can be said that fly ash has significant economic benefits when used in geotechnical engineering applications. Suryawanshi et al. [75] also pointed out that utilization of fly ash could lead to a considerable cost saving in rigid pavement construction by replacing cement which is one of the expensive materials.

3. Geotechnical Characteristics of Fly Ash-Stabilized Fine-Grained Soils

In this section, the studies on fine-grained soils (mainly clay and silt) stabilized with fly ash were collected and reviewed from journal papers, review papers, technical reports, conference papers, and standards. A detailed analysis of the literature in terms of geotechnical properties of the stabilized soil was presented.

3.1. Effects of Fly Ash Inclusion on Consistency Limits of Soil

The volume change potential of soil can be evaluated by consistency limit parameters, including plasticity index (PI), plastic limit (PL), and liquid limit (LL) [40]. The PI (=LL–PL) indicates the range of water content in which the soil is in plastic state [75]. Many researchers evaluated the clay soils stabilized with class C or class F fly ash in terms of consistency limits and the results are detailed in Table A1 (Appendix A). In general, it has been shown that the addition of fly ash to soil leads to a reduction in LL, an increase in PL, and a reduction in PI [4,5,10,60,76–84]. For example, Kumar and Sharma [4] showed that PI decreased by approximately 50% in a high plasticity clay (CH) by adding 20% class F fly ash (Figure 2). There are two reasons for changes in consistency limits due to the addition of fly ash [60]: (i) fly ash has silt-sized particles hence the clay fraction decreases when the fly ash content increases; (ii) fly ash particles lead to a flocculated structure in the clay and reduce the thickness of the diffuse double layer (DDL) of the clay. Striprabu et al. [85] also carried out consistency limit experiments on a clay soil stabilized with class F fly ash and cement. They attributed the decrease in PI to the flocculation and agglomeration of stabilized soil particles. Zhou et al. [84] conducted consistency limit tests on a clay soil stabilized with class F fly ash and lime. They explained the decrease in PI using the diffuse double layer (DDL) theory. The thickness of water in DDL has a considerable effect on the engineering properties of clay. The plasticity of clay increases by increasing the thickness of DDL. Fly ash includes many high-valent cations. When the concentration of high-valent cations in the diffuse double layer increases, the layer is thinned; in this way, the PI of the clay is decreased [84]. The plasticity index of the soil is also a critical indicator of swelling potential [60,76,84,86]. The swelling potential of stabilized soil decreases with increasing fly ash content. The classification of clay soil generally changes from CH (high plasticity clay) to CL (low plasticity clay), MH (high plasticity silt), or ML (low plasticity silt) with the addition of fly ash [66,68,70]. Seyrek [59] showed that CH turns into CL, MH, and ML with the addition of 20% class F fly ash, 10% class C fly ash, and 15% class C fly ash, respectively. According to Seyrek [60], class C fly ash is more effective than class F fly ash in decreasing the PI.

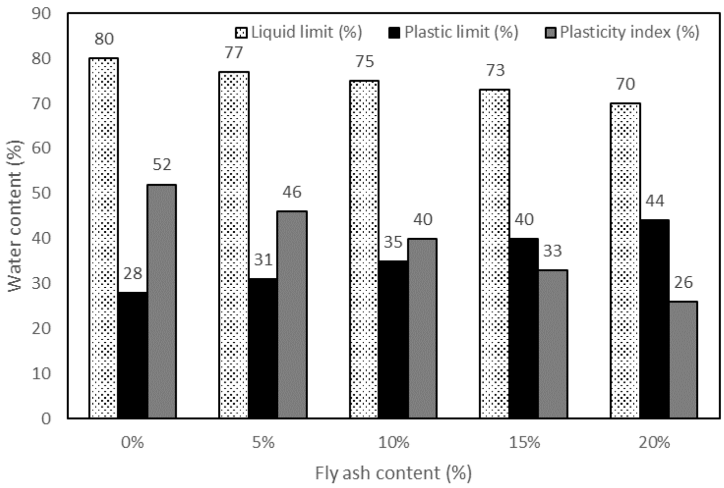
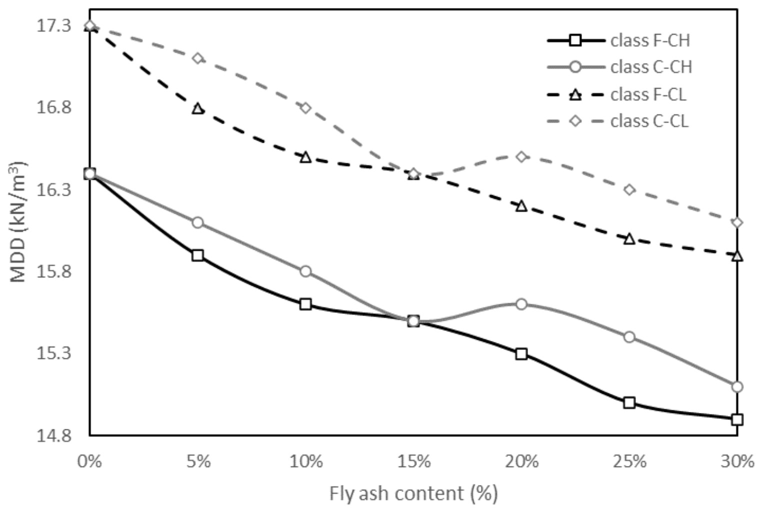


Figure 2. Effect of class F fly ash on consistency limits of clay (modified from Kumar and Sharma [4]).

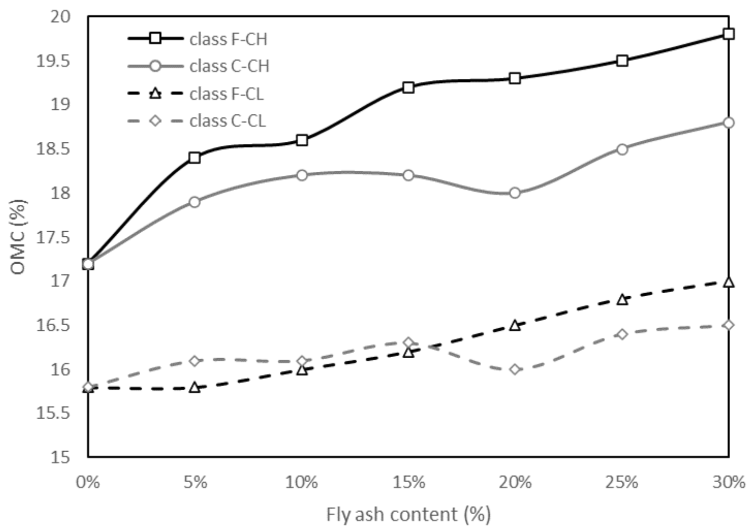
3.2. *Effects of Fly Ash Inclusion on Compaction Characteristics of Soil*

