CHAPTER- II

REVIEW OF LITERATURE

2.1 INTRODUCTION

The thermal power plants in the world are operating under the combustion efficacy of 32% maximum up to 45%. The advanced technologies have been developed that can achieve combustion efficiency between 50% to 53%, this will help in the extraction of utmost benefits from the coal (Brendow 2004). The estimated CO_2 emission from the coal in the first quarter year of the 21st century was found to be 1.1 billion metric tonnes which is much lesser than the emission from oil (1.5 billion tons) and natural gas (1.3 billion tons) (USDOE 2003). Also, in order to minimize the harmful effects of coal to the environment, the advancement in the clean coal combustion technology, carbon sequestration, methane drainage, reduction in the SO_2 and NO_x emission will be major area to focus in the future. In the year 2021, the world-wide coal fly ash production was found in between 600 to 1000 million tonnes, out of which China and India show remarkable ash production of 620 and 221 million tonnes respectively (Tao et al. 2022). Since, India is highly dependent on coal for the electricity generation and this situation will be continued for upcoming 2-3 decades as per the present growth of other sources. Hence, an attempt has been made in the present study to investigate the application potential of fly ash in various fields so that its bulk utilization can be recommended. The objective of the present study is to inspect the applicability of fly ash in homogeneous and stratified (soil-ash) form in seismic prone areas. Therefore, the studies related to the static and dynamic characterization of homogeneous and stratified soil-ash deposits have been focused here.

This chapter provides a comprehensive knowledge about the past studies that has already been done by several researchers. It includes brief summaries of fundamental and geotechnical characterization of coal ash and soil stabilization with coal ash. The dosage of fly ash required for stabilization has also been discussed. In addition, the static characterization studies of stratified soil-ash deposits have been explored. Furthermore, the dynamic characterization and liquefaction potential studies of homogeneous and stratified soil-ash deposits have been described considering low to high strain conditions. The previous research is reviewed under the following subheadings:

- Fly ash recognition as green/non-hazardous or hazardous material.
- Fundamental and geotechnical characterization studies of coal ash.
- Geotechnical characterization studies of soil stabilized with coal ash.
- Fly ash dosage in the various area of engineering.
- Laboratory studies on stratified soil-ash deposits.
- Dynamic characterization studies of soil and coal ash.
- Dynamic characterization studies of stratified soil-ash deposits.

2.2 FLY ASH RECOGNITION AS GREEN/NON-HAZARDOUS OR HAZARDOUS MATERIAL

A material is classified as hazardous when it shows the following nature: flammable, corrosive, toxic, reactive, and harmful to human health. Fly ash has most of the properties mentioned above, but it is classified as non-hazardous material. Table 2.1 represents the toxic chemical and their harmful effects to human body parts, out of these toxic chemicals majorities of the chemicals are generally found in the coal ash. The presence of arsenic, antimony, boron, lead, and cadmium affects the more number of body parts. Earlier, it was present under the group of hazardous industrial waste, eventually, after the year 2000, it was reclassified as waste material/non-hazardous material (Journal of Government Audits and Accounts-2015). As per National Hazardous Waste rules, if the ash residues are supposed to have remarkable hazardous materials, then it is important to test at the start of the plant operations for classification (EIA Guidance manual 2010). Seventy-six coal ash pond failures have been seen in the last decade (2010-2020). One of the health studies conducted in Chhattisgarh (India) reveals that the people living near the ash ponds are facing health issues like hair fall, head and body ache, kidney and gastrointestinal problems, etc. (Richin et al. 2017). Similar types of health studies have been conducted by the United States Environmental Protection Agency and found 1 in 50 chance of getting cancer from the water consumed, which was contaminated by arsenic (US EPA 2023). In comparison with other naturally available building materials, fly ash shows high radioactivity, but it remains under the permissible limits (Haquin 2008). Sjöblom (2014) discussed a feasible method to identify the hazardness/non-hazardness of the fly ash in a realistic manner. He selected a reference substance followed by finding the hazardous property of the selected substances with risk phrase. Thereafter, the sum value for each concentration was found out, which was compared with the permissible limits. If the sum value is greater than the limits, then it is classified as hazardous and vice-versa. Leaching results also plays a significant role in the selection of reference substances. From the above discussion, it is clear that the fly ash is a hazardous material if not managed/disposed properly. It contaminates surface water, sub-surface water, soil, air quality that resulting in various health related problems. Therefore, it is essential to identify the place that should be free from human habitations, sources of water, prone to earthquake, etc. for the safe disposal of coal/fly ash.

Table 2.1. Impact of toxic elements in all parts of the human body (Health Energy Initiative - 2020)

Sample No.	**All Parts of Body**	**Toxic elements**
1	Nervous System	Arsenic, Lead, Boron, Manganese, Mercury, Selenium, Thallium, Vanadium
2	Brain	Aluminium, Boron, Lead, Manganese, Mercury, PM2.5
3	Eyes	Antimony, Arsenic, Boron, Cadmium, Chromium
4	Nose	Antimony, Arsenic, Boron, Cadmium, Manganese
5	Throat	Antimony, PM2.5, Thallium
6	Lungs and Respiratory System	Aluminium, Boron, Lead, Manganese, Mercury, PM2.5
7	Heart	Antimony, PM2.5, Thallium
8	Liver	Antimony, Arsenic, Boron, Cadmium, Chromium, Manganese, Thallium
9	Kidney	Antimony, Boron, Cadmium, Chromium, Lead, Mercury, Silica
10	Intestine	Boron, Lead, Mercury
11	Muscle and Joints	Lead, Manganese, Molybdenum
12	Skin	Antimony, Arsenic, Cadmium, Chromium, Selenium, Zinc