Compaction characteristics can affect many engineering properties of soil like permeability, compressibility, dispersibility, and strength [60]. Many construction projects, such as roadway subgrades, highway or railway embankments, and earth dams use compaction and soil stabilizers to improve the strength and reduce the settlement potential of soils. Compaction tests are carried out to find maximum dry density (MDD) and optimum moisture content (OMC) of the soil. According to Bhatt et al. [41], when fly ash is mixed with soil, the values of MDD and OMC can be changed based on the types of fly ash and fly ash fraction in the mixture. Table A2 (Appendix A) shows the compaction results of unstabilized and fly ash-stabilized soil samples from the literature. The majority of works in the literature show that MDD decreased, and OMC increased as the content of fly ash (class C or class F) increased in the stabilized soil [10,12,16,29,76,80,83,87–92]. Figure 3 shows the typical effects of class F and class C fly ash on MDD and OMC of clay soil [60]. It is seen that the addition of both types of fly ash results in a decrease in MDD and an increase in OMC on both soil samples. Decrease in MDD is usually due to the low specific gravity of fly ash in comparison with any fine-grained soil [83,89,91,93]. The change in MDD of the mixture could also be due to a change in the gradation of the mixture [83]. Nath et al. [90] explained that agglomeration and flocculation occur between clay particles and stabilizing agents through cation exchange, which creates a larger space and reduces the weight/volume ratio. Seyrek [60] argued that, due to the quick formation of cemented products, the compressibility can decrease during compaction, resulting in a reduction in the MDD of the soil stabilized with fly ash. Mackiewicz and Ferguson [94] pointed out that compaction usually delays in everyday construction operations. This results in the hydration products in fly ash bonding with the soil particles in a loose state and these bonds cause disruption of material during compaction process. For example, if the compaction is delayed by 1 h after mixing the materials, MDD values could decrease from 0.6 to 1.6 kN/m^3. Therefore, delays in compaction should be kept to minimum in order to obtain a higher MDD. Dahale et al. [37] and Mahvash et al. [95] used lime and cement, respectively, with fly ash for soil stabilization. They also observed a decrease in MDD and an increase in OMC. Mahvash et al. [95] argued that these results were obtained when the fly ash content was significantly higher than the cement content. According to Nath et al. [90], the reason of the increase in OMC with the addition of fly ash could be that more water is needed for the formation and dissolution of the materials.

On the other hand, some researchers indicated that the MDD increased, and OMC decreased with increase of fly ash in stabilized soil [4,79,96]. Striprabu et al. [85] showed that the mixture of class F fly ash and a small amount of cement resulted in an increase in MDD and a decrease in OMC. The reason for the discrepancy of the results of MDD and OMC could be that fly ash shows a significant variety of specific gravity ranging from 1.6 to 3.1. The specific gravity of fly ash varies based on the specific power plant where the fly ash is sourced from. The values even show a variety over the time periods for the same power plant [41].



(**a**)



(**b**)

Figure 3. Effect of class F and class C fly ash on compaction characteristics (**a**) MDD and (**b**) OMC of high and low plasticity clay (modified from Seyrek [60]).

3.3. Effects of Fly Ash Inclusion on California Bearing Ratio of Soil

CBR values are usually used for designing the subgrade, subbase, and base layers for pavements [12,97]. CBR values are obtained by evaluating the force and penetration relationship when a cylindrical plunger penetrates the soil at a standard rate [11]. An unstabilized (fine-grained) soil usually has a very low CBR value (<3%) [98]. Therefore, the unstabilized soil can be considered as poor subgrade material based on the typical ratings of

CBR values [99]. Adding fly ash to improve fine-grained soil can increase the CBR value significantly [33,76,82,87,97,98,100,101]. Table A3 (Appendix A) shows the CBR values of some unstabilized soils and fly ash-stabilized soils with consideration of general rating and uses [99]. Fly ash-stabilized soil can be used as a subbase or base material for roads, backfilling, or improving the bearing capacity of soils [12,33,97,98]. Binal [82] indicated that the curing time is an important factor affecting the CBR value. A high improvement was observed in CBR values after 7 days of curing for fly ash-stabilized soil [82,87]. However, CBR value of fly ash-stabilized soil decreased with an increase of compaction water content [98,100]. The CBR values are also affected by the type of fine-grained soil. For instance, Senol et al. [87] reported that mixtures of fly ash with organic soil or CH soil had lower CBR values compared to CL soil or silt. The CBR values of the stabilized low plasticity silt increased from 5% to 38% with 18% fly ash content, whereas the values for the stabilized organic soil changed only from 2% to 5% with the same fly ash content. On the other hand, the CBR values of the stabilized low plasticity clay increased from 3% to 51%, and to 56%, with the addition of 16% and 20%, respectively [87].

3.4. Effects of Fly Ash Inclusion on Unconfined Compressive Strength (UCS) of Soil

Unconfined compressive strength (UCS) of soil is one of the most important geotechnical parameters used for the design and practice of many geoengineering projects [102]. UCS tests can be used to understand the deformational behavior of soil and evaluate its strength. Table A4 (Appendix A) shows the UCS of fly ash-stabilized soils determined by many investigators and Figure 4 summarizes the mechanism of strength improvement in fine-grained soils stabilized with class C and class F fly ash based on the literature. It has been shown that the strength of soil stabilized with class C or class F fly ash shows an increase [3,10,16,27,33,35,88,98,101,103–114]. However, several researchers have pointed out that there is an optimum level of fly ash addition to stabilize soil [51,60,104,115]. Seyrek [60] investigated UCS values of class C and class F fly ash-stabilized soil and reported that 25% (by dry weight of the soil) is an optimum level in terms of an increase in UCS. In addition, Sezer et al. [104] stated that an increase of fly ash substitution level beyond 15% (m/m) of the soil increased the UCS marginally.

Seyrek [60] and Savas et al. [91] found that the UCS of soil stabilized with class C fly ash is significantly higher than class F fly ash (Figure 5). Savas et al. [91] attributed this difference to the high lime content, and the better reaction of cation exchange, flocculation, and agglomeration in class C fly ash compared to class F fly ash. The higher the CaO content and CaO/SiO_2 ratio (or $CaO/SiO_2 + Al_2O_3$ ratio), the higher is the UCS [108]. Dahale et al. [37] indicated that class F fly ash does not have cementitious properties due to the low calcium content, hence, the marginal increase in strength of class F fly ash in short-term can be related to the soil gradation effects. Therefore, some investigators evaluated soil stabilized with class F fly ash and low amounts of traditional stabilizers (cement or lime) and reported considerably high strength results [37,85,93,106,109,116,117]. The amount of increase in UCS also depends on the soil type [86,107,89]. Tastan et al. [108] reported a high increase in UCS (from 30 kPa for unstabilized soil to 400 kPa with fly ash addition) in clay soil with an organic content less than 10% and a low increase in UCS (from 15 kPa for unstabilized soil to 100 kPa with fly ash addition) in organic sandy silty peat with 27% organic content. Kolias et al. [106] and Senol et al. [87] pointed out that low plasticity clay had higher UCS in comparison with high plasticity clay when they were stabilized by fly ash.

The curing time has a positive effect on the UCS results in soils stabilized with fly ash [5,85,90,104,109,113,118]. 1, 7, and 28 days of curing time have been selected by many researchers. It has been shown that 28 days of curing in stabilized soil would achieve much higher strength than one or seven days of curing due to the pozzolanic reaction [60,85]. Premkumar et al. [109] reported that the UCS of soil would still increase from 28 days to 90 days of curing for soils stabilized with class C fly ash. It was concluded that after the hydration process, the Ca^{2+} and $(OH)^-$ ion contents are high in the pore water. In this way, dissolved aluminum and silicon from clay minerals react with the Ca^{2+} in the pore solution to create a firm gel of calcium silicate and calcium aluminate. Thus, the increase in UCS over longer periods of curing time is a result of the hydration process followed by the formation of cementitious materials [109].

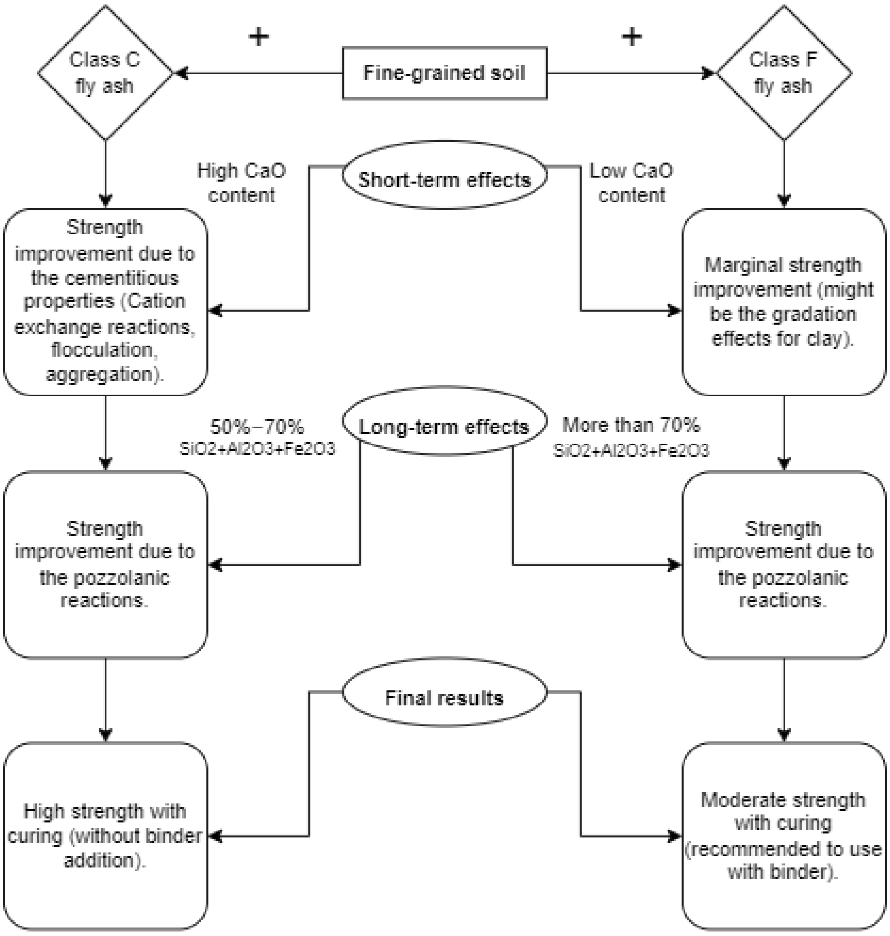


Figure 4. Schematic diagram of strength improvement in soils stabilized with class C and class F fly ash.

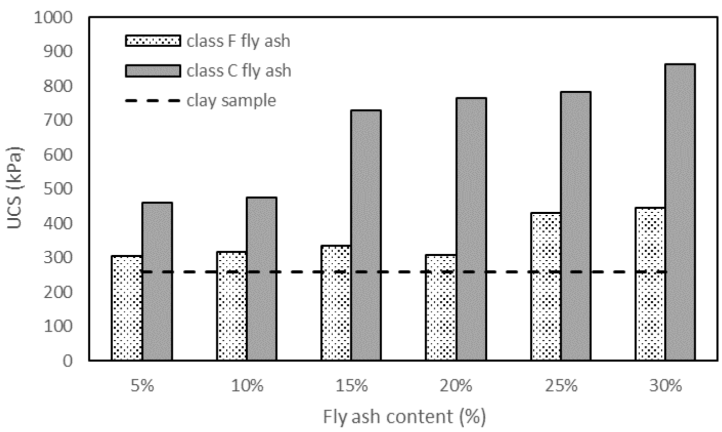


Figure 5. UCS results of low plasticity clay stabilized with class C and class F fly ash at 1 day curing (modified from Savas et al. [91]).

3.5. Effects of Fly Ash Inclusion on Shear Strength of Soil

Shear strength parameters are required in the analysis of soil stability problems [52]. These parameters for a specific soil can be determined by direct shear test or triaxial test. Previous studies have shown that the shear strength parameters of fine-grained stabilized soil increase with increasing fly ash content. It has been shown that the angle of shearing resistance (φ) increases with the increasing fly ash content in stabilized clay [82,92,104,119,120] and silt [12]. Prabakar et al. [12] found that the angle of shearing resistance improved from 17° for silty unstabilized soil to 27° for stabilized soil with 46% fly ash inclusion. Binal [82] and Bryson et al. [119] attributed the increase in angle of shearing resistance to the particle substitution. The silt fraction of fly ash roughens up to the surface of clay minerals, decreases the clay fraction, and increases the average grain size of the mixture. The cohesion (c) of soil also increases with increasing fly ash content [4,12,82,104]. Prabakar et al. [12] pointed out that the cohesion of unstabilized CL soil increased from 24 kPa to 39 kPa for stabilized soil with 46% fly ash inclusion. The increase in the cohesion and angle of shearing resistance of soil-fly ash mixture could be due to the pozzolanic reactions and formation of new cementitious compounds, calcium silicate hydrate (CSH) or calcium aluminate hydrate (CAH) from hydration [85,120]. The increase of curing time has also shown to increase c and φ values of fly ash-stabilized soils [82,104]. This effect could be related to the pozzolanic properties of fly ash which is more efficient during longer curing periods. Binal [82] reported that the angle of shearing resistance of CH soil increased 3 times and the cohesion value of the soil increased 16 times for 25% fly ash-stabilized soil with 28 days of curing. Also, higher deviatoric stress (q) was observed by increasing the fly ash content of stabilized soil due to the generation of strong bonds from hydration products, CSH and CAH [120]. Prabakar et al. [12] indicated that deviatoric stress of fly ash-stabilized soil showed an improvement by increasing the confining pressure. The maximum deviator stresses of CL were found 360.9, 466.8, and 584.5 kPa at confining pressures of 20, 40, and 60 kPa, respectively, while for the soil stabilized with 46% fly ash, the failure stresses increased to 505, 614.9, and 728.6 kPa, respectively, at the same confining pressures [12].

3.6. Effects of Fly Ash Inclusion on Swelling, Consolidation, and Permeability of Soil

Expansive soils can cause major damage and distortion in structures, especially in pavements and light buildings, due to significant changes in volume as a result of changes in water content [78]. Fly ash can also be used as an additive to control volume change and swelling behaviour of expansive soils.

Free swell index can be described as 'the ratio of the difference in volumes of soil fraction, <425 μm in water and air, to the volume of soil in air' as:

$$\mathrm{FSI} = \left(\frac{\mathrm{Vw} - \mathrm{Va}}{\mathrm{Va}}\right) \mathrm{x}00(\%)$$

where V_w is the final volume of soil in water and V_a is the final volume of soil in the air [78].