2.3. FUNDAMENTAL AND GEOTECHNICAL CHARACTERIZATION STUDIES OF COAL ASH

The fly ash is fine in nature with a maximum contribution of silt size particles, in general the size of the fly ash lies between 10 to 100 μm (Malviya et al. 1999). The Indian fly ash varies in a wide range of particle size, i.e., <0.1 μm to >100 μm (Kumar and Upadhyay 1983). Pond ashes are coarser than that of the fly ash which varies between 45 to 150 μm (Arumugan et al. 2011). According to ASTM C-618 (2022), the fly ash, having a combined percentage of silica, alumina, and iron (SiO_2+Al_2O_3+Fe_2O_3) greater than 70 and 50 are classified as class F and class C respectively. The class F fly ash generally originates from the combustion of anthracite and bituminous coal whereas class C fly ash originates from the burning of sub-bituminous and lignite coal. Out of the four types of coal (Anthracite, bituminous, sub-bituminous, and lignite), the bituminous coal is extensively used for the generation of electricity. Therefore, the class

F fly ash is predominantly generated as compared to class C fly ash. Class F fly ash contains less cementitious properties because of the low calcium oxide content (<15%) than that of the class C fly ash. At high temperature, the performance of the non-concrete mortar produced from the class F fly ash is higher than the mortar produced from the class C fly ash (Wardhono 2018). When compared to class C fly ash, the majority of the fly ash produced in India is of the class F kind, which contains a higher percentage of cenospheres. This is a reason why the class C type fly ash has a higher specific gravity than that of the class F fly ash. The specific gravity of crushed fly ash (425 m passing) is higher than that of the uncrushed fly ash, indicating that its specific gravity decreases as the particle size increases. When fly ash, bottom ash, and pond ash are all collected from the same place, fly ash shows higher specific gravity than the other two. It decreases with the rise in temperature of the boiler under operation (Moghal 2017).

The shape of the fly ash particles is mostly spherical in nature, having a glass content of transparent impression (Davison et al. 1974). The disposal of fly ash in slurry form results in a higher fraction of sand size particles at the near end disposal point as compared to the far end disposal point where silt size particle fractions are predominant. The particle size distribution profile of the fractions passing through 75 microns can be done by hydrometer analysis for low calcium fly ash. On the other hand, XR sedimentation, counting of grain by laser particle, and electrolyte resistivity methods are employed for the high calcium fly ash. The inapplicability of hydrometer analysis for high calcium fly ash is associated with the reaction between lime and water, which form cementitious compounds. The general classification of fly ash is silty sand or sandy silt. The parameters responsible for the lower dry density are low specific gravity, high content of silt size particle (Raymon 1961), and the presence of cenospheres that has a tendency to absorb appreciable quantities of water (Das and Pakrashi 1990). The shape of the plot between maximum dry density (MDD) versus optimum moisture content (OMC) of fly ash was found to be the same as that of cohesive soils (Digioia and Nuzzo 1972; Dayal et al. 1989; Singh 1996). The high calcium fly ash has shown higher MDD and lower OMC as compared to the low calcium fly ash (Yudhbir and Honjo 1991). The vibratory smooth drum roller and Pneumatic tired drum roller required more than 8 passes for a thickness of 150 mm (approximately) to achieve 95% of MDD.

The strength characteristics of the fly ash can be estimated by knowing the angle of internal friction (φ) and cohesion (c) value which can be determined using the triaxial shear test (Raymon 1961; Kumar and Mandal 2016) & direct shear test (Muhunthan et al. 2004; Ratna and Darga 2015). In the loosest state, fly ash develops its shear strength mostly from friction between the particles, whereas in compacted state, the development of shear strength accounts due to the frictional resistance (Sridharan et al. 1998). The crushing strength of the granulated coal ash is independent of the size of the particle whereas it has a significant influence on the shear strength. It was reported that shear strength increases with an increase in the crushing strength of a single particle (Yoshimoto et al. 2012). Similarly, the permeability of fly ash is a critical parameter in the following cases: settlement of foundations, the time required for consolidation, and for the dissipation of pore pressure (Shil and Pal 2015). It is dependent on many factors such as degree of densification, void ratio, grain size distribution, internal structure, soil type, etc. (Wang et al. 1984; Rajasekhar 1995). The permeability of fly ash resembles the permeability of non-plastic silts, on the other hand, compacted fly ash is defined as moderately permeable (Kaniraj and Gayathri 2004). The permeability of fly ash is low followed by pond ash and bottom ash. Pond ash is showing intermediate permeability because it disposes directly by blending fly ash and bottom ash. In field applications like road subgrade, it is applied and compacted in an alternate layer form, leading to the generation of an interface. This results in the variation of field permeability in comparison to the laboratory. Some of the brief outcomes of geotechnical characterization of coal ash from the past studies have been described in Table 2.2.

Table 2.2. Tabular representation of geotechnical characterization of coal ash.