Comprehensive research has demonstrated the successful application of fly ash in controlling the swelling behavior of expansive soils. It has been shown that free swell index (FSI), swelling potential, swelling pressure, and swelling index (C_s) decrease significantly with increasing fly ash content [4,5,58,76,78–84,86,118–125]. Table A5 (Appendix A) shows the studies of FSI (%), swell potential (%), and swell pressure (kPa), and Table A6 (Appendix A) presents the studies of swelling index in unstabilized and fly ash-stabilized soils. Mir and Sridharan [80] and Seyrek [60] reported that class C fly ash is more effective in reducing the swelling of soils in comparison with class F fly ash. For instance, Mir and Sridharan [80] showed that 10% class C fly ash is the optimum content needed to control the swelling of CH soil compared to 40% class F fly ash. The reduction in swelling of fly ash-stabilized soil can be explained with several reasons. The first reason is the replacement/reduction of plastic fines of expansive soil with non-plastic silt-sized fines of fly ash [10,12,78,86,121,123]. The diameter of fly ash particles can vary between 0.075 and 0.002 mm which is larger than the diameter of clay particles (<0.002 mm) [121]. Moreover, the flocculation process in samples creates particles with a larger diameter. In this way, when the size of particles increases, the initial suction before inundation of the sample is reduced compared to the expansive soil, resulting in a decrease of swelling with fly ash content [121]. Cokca [86] and Seyrek [60] pointed out that fly ash is primarily comprised of silicate, aluminum, and iron oxides, hence it has the potential to provide multivalent cations (Ca^{2+}, Al^{3+}, F^{3+}, etc.), which lead to flocculation of clay particles by cation exchange. In this way, the surface area and water affinity of the stabilized soil could be decreased, resulting in a reduction in swelling. In addition, cementation could occur at the particle contacts which restrains the swelling of fly ash-stabilized soil [121]. Nalbantoglu [58] also explained the decrease in swelling potential of stabilized soil with fly ash in terms of cation exchange capacity (CEC). CEC is the amount of exchangeable cations held by clay and is equal to the negative charge. Expansive soils with larger specific surface areas have higher CEC and surface activity resulting from higher water absorption potential. It has been observed that CEC decreases with the addition of fly ash. The decrease of CEC could be due to the formation of new phases with coarser particles leading to lower surface activity, and therefore lower water absorption potential [58]. Increase in curing time is also very effective in reducing the swelling behavior of fly ash-stabilized soils [58,80,86,123]. The decrease in swelling with the curing time could be mainly due to the time-dependent pozzolanic reactions and the formation of calcium silicate hydrate/calcium aluminate hydrate (CSH/CAH) in fly ash-stabilized soil [78,123].

Many consolidation characteristics such as compression index (C_c), coefficient of volume compressibility (m_v), coefficient of consolidation (c_v), pre-consolidation pressure, and permeability or hydraulic conductivity (k) were studied using one-dimensional consolidation tests [35,81,83,111,119,121–123]. Compression indices of the unstabilized soil and stabilized soil with different percentages of fly ash are shown in Table A6 (Appendix A). The results show that the value of C_c decreased with increasing the class C or class F fly ash content in fine-grained soils. However, Phanikumar [79] reported that the value of C_c initially increased up to certain content of class F fly ash, and thereafter it decreased. Bryson et al. [119] showed that class C fly ash is more effective in decreasing compression index compared to class F fly ash. For example, the compression index of the soil stabilized with class C fly ash decreased from 0.503 to 0.376 with the addition of 40% fly ash, and to 0.432 with the 40% class F fly ash. Based on the swelling index results, the soil stabilized with 40% class C fly ash showed a decrease in swelling index from 0.079 to 0.025, whereas for the soil stabilized with 40% class F fly ash, the swelling index decreased to 0.069. The decrease of C_c with fly ash content indicates an improvement in compressibility of the stabilized soil owing to the formation of cementitious bonds [123] and pozzolanic reactions [122]. The value of C_c also decreased with an increase in curing time. This is because the cation exchange reaction leads to flocculation and aggregation which creates an increase in the vertical effective yield stress and a decrease in compressibility [122]. Shil and Pal [89] showed that coefficient of volume compressibility (m_v) decreased with the addition of fly ash in fine-grained soils. They highlighted that the higher percentage of silt content in fly ash and lower plasticity of fly ash lead to lesser volume change in stabilized soil. Pal and Ghosh [81] observed that m_v of a CH soil was 2.62×10^{-4} m²/kN, and it decreased to, 1.41×10^{-4} m²/kN, 1.01×10^{-4} m²/kN, 0.72×10^{-4} m²/kN, and 0.37×10^{-4} m²/kN when 50%, 60%, 70%, and 80% of class F fly ash were added, respectively. Efthymiou et al. [111] reported that pre-consolidation pressure showed a significant increase with increase of fly ash and curing time. Mir and Sridharan [123] also showed that the value of c_v increased with the addition of fly ash. This is mainly owing to the increase in the rate of permeability [89].

Permeability/hydraulic conductivity of soil stabilized with fly ash is usually studied based on one-dimensional consolidation or permeability tests. The permeability results of fly ash-stabilized soil are presented in Table A7 (Appendix A). It has been reported that permeability increases with increasing the fly ash content in fine-grained soils [5,79,81,89,123]. This is because flocculation and aggregation occur due to the cation exchange reaction, and they increase permeability [79]. In addition, when the silt size particles increase in the soil owing to the addition of fly ash, the stabilized soil becomes comparatively coarser [123]. An increase in permeability also indicates an increase in the rate of consolidation of soil [81]. Mir and Sridharan [123] reported that the permeability of stabilized soil decreased with an increase in curing time. A possible explanation for this could be that cementitious gel is formed in the soil due to the reaction of calcium aluminum silicate hydrate (CASH) or calcium silicate hydrate (CSH) structure which fills the pores during the curing [126,127].

4. Field Applications of Fly Ash-Stabilized Soil

There have been limited field studies of fly ash-stabilized soil in comparison with laboratory studies. However, several standards encourage the use of fly ash in field applications. According to the US Federal Highway Administration (FHWA) report [128], soil + class C fly ash or soil + class F fly ash + lime mixtures can be used in many geotechnical applications, commonly in highway construction. Fly ash can be used to stabilize base or subgrade, backfill for reducing lateral earth pressure, and embankments for improving slope stability. The main reason for adding fly ash in soil is to improve the compressive strength and shear strength of the soil. For field applications, the strength of the soil can be changed with delay in compaction, in situ soil properties, moisture content at the time of compaction, and fly ash content. FHWA [128] indicated that density and strength can be decreased by increasing the delay of compaction. Thus, it is recommended to apply compaction without any delay, or with a one-hour compaction delay in construction. The maximum strength is obtained with moisture content of about 4 to 8% below OMC (for silt and clay). For field applications, the addition of fly ash to the soil is recommended to be typically between 8 to 16% based on the dry weight of the soil. Organic soils are generally not suitable for stabilization with fly ash. According to ASTM D7762 [129], self-cementing (class C) fly ash can be applied in road construction, including stabilized subgrade, subbase, and base layers. Fly ash stabilization method can also be applied to decrease the compressibility of fills below buildings. Fly ash has been shown to be an effective stabilization material for fine-grained soils used in subgrade for pavements, in decreasing swelling potential of clay soils, in increasing shear strength of fine-grained soils, and in reducing the settlement of fills under foundations [129].

Senol et al. [103] investigated the performance of class C fly ash-stabilized subbase of a pavement system in a field site in Wisconsin. The subgrade soil was classified as low plasticity clay. Laboratory experiments, including UCS, CBR, and resilient modulus (M_r) tests, were initially carried out with the addition of 12%, 16%, and 20% fly ash by dry weight of the soil. Based on the laboratory test results, the subgrade was stabilized with the addition of 12% fly ash in the field site. Post construction tests, including UCS, CBR, and Mr tests, were applied by collecting Shelby tube samples from the field. The values of UCS, CBR, and Mr increased significantly with the addition of fly ash. The CBR value increased from 1 to 25. The general rating of the subgrade soil improved from 'very poor' to 'good' and the application terms of subgrade soil changed to base or subbase soil [99]. A Geo gauge stiffness (GGS) survey was carried out to measure stiffness and it was found that the average stiffness increased from 5 MN/m for the unstabilized soil to 13 MN/m for the stabilized soil. Bin-Shafique et al. [33] investigated a case study involving pavements of two sites by mixing class C fly ash and low plasticity clay soil to stabilize a subgrade. A comparison was made between the fly ash stabilized soil and the conventional cut-and-fill method in the field. CBR, M_r, and UCS tests were conducted in the laboratory. Based on the laboratory test results, the most effective fly ash contents were determined as, 10% and 12%, for application in the field sites. It was pointed out that the strength and stiffness characteristics of the subgrades were significantly improved with the addition of fly ash based on laboratory and field tests. The results of the cut-and-fill method and the fly ash stabilization method were similar from the field tests. A similar study was conducted by Trzebiatowski et al. [98] to improve the understanding of the effects of fly ash in soil stabilization in highway subgrade. Laboratory tests, including CBR, UCS, and M_r, were carried out on sandy clay with the addition of 10% class C fly ash. Field tests, including falling weight deflectometer (FWD) and soil stiffness gage (SSG) tests, were also carried out. Based on the laboratory tests, the average UCS of the stabilized soil increased by 1.5 times compared to the unstabilized soil. The average CBR and M_r values increased from 2 to 85, and from 0 to 21 MPa, respectively. The field test results confirmed that the subgrade improved considerably with the addition of fly ash to the soil. The highest strength results were obtained at 28 days curing time according to M_r test results. By contrast, the CBR and UCS result increased inconsiderably after 7 days of curing. Parsons and Kneebone [77] evaluated a class C fly ash-stabilized clay and unstabilized clay for subgrades of pavements by using laboratory and field tests. Atterberg limit and one-dimensional swell potential tests were conducted with the addition of 12% and 16% fly ash in the laboratory. Field tests, including dual-mass dynamic cone penetrometer (strength test) and soil stiffness gauge (stiffness measurement) tests, were also conducted. Based on the laboratory tests, it was concluded that both the plasticity index and swell potential of the soil decreased with the addition of fly ash, however, the swelling rate of the stabilized soil was still considerable for subgrade construction. Therefore, it was recommended that the utilization of only fly ash in high plasticity clay soil may not be adequate to prevent swelling. According to the field tests, after 28 days, the stiffness of the stabilized soil increased by around 45% compared to unstabilized soil. The final strength results obtained from dynamic cone penetrometer tests showed an improvement of 40–250% compared to the unstabilized soil for the pavement system. Bhuvaneshwari et al. [130] carried out laboratory and field tests for a trial embankment. Atterberg limits and compaction tests were carried out by adding 10–50% fly ash in clay soil. The fly ash stabilized soil with maximum of 25% fly ash was found to be suitable. Li et al. [131] reported mechanical improvement of fly ash-stabilized soil in field and laboratory tests. CBR, M_r, and UCS tests were carried out on subgrade soil, recycled pavement material (RPM), and road surface gravel (RSG) using class C fly ash as the agent. The subgrade soil, RPM, and RSG were described as fine-grained soils (CL, CL-ML, CH), sandy-gravel size particles, and well graded gravelly sand, respectively. The values of CBR, M_r, and UCS increased with the addition of fly ash in both conditions, however with all types of soil, the field-mix values of CBR, M_r, and UCS were found lower than laboratory-mix values. This indicates that mixing the material in the laboratory leads to a more uniform distribution of fly ash in the mixture compared to field conditions. Based on the case studies, it was noticed that fly ash has been extensively used for road embankment construction in India. Investigation and design of fly ash-based road embankment in New Delhi, India was reported by Sinha et al. [132]. Standard penetration and cone penetration tests were initially conducted to investigate the subsoil condition. At shallow depths, the material was found to be sandy silt in a loose state, while higher depths were predominantly included poorly graded fine sand. The SPT 'N' values was less than 5 at shallow depths. The total length of the alignment was 3.6 km. The design was conducted based on 5 m high embankment. According to the Bishop's method, Factor of Safety (FoS = 1) was found critical, thus an additional 3 m berm was built on each side of the embankment to increase the FoS = 1.3. The maximum settlement of 14.5 cm was expected in between 1600 and 2000 m. The settlement was also expected to be during construction phase due to the silty sand soil type.

5. Future Research and Prospects

The literature showed that fly ash is a valuable raw material to stabilize fine-grained soils and thus to use in geotechnical applications. However, further research areas that still need to be investigated in future research are recommended below:

A review of the literature reveals that most of the research has been conducted on clay soils. More research needs to be done on silty soils from the fine-grained soil category to analyze how the type of soil affects the geotechnical properties of stabilized soil. Considerable amount of research has been conducted to evaluate the Atterberg limit, compaction, unconfined compressive strength, and swelling index tests of soil stabilized with fly ash and with different curing times. However, limited investigation has been carried out in triaxial, oedometer, and permeability tests to understand the effects of the inclusion of fly ash on soil stabilization. Therefore, more research should be carried out, using triaxial tests to investigate the shearing behavior and oedometer tests to analyze the consolidation behavior of fly ash-stabilized soil. In addition, tests can be done with different curing times to investigate the short-term and long-term behavior of the stabilized soil.

There is limited study in the literature on the durability of soils stabilized with fly ash. Thus, to understand the applicability of soils stabilized with fly ash, studying the behavior of the stabilized soils in cycles of wetting-drying and freeze-thaw can be recommended.

Most of the investigations on the behavior of soils stabilised with fly ash have been conducted at laboratory scale. Further research is required to carry out large-scale or field tests for a better understanding of the in-situ behavior of fly ash-stabilized soils. In this way, the effects of scale on the behavior of soil can be evaluated.

In terms of large-scale applications, embankments and roadways are the two major applications where fly ash can be successfully used. Further research is needed to investigate the potential benefits and limitations of fly ash, and to allow fly ash-based application to more complex geotechnical structures, such as fill material behind retaining walls and foundation engineering.

The reuse of fly ash may contribute to some cost savings in many soil stabilization applications, but the cost-benefit analysis of fly ash is found to be limited. Therefore, a cost-benefit analysis of fly ash against traditional construction materials can increase the utilization of fly ash.

The utilization of fly ash to stabilize soil brings environmentally friendly solution due to the immobilization of heavy metals in soil matrix. In this way, no contamination or pollution can be transported to the environment or water systems. Leaching tests can be used to verify and support the environmentally friendly aspect of the binders, along with the rigorous assessment of possible environmental impacts through Life Cycle Assessment (LCA) methods.

6. Conclusions

This paper presented a review of the concept of using fly ash in the stabilization of fine-grained soils. Classification, properties, health concerns, disposal, availability, and cost of fly ash were discussed.

There is an increasing demand for coal in many developing countries. Even though coal fired power plants are expected to be closed in the next 50 years in developed countries, reports indicate that fly ash will be stored in landfills or used in industry. Therefore, considering its availability, cost-effectiveness, environmentally friendly, and effective engineering properties, fly ash can be used for soil stabilization. The geotechnical behavior of fly ash-stabilized soil can be summarized as the following:

- LL decreases, PL increases, and PI decreases with increasing the fly ash content in the soil.
- The addition of fly ash to soil leads to a decrease in MDD and an increase in OMC. However, a number of studies have shown that the MDD increased and OMC decreased with the addition of fly ash. This discrepancy could be due to the differences in the specific gravity of the fly ash used.
- Fly ash-stabilized soil could be used as a subbase or base material for roads, backfilling, or other geotechnical structures.
- UCS of soil increases with the addition of fly ash, however, class C fly ash is more effective in comparison with class F fly ash. An increase in curing time has a positive effect on the UCS of soil due to the time-dependent pozzolanic properties of fly ash.
- The shear strength parameters, angle of shearing resistance, and cohesion improve with increasing the fly ash content in the soil.
- Swelling of expansive soils decreases with the addition of fly ash. The compression index (C_c) and coefficient of volume compressibility (m_v) of the soil generally

decrease and the pre-consolidation pressure increases with the addition of fly ash. Also, the coefficient of consolidation and permeability increase with the addition of fly ash in the soil, hence, the majority of the settlement could be completed during the construction stages when fly ash stabilized soil is used.