Authors	Material type	Key findings
Sridharan et al. 1998	Indian fly ash	• The angle of internal friction varies between 27 to 34°. • Maximum dry density falls in the range of 0.7 to 1.3 g/cc.
Pandian et al. 1998	Indian coal ash	• Fly ash exhibits higher specific gravity than that of bottom/pond ash at particular location. • The crushed ash particles show high specific gravity than that of the uncrushed one.
Sridharan et al. 2001	Indian coal ash	• The maximum dry density of coal ash changes between 5.8 to 17.2 kN/m^3 and the optimum moisture content changes between 17.9 to 75.1%.
Prashanth et al. 2001	Fly ash	• The pozzolanic fly ash has potential to act as hydraulic barrier to entrap alkaline leachates.
Pandian 2004	Fly ash	• It is usually classified as sandy silt to silty sand. • According to the findings, fly ash has an internal friction angle of more than 30 degrees and freely drains.
Kim et al. 2005	Fly ash and Bottom ash mixtures	• Ash mixtures at higher density resembles well with dense sandy soil. • The critical state friction angle was also found in the similar range of sands.
Das and Yudhbir 2005	Indian fly ash	• The fly ash having high calcium content shows higher specific gravity than that of the low calcium fly ash. • The geotechnical behaviour of fly ash were govern by its lime content, iron oxide, shape and mineral content.
Prakash and Sridharan 2009	Coal ashes	• The specific gravity of fly ash, pond ash, and bottom ash lies between 1.66-2.55, 1.64-2.66, and 1.47-2.19 respectively.

Kumar et al. 2012	Fly ash and Bottom ash mixtures	• The CBR of coal ashes are relatively higher as compared with the CBR of fine grained soil. • Fly ash exhibits higher density than that of the bottom ash. • Ash mixture with low percentage of fly ash results in higher value of CBR.
Zhu et al. 2013	Coal fly ash	• The larger particle in fly ash are resulted from the unburned carbon with irregular surface. • Unburned carbon could be primarily responsible for fly ash's surface area and sorption capability.
Kumar et al. 2016	Fly ash	• The fly ash has predominance of silica, alumina, and iron oxide. • Quartz and Mullite are the two crystalline mineral phase present in the fly ash.
Kumar et al. 2018	Indian fly ash	• With decrease in particle size, the increase in specific gravity and bulk density has been observed. • Fly ash's finer particles are more deleterious than its coarser particles.
Patel et al. 2019	Fly ash	• The fly ash improved with 6% lime and cement content can fulfill the strength requirement of sub-base as per IRC (Indian Road Congress).

2.4 GEOTECHNICAL CHARACTERIZATION STUDIES OF SOIL STABILIZED WITH COAL ASH

The coal ash was not only used in the industrial applications but has also been used for the reclamation/stabilization of problematic soils such as soft soil, peat, expansive soil, high clay content soil. The complication associated with these kinds of soils are low shear strength property, volume expansion (swelling) behaviour when comes in contact with water, shrinkage behaviour upon drying, higher optimum moisture content corresponding to lower dry density. Since, coal ashes are non-plastic in nature, therefore, it helps in the minimization of plastic behaviour of aforementioned soils that is some of the cause of problems associated. The extensive research has been done on the stabilization of expansive soil, and improvement of stiffness of low bearing capacity soil for the application in pavement layers. The copper slag and fly ash were projected to stabilize the locally available soil of Gujrat as a base layer. The results show that all the combinations like copper slag + local soil (50:50%), copper slag + fly ash (75:25%) performs satisfactorily as per the IRC guidelines (Havanagi et al. 1989). Indraratna et al. (1991) attempted to mitigate the erosive nature of dispersive soil with the help of fly ash. The fly ash not only reduces the dispersive nature but also increases the maximum dry density (MDD), pre-consolidation pressure, and shear strength parameters till 8% of fly ash. This study further extends to reduce the dispersive nature of colluvial soil by Indraratna (1996) using fly ash along with the lime and steel slag. With the addition of 12% fly ash and 5% hydrated lime & slag exhibits significant improvement in the angle of internal friction, cohesion, and self-hardening characteristics. A systematic literature has also been tabulated in Table 2.3 regarding the stabilization of soil using coal ash.

The collapsible soils also known as loess soils are abundantly available in the American region. The loess soil contains high porosity with loose structure which shows high strength and low compressibility below the optimum moisture content (OMC) due to the cementation behaviour of the calcium carbonate, clay mineral, and iron oxide. Beyond OMC, the bond formed by the calcium carbonate and clay minerals gets soften and results in the collapse of the soil structure. The difficulties attributed from loess in the road construction have been tried to solve by the stabilizing agent class C fly ash. The addition of fly ash helps in the enhancement of dry density, cementing properties, unconfined compressive strength, swelling reduction (Zia and Fox 2000). In the same way, several researchers have focused on the stabilization of the expansive soil using coal ash in different proportion. Ji-ru and Xing (2002) studied the improvement of the expansive soil with the fly ash in addition to lime and found desirable outcomes for 40 to 50% of fly ash & 4 to 6% of lime in the dry form mixing. Similarly, Kumar and Sharma (2004) observed remarkable shifting of moisture-density plot towards the left side upward and also noticed a promising reduction in plasticity index, swelling potential, and free swell index. The dosage of fly ash mostly varies in the range between 15-35%, especially in the case of expansive soil according to the past studies. Both Nalbantoglu (2004) and Bhuvaneshwari et al. (2005) experimentally found the optimum quantity of fly ash equals to 25% for expansive soil modifications. For better validation of the laboratory data, Bhuvaneshwari et al. (2005) also performed field testing of trial embankment (length: width: height = 30:6:0.6m) and found best suitability to apply in the field. Similar type of experimental investigation has been done by several researchers which observed 9%, 15%, 20%, and 35% as the optimum percentage of fly ash for expansive soil stabilizations (Zha et al. 2008; Hasan 2012; Bose 2012; Mollamahmutoglu 2009). The stabilization of expansive soil has extended with various other kinds of materials such as lime, granulated blast furnace slag, rice husk ash, polyester fiber, etc. along with fly ash. Kumar et al. (2007) and Sivapullaiah and Jha (2014) considered lime by optimum percentage of 8% & 6% with fly ash results in an increment of strength for high curing days. Sharma and Sivapullaiah (2016) incorporated ground granulated blast furnace slag (GGBFS) with fly ash, the advantage of GGBFS plus fly ash is that because of the pozzolanic property, it has a higher probability of the formation of cementitious gel (C-S-H) which led to the hardening behaviour. The increase in the unconfined compressive strength, cementation behaviour, MDD and decrease in OMC, swelling pressure, liquid & plastic limit was noticed, but in contrast Phanikumar and Nagarajan (2018) has observed a decrease in MDD with the increase in fly ash content.