In summary, the technical benefits of using fly ash in soil stabilization include: increasing strength parameters and CBR values, decreasing plasticity index, preventing swelling of expansive soils, and improving hydraulic conductivity. The ease of adaptability, availability, cost-effectiveness, and being environmentally friendly is the main benefits of using fly ash in geotechnical applications.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Consistency limits of soils stabilized with fly ash from different studies.

Type of Fly Ash	Fly Ash Content	LL (%)	PL (%)	PI (%)	Soil Classification (USCS)	References
class F	unstabilized (0%)	80	28	52	CH	Kumar and Sharma [4]
	5%	77	31	46	CH	
	10%	75	35	40	CH	
	15%	73	40	33	MH	
	20%	70	44	26	MH	
Low-Ca fly ash	unstabilized (0%)	84	29	55	CH	Phanikumar and Nagaraju [5]
	5%	79	30.5	49.5	CH	
	10%	74	31	43	CH	
	15%	68	31.5	36.5	CH	
	20%	62	32.5	29.5	MH	
	25%	54	33	21	MH	
	30%	44	33.5	10.5	ML	
class F	unstabilized (0%)	62.2	25.1	37.1	CH	Ji-ru and Xing [76]
	40%	54.4	27.5	26.9	CH	
	50%	51.4	24.9	26.5	CH	
class C	unstabilized (0%)	-	-	30	CH	Parsons and Kneebone [77]
	12%	-	-	16	-	
	16%	-	-	12	-	
	unstabilized (0%)	-	-	15	CL	
	12%	-	-	11	-	
	16%	-	-	9	-	
	unstabilized (0%)	-	-	17	CL	
	12%	-	-	12	-	
	16%	-	-	9	-	
class F	unstabilized (0%)	59.8	27.5	32.3	CH	Zha et al. [78]
	3%	58.2	29.2	28.9	CH	

	6%	57.3	31	26.2	MH	
	9%	55.1	32.5	22.6	MH	
	12%	53.7	33.3	20.4	MH	
	15%	52.4	35.1	17.3	MH	
class F	unstabilized (0%)	100	27	73	CH	Phanikumar [79]
	10%	92	32	60	CH	
	20%	86	36	50	CH	
class F	unstabilized (0%)	84	25.4	58.6	CH	Mir and Sridharan [80]
	20%	72	33	39	MH	
	40%	63	31.6	31.4	MH	
	60%	53	32.5	20.5	MH	
class C	unstabilized (0%)	84	25.4	58.6	CH	
	10%	81	45	36	MH	
	20%	76	49	27	MH	
	40%	66	54	12	MH	
	60%	56.5	45	11.5	MH	
class F	unstabilized (0%)	159	36.9	122.1	CH	Pal and Ghosh [81]
	50%	91.4	20.9	70.5	CH	
	60%	75.1	23.4	51.8	CH	
	70%	60.8	24.6	36.1	CH	
	80%	45.7	25.9	19.8	CL	
class C	unstabilized (0%)	88.7	35	53.7	CH	Binal [82]
	5%	-	-	-	MH	
	10%	-	-	-	MH	
	15%	-	-	-	MH	
	20%	-	-	-	MH	
	25%	-	-	-	MH	
class C	unstabilized (0%)	75.8	28.5	-	-	Kolay and Ramesh [83]
	10%	75.2	25.5	-	-	
	20%	73.9	24.4	-	-	
	30%	69.3	21.3	-	-	
	40%	64.9	19.6	-	-	
	50%	61.5	17.9	-	-	
	unstabilized (0%)	603.1	94.5	-	-	
	10%	512	81.8	-	-	
	20%	432	73.9	-	-	
	30%	346	65.8	-	-	
	40%	283	59.9	-	-	
	50%	237	54.8	-	-	
class F	unstabilized (0%)	-	-	-	CH	Seyrek [60]
	20%	-	-	-	CL	
class C	unstabilized (0%)	-	-	-	CH	
	10%	-	-	-	MH	
	15%	-	-	-	ML	
class F	unstabilized (0%)	-	-	-	CL	
	15%	-	-	-	ML	
class C	unstabilized (0%)	-	-	-	CL	
	10%	-	-	-	ML	
class F	unstabilized (0%)	48.3	23.4	24.9	CL	Zhou et al. [84]
	30%	43.1	26.5	16.6	ML	

Table A2. Compaction characteristics of soils stabilized with fly ash from different studies.

Type of Fly Ash	Type of Soil	Fly Ash Content	MDD (kN/m³)	OMC (%)	References
class F	CH	unstabilized (0%)	13.8	40	Kumar and Sharma [4]
		5%	13.9	38	
		10%	14.1	35	
		15%	14.2	33	
		20%	14.3	31	
class C	CH	unstabilized (0%)	13.8	30.5	Kumar et al. [10]
		5%	13.4	30.5	
		10%	13.2	31	
		15%	13.1	31.5	
		20%	13.0	31.5	
		100%	11.0	39	
-	CL	unstabilized (0%)	16.8	14.6	Prabakar et al. [12]
		9%	15.5	15.8	
		20%	15.4	17.9	
		28.5%	14.1	20.4	
		35.5%	13.6	22.3	
		41.2%	13.3	25.2	
		46%	13.1	27.2	
		100%	9.2	44.2	
-	MH	unstabilized (0%)	14.0	30.1	
		9%	13.5	29.5	
		20%	13.2	29.5	
		28.5%	12.8	30.1	
		35.5%	12.2	31.9	
		41.2%	12.3	33.3	
		46%	11.9	34.3	
High-Ca fly ash	Silty clay	unstabilized (0%)	15.3	23	Jafer et al. [16]
		3%	14.5	26	
		6%	14.3	27.5	
		9%	14.2	28	
		12%	14.1	29	
		15%	13.7	30.5	
class F	CL	unstabilized (0%)	17.8	16	Shaunik and Gupta [29]
		20%	16.3	20	
		40%	12.7	22	
		60%	11.4	24	
		80%	10.2	26	
		100%	9.0	28	
class F	CH	unstabilized (0%)	17.5	17.2	Ji-ru and Xing [76]
		40%	13.9	16.0	
		50%	13.3	18.4	
class F	CH	unstabilized (0%)	13.6	34	Phanikumar [79]
		10%	14.0	27	
		20%	14.4	21	
class F	CH	unstabilized (0%)	14.4	28.3	Mir and Sridharan [80]
		20%	13.9	30.0	
		40%	13.6	31.1	
		60%	12.7	33.0	
		80%	11.8	35.4	
		100%	10.6	38.2	
class C	CH	unstabilized (0%)	14.4	28.3	
		10%	14.1	29.5	

		20%	13.9	29.7	
		40%	13.7	29.9	
		60%	13.5	30.5	
		80%	13.1	31.1	
		100%	12.6	32.0	
class C	CH (kaolinite)	unstabilized (0%)	13.4	30.1	Kolay and Ramesh [83]
		10%	13.2	31.0	
		20%	13.0	32.2	
		30%	12.9	33.0	
		40%	12.8	34.5	
		50%	12.7	35.4	
	CH (bentonite)	unstabilized (0%)	11.7	40.5	
		10%	11.7	40.5	
		20%	11.5	41.3	
		30%	11.4	41.5	
		40%	11.3	41.6	
		50%	11.3	42.5	
class F	CH	unstabilized (0%)	16.4	17.2	Seyrek [60]
		5%	15.9	18.4	
		10%	15.6	18.6	
		15%	15.5	19.2	
		20%	15.3	19.3	
		25%	15.0	19.5	
		30%	14.9	19.8	
	CL	unstabilized (0%)	17.3	15.8	
		5%	16.8	15.8	
		10%	16.5	16.0	
		15%	16.4	16.2	
		20%	16.2	16.5	
		25%	16.0	16.8	
		30%	15.9	17.0	
class C	CH	unstabilized (0%)	16.4	17.2	
		5%	16.1	17.9	
		10%	15.8	18.2	
		15%	15.5	18.2	
		20%	15.6	18.0	
		25%	15.4	18.5	
		30%	15.1	18.8	
	CL	unstabilized (0%)	17.3	15.8	
		5%	17.1	16.1	
		10%	16.8	16.1	
		15%	16.4	16.3	
		20%	16.5	16.0	
		25%	16.3	16.4	
		30%	16.1	16.5	
-	CL	unstabilized (0%)	17.9	14.0	Santos et al. [88]
		20%	15.5	22.5	
		40%	14.6	25.0	
		60%	13.9	28.0	
		100%	10.4	45.5	
class C	CL (PI = 20)	unstabilized (0%)	16.2	18.7	Savas et al. [91]
		5%	15.7	20.5	
		10%	15.2	22.3	
		15%	15.0	23.0	
		20%	14.9	23.6	

		25%	14.7	24.3
		30%	14.6	24.9
class F	CL (PI-19)	unstabilized (0%)	16.9	15.7
		5%	16.6	15.8
		10%	16.2	15.9
		15%	15.9	15.7
		20%	15.7	15.7
		25%	15.5	17.1
		30%	15.3	17.7
	CL (PI = 20)	unstabilized (0%)	16.2	18.7
		5%	16.0	19.0
		10%	15.8	19.3
		15%	15.4	19.9
		20%	15.1	20.5
		25%	15.0	21.2
		30%	14.9	21.8
	CL (PI-19)	unstabilized (0%)	16.9	15.7
		5%	16.9	15.7
		10%	16.7	15.4
		15%	16.4	15.6
		20%	16.1	15.1
		25%	15.9	15.2
		30%	15.8	15.5

Table A3. CBR values of soils stabilized with fly ash from different studies.

Type of Fly Ash	Type of Soil	Fly Ash Content	CBR (%)	General Rating, Bowles [83]	Uses, Bowles [83]	References
-	CL	unstabilized (0%)	4.7	poor to fair	subgrade	Prabakar et al. [12]
		9%	7	fair	subbase	
		20%	8.84	fair	subbase	
		28.5%	9.24	fair	subbase	
		35.5%	9.93	fair	subbase	
		41.2%	10.67	fair	subbase	
		46%	11.6	fair	subbase	
class C	CL	unstabilized (0%)	1	very poor	subgrade	Bin-Shafique et al. [33]
		12%	37	good	base, subbase	
	CL-ML	unstabilized (0%)	3	very poor	subgrade	
		10%	32	good	base, subbase	
class F	CH	unstabilized (0%)	2	very poor	subgrade	Ji-ru and Xing [76]
		40%	17	fair	subbase	
		50%	20.2	good	base, subbase	
class C	CH	unstabilized (0%)	6.7	poor to fair	subgrade	Binal [82]
		28% (28 days cured)	68.7	excellent	base	
class C	CL	unstabilized (0%)	3	poor to fair	subgrade	Senol et al. [87]
		12% (7 days cured)	34	good	base, subbase	
		16% (7 days cured)	51	excellent	base	
		20% (7 days cured)	56	excellent	base	
	ML	unstabilized (0%)	5	poor to fair	subgrade	
		10% (7 days cured)	32	good	base, subbase	
		14% (7 days cured)	36	good	base, subbase	
		18% (7days cured)	38	good	base, subbase	
	OH	unstabilized (0%)	2	very poor	subgrade	
		18% (7 days cured)	5	poor to fair	subgrade	
-	CH	unstabilized (0%)	2.1	very poor	subgrade	Than and Zaw [97]

		4%	4.9	poor to fair	subgrade	
		8%	11.5	fair	subbase	
		12%	21.3	good	base, subbase	
		16%	30.7	good	base, subbase	
		20%	25.1	good	base, subbase	
class C	CL	unstabilized (0%)	2	very poor	subgrade	Trzebiatowski et al. [98]
		10%	57	excellent	base	
	CL	unstabilized (0%)	3	poor to fair	subgrade	
		10%	47	good	base, subbase	
class C	CH	unstabilized (0%)	2	very poor	subgrade	Edil et al. [100]
		10% (7 days cured)	8	fair	subbase	
		18% (7 days cured)	24	good	base, subbase	
	CL	unstabilized (0%)	5	poor to fair	subgrade	
		10% (7 days cured)	11	fair	subbase	
		18% (7 days cured)	30	good	base, subbase	
	CH	unstabilized (0%)	3	poor to fair	subgrade	
		10% (7 days cured)	12	fair	subbase	
		18% (7 days cured)	15	fair	subbase	
class F	expansive soil	unstabilized (0%)	7.5	fair	subbase	Jose et al. [101]
		10%	12.6	fair	subbase	
		15%	13.2	fair	subbase	

Table A4. UCS of soils stabilized with fly ash from different studies.

Type of Fly Ash	Type of Soil	Curing Days	Fly Ash Content	UCS (kPa)	References
class F	CH	1	unstabilized (0%)	285.7	Seyrek [60]
		28	25%	1088.3	
class C	CH	1	unstabilized (0%)	285.7	
		1	25%	559.9	
		7	25%	948.4	
		28	30%	1442.5	
class F	CL	1	unstabilized (0%)	215.4	
		28	25%	657	
class C	CL	1	unstabilized (0%)	215.4	
		28	30%	915.5	
class C	CL	7	unstabilized (0%)	140	Senol et al. [87]
			12%	772	
			16%	828	
			20%	863	
	ML	7	unstabilized (0%)	133	
			10%	566	
			14%	614	
			18%	649	
class C	CL (PI = 20)	1	unstabilized (0%)	257.6	Savas et al. [91]
			5%	459.9	
			10%	476.5	
			15%	729.5	
			20%	765.2	
			25%	784.3	
			30%	862.9	
class F	CL (PI = 20)	1	unstabilized (0%)	257.6	
			5%	305.7	
			10%	317.5	
			15%	336.1	
			20%	307.9	

			25%	430.7	
			30%	444.9	
class C	CL (PI = 19)	1	unstabilized (0%)	234.8	
			5%	308.9	
			10%	426.1	
			15%	559.6	
			20%	761.7	
			25%	790.4	
			30%	845	
class F	CL (PI = 19)	1	unstabilized (0%)	234.8	
			5%	315.8	
			10%	366.5	
			15%	358.9	
			20%	365.2	
			25%	435.1	
			30%	448	
class C	CL	7	unstabilized (0%)	200	Trzebiatowski et al. [98]
			10%	448	
	CL	7	unstabilized (0%)	145	
			10%	490	
class C	CL	7	unstabilized (0%)	212	Bin-Shafique et al. [105]
			5%	520	
			10%	713	
			20%	804	
	CH	7	unstabilized (0%)	180	
			5%	364	
			10%	456	
			20%	567	
High-Ca fly ash	CI	1	unstabilized (0%)	-	Premkumar et al. [109]
			3%	514	
			6%	536	
			9%	437	
			12%	388	
	CL	1	unstabilized (0%)	-	
			3%	401	
			6%	415	
			9%	445	
			12%	407	
class C	CH	1	unstabilized (0%)	182	Mir and Sridharan [112]
			10%	189	
		7	unstabilized (0%)	202	
			10%	446	
		28	unstabilized (0%)	268.5	
			10%	557	
class C	CI	1	unstabilized (0%)	226	Turan et al. [113]
			30%	295	
		7	unstabilized (0%)	245	
			25%	517	
		28	unstabilized (0%)	235	
			25%	599	

Table A5. Swelling parameters of soils stabilized with fly ash from different studies.