In order to maximize the bulk utilization of fly ash, the application of fly ash as base/sub-base material was recommended based on California bearing ratio (CBR) value. The CBR value of fly ash is comparative low which has been improved with the addition of murrum in the proportion of 80:20% (Pandian and Krishna 2001). In the same way, Prabakar et al. (2004) improved the CBR value of weak/soft soil from 2.03% to 11.41% using fly ash whereas Jorat et al. (2011) observed this improvement in Kaolin soil by replacing bottom ash in equal proportion. The engineering/geotechnical properties of clayey soil were stabilized using coal ash and these improved clayey soils were recommended for the application as an embankment fill material (Muhunthan et al. 2004; Solanki et al. 2009; Sharma et al. 2012). Some the researchers blended two type of coal ash, i.e., bottom ash and fly ash and witnessed notable enhancement in the shear strength, friction angle, load resistance property, low compressibility that makes the coal ash mixture more suitable for the application as pavement layers (Awang et al. 2011; Jayaranjan et al. 2014; Latifi et al. 2015). Wang et al. (2019) after performing cyclic loading on the mixture of coal wash and fly ash found that the mixture is not capable of taking a high traffic loading, it is recommended to apply traffic load below 350 kPa. Similar types of results have also been observed by Praveen et al. (2021) in the case of modified soil with fly ash used as a subgrade material. They suggested the application of this combination in rural areas or the areas having low traffic volume. Same type of effort has been given by several researchers in the ground improvement of low bearing capacity soil by stabilizing with coal ash, so that the bulk utilization of waste materials can be achieved (Seder et al. 2006; Singh et al. 2008; Geliga and Ismail 2010; Mir and Sridharan 2013 & 2014; Shirkhanlooo et al. 2021).

Table 2.3. Summary of past literature on soil stabilization using coal ash.

Authors	Application	Key findings
Havanagi et al. 1989	Soil mixed with fly ash and copper slag	• The mixture of copper slag and fly ash (75%:25%) can be effectively use as a subgrade material. • Copper slag also plays a crucial role in the bituminous mixes by improving the stability, flow and tensile strength of Marshall specimens.
Indraratna et al. 1991	Dispersive soil blend with fly ash	• The increase in fly ash increases the MDD and decreases the OMC of dispersive soil. • The improvement in strength properties has been seen upto 8% of fly ash.
Zia and Fox 2000	Loess and fly ash mix for road base	• The increment in MDD has been observed upto 9% of fly ash addition. • Swelling and reduction in strength was observed for greater than 10% of fly ash.
Ji-ru and Xing 2002	Expansive soil stabilization by fly ash and lime	• The blending of 40 to 50% fly ash and 4 to 6% lime shows remarkable improvement in the expansive soil. • These stabilizer helps in reducing the plasticity index and swell potential of the expansive soil.
Kumar and Sharma 2004	Expansive soil improved with fly ash	• The compaction plot shifted left side upward and increases the undrained cohesion. • Addition of fly ash minimizes the plasticity, swelling potential and swelling pressure of the expansive soil.
Sezer et al. 2006	Improvement of Izmir clay using high lime fly ash	• Izmir clay was stabilized effectively with 15% of fly ash. • This fly ash increases the cohesion and self-hardening property of the Izmir clay.
Zha et al. 2008	Expansive soil improvement with fly ash	• The fly ash between 9-12% has been determined as the optimum content for the treatment of soil. • The MDD, OMC, swelling potential, linear shrinkage decreases with the increase in fly ash.
Awang et al. 2011	Mixture of fly ash and bottom ash	• Mixture of ash compacted at 95% of RC exhibits comparable shear strength same as that of the compacted sand. • Fly ash and bottom ash mixture (50 to 100%) shows good relationship between density and moisture.
Latifi et al. 2015	Fly ash and bottom ash mixture	• The bottom ash and fly ash mixture in proportion 70:30 results in higher shear strength. • Lower percentage of bottom ash did not show significant improvement in the shear strength.