Type of Fly Ash	Type of Soil	Fly Ash Content	Free Swell Index (%)	Swell Potential (%)	Swell Pressure (kPa)	References
class F	CH	unstabilized (0%)	250	10.8	90	Kumar and Sharma [4]
		5%	200	8.8	72	
		10%	165	7.2	60	
		15%	140	6.0	50	
		20%	125	5.5	45	
Low-Ca fly ash	CH	unstabilized (0%)	125	-	120	Phanikumar and Nagaraju [5]
		5%	118	-	-	
		10%	100	-	105	
		15%	85	-	-	
		20%	70	-	60	
		25%	50	-	-	
		30%	35	-	20	
class F	CH	unstabilized (0%)	165	26.7	330	Phanikumar [79]
		10%	130	13.9	90	
		20%	110	8.9	74	
class C	CH (kaolinite)	unstabilized (0%)	84	-	1116.19	Kolay and Ramesh [83]
		10%	75.7	-	755.31	
		20%	70.8	-	514.72	
		30%	64.5	-	240.71	
		40%	59.1	-	150.40	
		50%	54.8	-	75.13	
	CH (bentonite)	unstabilized (0%)	477.1	-	3522.1	
		10%	340.8	-	3281.5	
		20%	307.4	-	2680.0	
		30%	273.3	-	2078.5	
		40%	263.8	-	1356.8	
		50%	246.9	-	1248.5	
class F	CH	unstabilized (0%)	-	7.03	57.6	Seyrek [60]
		30%	-	2.58	25.5	
class C	CH	unstabilized (0%)	-	7.03	57.6	
		30%	-	1.04	14.8	
class F	CL	unstabilized (0%)	-	4.09	16.4	
		30%	-	1.39	7.9	
class C	CL	unstabilized (0%)	-	4.09	16.4	
		30%	-	0.60	4.6	
class F	CL	unstabilized (0%)	59.4	-	-	Zhou et al. [84]
		20%	35.3	-	-	
class F	CH (PI = 352)	unstabilized (0%)	377	22	425	Kate [118]
		20%	260	11	305	
	CH (PI = 307)	unstabilized (0%)	326	17.5	345	
		20%	214	8.7	207	
	CH (PI = 215)	unstabilized (0%)	230	13.7	259	
		20%	105	6.8	185	
	CH (PI = 116)	unstabilized (0%)	168	9	167	
		20%	116	4.7	110	
class C	CH	unstabilized (0%)	-	19.6	-	Nalbantoglu [58]
		15%	-	5	-	
		25%	-	3.7	-	
		25% (30 days cured)	-	0	-	
class C	CH	unstabilized (0%)	155	15.3	350	Phanikumar et al. [125]

5%	124	13.5	270
10%	110	12.7	330
15%	83	12	380
20%	77	11.4	290
25%	77	10.3	420

Table A6. Compression and swelling indices of soils stabilized with fly ash based on oedometer tests from different studies.

Type of Fly Ash	Type of Soil	Fly Ash Content	Compression Index (Cc)	Swelling Index (Cs)	References
class F	CH	unstabilized (0%)	0.5	-	Phanikumar [79]
		10%	0.65	-	
		20%	0.5	-	
class F	CH	unstabilized (0%)	0.645	-	Pal and Ghosh [81]
		50%	0.271	-	
		60%	0.200	-	
		70%	0.125	-	
		80%	0.071	-	
		100%	0.112	-	
class C	CH (kaolinite)	unstabilized (0%)	1.00	0.23	Kolay and Ramesh [83]
		10%	0.37	0.21	
		30%	0.15	0.12	
		50%	1.53	0.09	
	CH (bentonite)	unstabilized (0%)	1.07	0.21	
		10%	1.23	0.14	
		30%	1.54	0.11	
		50%	1.42	0.07	
-	ML	unstabilized (0%)	0.118	-	Shil and Pal [89]
		20%	0.063	-	
		30%	0.056	-	
class F (1)	CL	unstabilized (0%)	0.503	0.079	Bryson et al. [119]
		10%	0.508	0.080	
		20%	0.377	0.043	
		40%	0.432	0.069	
		100%	0.041	0.017	
class F (2)		unstabilized (0%)	0.503	0.079	
		10%	0.472	0.073	
		20%	0.425	0.064	
		40%	0.354	0.044	
		100%	0.096	0.013	
class F (3)		unstabilized (0%)	0.503	0.079	
		10%	0.508	0.090	
		20%	0.431	0.063	
		40%	0.356	0.044	
		100%	0.065	0.013	
class C		unstabilized (0%)	0.503	0.079	
		10%	0.469	0.061	
		20%	0.469	0.050	
		40%	0.376	0.025	
		100%	0.036	0.012	

Table A7. Coefficient of consolidation and permeability of soil stabilized with fly ash from different studies.

Type of Fly Ash	Type of Soil	Fly Ash Content	Coefficient of Consolidation (cv)	Permeability (k)	References
Low-Ca fly ash	CH	unstabilized (0%)	-	4.6×10^{-7} cm/s	Phanikumar and Nagaraju [5]
		10%	-	6.0×10^{-7} cm/s	
		20%	-	8.5×10^{-7} cm/s	
		30%	-	1.8×10^{-6} cm/s	
class F	CH	unstabilized (0%)	0.32×10^{-3} cm²/s	0.10×10^{-9} cm/s	Phanikumar [79]
		10%	0.8×10^{-3} cm²/s	1×10^{-9} cm/s	
		20%	2.71×10^{-3} cm²/s	2.5×10^{-9} cm/s	
class F	CH	unstabilized (0%)	6.343×10^{-9} m²/s	8.211×10^{-11} m/s	Pal and Ghosh [81]
		50%	1.418×10^{-8} m²/s	1.72×10^{-10} m/s	
		60%	2.005×10^{-8} m²/s	3.63×10^{-10} m/s	
		70%	2.197×10^{-8} m²/s	5.70×10^{-10} m/s	
		80%	0.026×10^{-4} m²/s	9.44×10^{-10} m/s	
		100%	2.874×10^{-4} m²/s	2×10^{-7} m/s	
-	ML	unstabilized (0%)	9.07×10^{-3} cm²/s	3.38×10^{-6} cm/s	Shil and Pal [89]
		20%	11.4×10^{-3} cm²/s	$3.43–2.21 \times 10^{-6}$ cm/s	
		30%	13.4×10^{-3} cm²/s	$2.93–1.58 \times 10^{-6}$ cm/s	

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