Phanikumar and Nagaraju 2018	Expansive clay stabilized with fly ash and rice husk ash	• MDD and OMC decreases with the increase in fly ash and rice husk ash content. • The 30% fly ash and 30% rice husk ash provides the significant contribution in the elimination of the undesirable properties.
Htun et al. 2022	Lateritic soil stabilized with bottom ash	• For the bottom ash mixing range 30-60% and compacted at optimum moisture content shows higher CBR value.
Zimar et al. 2022	Expansive clay stabilization with fly ash	• It is recommended to add 15% class C and 9-12% class F fly ash for the improvement of soft soil. • Long term UCS strength of stabilized soil increased by four times.

2.5. FLY ASH DOSAGE IN THE VARIOUS AREA OF ENGINEERING

The dosage of fly ash is a very important aspect for the utilization of fly ash because it is different for different applications. Fly ash alone cannot achieve the desired strength when used in concrete. Therefore, fly ash is generally added as a partial replacement of cementitious material. Consoli et al. (2011 & 2016) studied the combination of soil, fly ash, and lime based on an unconfined compression test and proposed some equations, which is valid for fly ash range, 0%–25%, lime range, 3%–9%, and dry unit weight range 14–17 kN/m^3. The equation relating to dosage of the above material with strength is mentioned below:

$$\eta = 100\left[1 - \frac{\gamma_d}{1+\left(\frac{L}{100}\right)}\left(\frac{100-FA}{100\,\gamma_s} + \frac{FA}{100\,\gamma_{FA}} + \frac{L}{100\,\gamma_L}\right)\right] \tag{2.1}$$

$$L_{iv} = 100\left(\frac{\gamma_d}{1+\frac{L}{100}}\right)\left(\frac{L}{100\,\gamma_L}\right) \tag{2.2}$$

$$q_u = 5.89 \times 10^8\, FA\left[\frac{\eta}{(L_{iv})^{0.12}}\right]^{-4.6} \tag{2.3}$$

where, η: porosity, L_{iv}: volumetric binder content, q_u: unconfined compressive strength, FA: fly ash (%), L: lime content (%), γ_d: dry unit weight.

Kumar et al. (2005) investigated the yields of agricultural fields using fly ash from 50 different locations and found that the yield increases from 10% to 40% with the addition of 10 to 200 tonnes/ha of fly ash. The dose of fly ash required for rice in the alluvial soil and black soil is higher than that of the lateritic soil. The fly ash increases the physical and hydrological properties of the soil when its proportion is less than 2% by weight (Yunusa et al. 2011).

Table 2.4. Demonstration of dosage/proportion of fly ash in different areas of application.

Scope	**Constituents**	**Proportion**	**Remarks**	**Reference**
Construction material	Cement mortar – Fine FA	40*	Very fine FA gives higher strength	Chindaprasirt et al. 2004
	Fired Bricks – FA: Clay	50 : 50	PI of mixture reduces with increment of FA	Lingling et al. 2005
	Self-compacting concrete – FA	40*	High replacement of FA leads to reduction in strength	Liu 2010
	Polymer concrete - Epoxy resin : FA & Silica : Aggregate	13.2 : 7.2 : 79.6	FA and Silica helps in high development of strength	Barbuta et al. 2010
	Self-compacting concrete (SCC) – FA	25*	Abrasion resistance decreases with increase in FA beyond 25%	Turk and Karatas 2011
	Self-compacting concrete – FA	30*	30% of FA replacing cement results in concrete of 100 MPa strength	Dinakar 2013
	Reclaimed Asphalt Pavement (RAP) – FA : Aggregates & RAP	40 : 60 (80 : 20)	This proportion met the IRC guidelines for base/subbase material	Saride et al. 2015
	Nanosilica: FA : Cement : Aggregates	6 : 30 : 15 : 49	Adding Nanosilica & FA enhanced its binding in the matrix	Ghazy et al. 2016
	Cement stabilized macadam (CSM) – FA	25*	Increasing curing time will enhanced mechanical properties of CSM	Yan et al. 2019
By-products	Artificial light weight aggregate – FA : Fine quartz sand : Lime & Additives	50 : 45 : 5	Sintering process adopt FA with high carbon content	Bijen 1986
	Sound absorbing material – FA : Coal powder : H_2O_2 : Slag	50 : 30 : 1.0 : 19	Material shows high sound absorption and good mechanical properties	Sun and Guo 2015
Soil stabilization	FA : Lime : Clayey soil	20 : 8.5 : 71.5	CBR value increases 5.7% by adding FA & Lime	Sharma et al. 2012
	Lime : FA : Soil	9 : 25 : 66	Lime & FA increases its MDD	Consoli et al. 2016
	BA : Soil	30 : 70	BA can be used as both improvement and replacement	Hamza Gullu 2014
	FA : Lime : Cr^{6+} contaminated soil	25 : 10 : 65	Significant reduction in leachability has been achieve	Kostarelos et al. 2016
	Brick - FA : Clay	20 : 80	Lower efflorescence has observed in FA added bricks	Abbas 2017
Agricultural field	Alluvial soil	0-200 t/ha	Rice, Wheat	Kumar et al. 2005
	Laterite soil	0-10 t/ha	Rice, Groundnut	
	Black soil	0-80 t/ha	Sunflower, Maize	
	Red soil	30-60 t/ha/3 yrs	Sunflower, Groundnut	
Elimination of elements	Removal of Phosphorus	4-20 g per lit	Removal efficiency > 99% and higher at 40 °C	Ugurlu and Salman 1998
	Removal of Phenol	1.0 g per 50 mL	Mechanism of adsorption is governed by the surface characteristics of FA	Sarkar et al. 2006

FA: Fly Ash, IRC: Indian Road Congress, CBR: California Bearing Ratio, MDD: Maximum Dry Density, * Cementitious material replaced by Fly ash.

Similarly, the replacement of binding material for concrete is generally kept 25%–30% by the weight of cementing materials as shown in Table 2.4. According to the dose level of fly ash in concrete, it is divided into low (<15%), medium (15%–30%), high (30%–50%), and very high (>50%) (Thomas 2007). A higher dose level (30%–50%) can also be used to control the rise in the temperature in huge structures like dams and foundations. Marceau (2002) reveals that the dose level, 40%–0% can be used in structural constructions with sufficient durability and superior mechanical properties. It is used in the manufacturing of paver blocks, cement bricks, and clay bricks. The compressive strength of the fly ash-clay fired brick was observed to be 98.5 MPa (Lingling et al. 2005). For successful utilization of fly ash as construction material, it is essential to maintain the range/proportion discussed in Table 2.4. This is because it depends upon many factors such as the type of the application, required properties, durability, type of mixing material, location of the application, type of fly ash, etc. It has to be noted that higher dose of fly ash is undesirable for construction works as it reduces the required strength. From Table 2.4, it can be seen that for higher amount of utilization of fly ash, the application must be focused on areas such as fired bricks, asphalt pavement, lightweight aggregate, and sound absorbing materials.

2.6 LABORATORY STUDIES ON STRATIFIED SOIL-ASH DEPOSITS

The stratification phenomena are very common in the alluvial soil deposits. The soil settles down into multiple layers of various void ratio and thickness such that each layer shows independent behaviour whereas the combined layered form shows different behaviour. The investigation of the engineering property of the homogeneous soil has been extensively explored by several researchers, but very limited study on multi-layered deposit has been reported so far. In order to address these anisotropic characteristics of the stratified soil, some of the laboratory studies has been attempted. The major challenge in the investigation of the stratified soil was to prepare the soil specimen that simulates the exact field conditions. Hence, Townsend and Gay (1964) presented a laboratory method for the preparation of artificial varved clay but did not receive worldwide acceptance. After that, the concept of sedimentation for the stratified soil specimen preparation has been incorporated by Murthy et al. (1976) for the preparation of horizontal, vertical, and inclined stratified specimen. The stratified sample of fine sand and kaolin were prepared and found similar denseness of repeated samples. The sedimentation approach has also been utilized by Nacci and Andrea (1976) followed by consolidation and freezing. The freezing has been done for the convenient extraction of trimmed sample and to maintain its rigidity. The sedimentation (water pluviation) method has problem of segregation in the case of well graded sand, this associated problem has been rectified by Kuerbis and Vaid (1988) by introducing a slurry deposition technique. The slurry deposition method is not only suitable for the preparation of stratified soil, but also found to be suitable for the homogeneous soil. Also, this technique requires (1.5 hrs) less time than that of the sedimentation technique (24 hrs for each layer).

Apart from that, the geotechnical aspect of stratified soil deposit has been reported in terms of shear strength, bearing capacity, consolidation, coefficient of permeability etc. The identification of the real boundary condition of the stratified deposit is a major challenging task. Li et al. (2016) attempted to provide a probabilistic solution of soil stratification by analyzing 26 cone penetration test data which was found to be good agreement with field results. Therefore, it is significant to carry out investigation on the undisturbed sample or sample collected directly from the field (Rowe 1968). Barden and Younan (1969) examined the consolidation behaviour of the layered clayey soil and observed that it is impossible to determine the consolidation rate due to the complexity involved in it and suggested to use very rapid transformation method (approximate solution) for better results. In the same way, Nixon (1973) investigated the consolidation response of permafrost two layered soil profile, the results stated that the surface water has remarkable effect on the consolidation time of beneath layers. The rate of consolidation of layered soil is largely influenced by the equivalent coefficient of permeability. The coefficient of permeability of stratified soil changes significantly when multiple layers are combined having a different individual layer permeability. The study associated with the equivalent coefficient of permeability of two layered deposits has done by Sridharan and Prakash (2002). They have considered seven kinds of soils having permeability from very low to very high, and found that the equivalent permeability of stratified soil has major dominance of permeability of exit layer. The equivalent permeability also depends on the mutual interaction between the layers. This study has been further extended to three layered soils by Prakash and Sridharan (2013) considering same setup and soil. They have observed that the equivalent permeability is a function of the relative position of the layer along with the permeability of individual layer. These studies generally focused on the permeability across the bedding plane whereas the permeability also varies when flow is parallel to the bedding plane. Laskar and Pal (2018) have incorporated the consolidation behaviour of silty sand using horizontal and vertical permeability into the 3D consolidation apparatus. The horizontal permeability was observed to be higher than the vertical permeability.

The shear strength parameters (c & ϕ) of the stratified soil largely affected due to the heterogeneity involved, and these parameters have high dominance on the other parameters related to load carrying capacity, hence need to be determined correctly.

Lo and Milligan (1967) initiated the examination of the shear strength performance of the stratified clays and explained its behaviour using Jaegar's hypothesis for failure considering only one plane as weakest plane. Whereas, the study carried out by Murthy et al. (1980) stated that the shear strength parameters show unique behaviour and not dependent on any independent parameters such as stress path & principal orientation. Saha and Pal (2013) attempted to sandwiched fly ash in between laterite soil and vice-versa, and found maximum shear strength of soil as a middle layer between fly ash. Similar results have been observed by Ronad (2014) for the red soil in between black cotton soil. These shear strength parameters were utilized for the further estimation of safe bearing capacity of the soil. For better understanding of the strip footing on stratified soil, Azam et al. (1991) used a finite element approach which explains that the thickness of the upper layer and strength ratio is the governing factor for the strip footing performance. Khan et al. (2013) recommended to consider 3:1 combination of fly ash and bentonite layered arrangements for suitable application as road embankment. Considering the complexity of laboratory experiments, Misir and Laman (2017) performed a regression analysis on the bearing capacity of circular footing on the layered granular soil and soft clay and given one logarithmic model for the prediction of bearing capacity. Also, to increase the bearing capacity of stratified soil deposit for higher load resistance applications some of the researchers applied reinforcement in the form of geogrid or geotextile (Kumar and Walia 2006; Ullagaddi and Nagaraj 2013). In addition, to minimize the failure of stratified soil, the response of stratified soil subjected to cyclic/moving load has been significantly explored by several researchers (Siddharthan et al. 1993; Khan et al. 2008; Mandal et al. 2012).

Brahma and Mukherjee (2010) compared the equivalent Young's modulus of the layered soil estimated using weighted arithmetic and harmonic mean. The equivalent modulus evaluated from the arithmetic mean was underestimating the immediate settlement as compared to the harmonic mean that ultimately results in the overestimation of bearing capacity. Similarly, Patel et al. (2017) studied about the deformation property (Poission's ratio) of the homogeneous and stratified soil deposit. The results show increment in Poission's ratio with confining pressure and noticed higher dependency on the properties of individual layer rather than its position. A brief literature about the fundamental studies on the stratified soil deposit has been described in Table 2.5.

Table 2.5. Systematic literature about the fundamental studies on the stratified soil deposit.

Authors	Applications	Key findings
Lo and Milligan 1967	Shear strength of stratified soil	• Shear strength of stratified clay is explained using Jaegar hypothesis of failure. • Shear behaviour of stratified soil is different from that of the homogeneous soil.
Murthy et al. 1976	Laboratory preparation of stratified soil	• Sedimentation approach has been followed to extract the horizontal, vertical and inclined samples.
Azam et al. 1991	Strip footing performance on stratified soil	• The footing performance was influence by the thickness of top layer and strength ratio of two layer. • Finite element method has been employed to evaluate its performance.
Sridharan and Prakash 2002	Coefficient of permeability of 2-layer soil	• The permeability of layered soil is not equivalent to the theoretically determined permeability. • Permeability of layered soil is dependent on the thickness of layer, and permeability of the individual layer.
Kumar and Walia 2006	Bearing capacity of footing on reinforced stratified soil	• An approximate method has been developed to estimate the bearing capacity of reinforced soil.
Khan et al. 2008	Resilient modulus of soil-fly ash system	• The deviator stress and cohesion show increasing trend with the increase in the number of cycles. • This layered combination has potential to use as an embankment material.

Brahma and Mukherjee 2010	Equivalent Young's modulus	• For settlement estimation weighted harmonic mean is best suited than that of the weighted arithmetic mean.
Mandal et al. 2012	Dynamic response of foundation on layered soil	• The increase in the thickness of top (stiff) layer results in the increase in resonance frequency of foundation. • Material damping is considered for the analysis.
Prakash and Sridharan 2013	Equivalent coefficient of permeability	• The equivalent permeability of the stratified soil is governed by the permeability of the exit layer. • The relative position of the layer also significantly affects the equivalent permeability.
Patel et al. 2017	Poission's ratio of stratified soil	• The Poission's ratio of the stratified soil is highly dependent on the individual layer property rather than its position. • Poission's ratio is directly proportional to the confining pressure.

2.7 DYNAMIC CHARACTERIZATION STUDIES OF SOIL AND COAL ASH

The dynamic properties of soil determined by using different field and laboratory methods are important for the seismic design of structures. The stiffness, shear modulus, Poisson's ratio, damping characteristics, etc., are essential dynamic properties that influence the propagation of waves in the soil medium. Maintaining the accuracy in the calculation of dynamic soil properties is a challenging job in solving geotechnical earthquake engineering problems (Kramer 1996). All the methods available for the determination of shear modulus are divided into three parts, i.e., larger strain (> 0.1%), small strain (0.1–0.0001%), and very small strain levels (< 0.0001%) (Ingale et al. 2017). Due to the nonlinearity in the stress–strain response of soil, the dynamic characteristics reported by large strain are different as compared to that of the small strain (Ishihara 1996). Previous study revealed that the cyclic shear strain required to initiate liquefaction for an earthquake of Mw = 7.5 is in the range of 0.03–0.3% (Dobry et al. 2015). The various field and laboratory methods like SPT, CPT, cyclic triaxial test, resonant column test, bender element test, etc., are useful in the determination of dynamic characteristics and liquefaction potential of soil. The specific cyclic shear strain ranges of various test/experiments have been shown in Fig. 2.1.

The cyclic strength of cohesionless soil is highly dependent on the sample preparation, compacted density, and prestraining whereas least affected by the sample size, frequency of loading, and friction between the sample caps. Similarly, factors such as lateral confinement, type of loading wave, overconsolidation ratio, and particle size distribution has an intermediate effect (Townsand 1978). The dynamic soil properties of cohesionless materials depend mostly on the void ratio rather than relative density. The non-plastic nature of fly ash causes similar dynamic response as silty soil. However, the tailings possess little plastic behaviour shows higher cyclic strength than that of the fly ash (Yu and Qin 1991). Similar type of observations has been witnessed by Wang and He (1985) and Wang et al. (1987) from the investigation of six sluiced fly ash and also observed high liquefaction susceptibility of the fly ash. The fly ash has the more liquefaction tendency and high damping behaviour as compared to typical soil (Kalinski and Wallace 2011). Boominathan and Hari (2002) attempted to improve the liquefaction resistance of fly ash by reinforcing with randomly distributed fibres (polypropylene geogrid), the results show promising improvement in the liquefaction resistance of the fly ash. The field investigation of coal ash slurry deposit done by Ramaiah et al. (2010) using spectral analysis of surface waves (SASW) observed low shear wave velocity due to the loose dumping condition of the coal ash. Along with the SASW, this study has been extended with multichannel analysis of surface wave (MASW) for the depth profiling of soil, coal ash, and municipal solid waste (MSW) dumping site. The shear wave velocity profile of the MSW site was found comparable with the coal ash deposit and lower than that of the soil (Ramana and Ramaiah 2014). For better simulation of field density in the laboratory, Dingrando et al. (2013) prepared sample using the water pluviation technique, the result shows dilate behaviour with low deformation during cyclic loading. In the same way, considering the devastating effect of the expansive clay, Saride and Dutta (2016) stabilized it using fly ash which improves its shear modulus characteristics and reduces the energy dissipation nature (damping ratio). Chattaraj and Sengupta (2017) examined the influencing factor on which the dynamic behaviour of fly ash depends under medium strain range using resonant column and cyclic triaxial tests. The shear modulus is dependent on the grain size distribution and light weight nature, whereas damping is much dependent on the confining pressure and cyclic shear strain. The fly ash exhibits higher liquefaction and lower damping behavior than that of the sand.

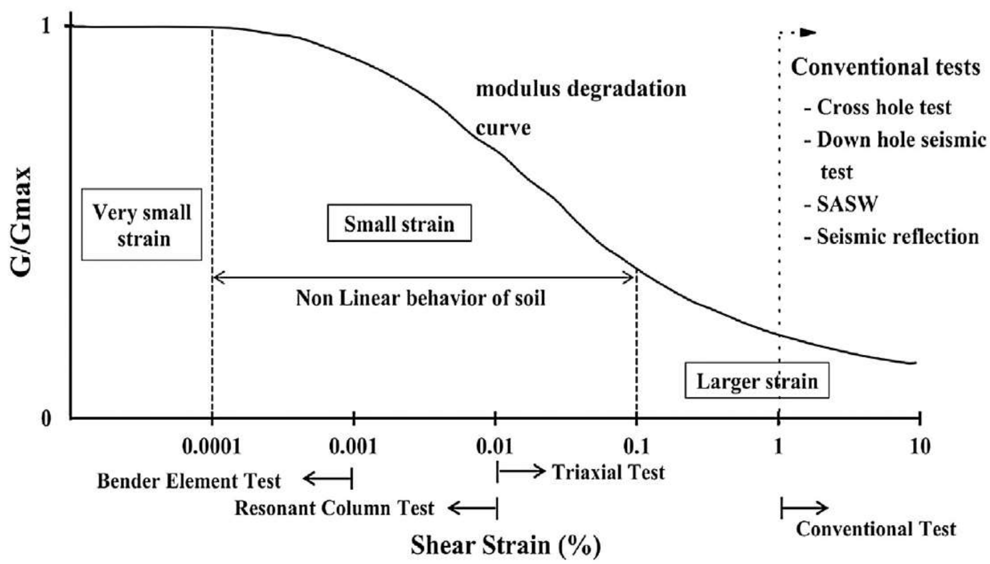

Fig. 2.1. Illustration of cyclic shear strain range of various dynamic tests in normalized modulus reduction curve

The parametric study on the cyclic behaviour of Indian pond ash has been done by Mohanty and Patra (2014) incorporating cyclic triaxial test. Because of the presence of angular particles, the pond ash shows efficient frictional resistance ultimately results in high resistance to liquefaction. The cyclic strength is directly proportional to the confining pressure and inversely proportional to the loading frequency & cyclic shear strain. These pond ash sites have also been explored in their ground response analysis under the excitation of Chamba, Chamoli, Uttarkashi, and Nepal earthquakes (Mohanty and Patra 2018). All the seismic response of the pond ash site was more for Nepal earthquake. To increase the cyclic strength of the pond ash, the geotextile reinforcement has been applied and achieved significant improvement in the cyclic strength & liquefaction potential (Vijayasri et al. 2016). To ease the comparison between the experimental analysis and realistic energy release during a seismic event, the concept of energy dissipation was introduced which was implemented in the case of pond ash (Reddy et al. 2020).

Hardin and Drnevich (1972) carried out model study on the intact and reconstituted cohesive soil & clean sand, and presented the results in the form of equations and graphical plots. Generally, the normalized modulus reduction curve follows decremental trend whereas the damping ratio follows incremental trend with the increase in shear strain. But this decrease and increase in shear modulus and damping ratio were observed to be at a faster rate for the residual soils than that of the sand (Borden et al. 1996). The reduction in shear modulus is due to the separation or slippage of grain to grain contact and because of the generation of excess pore pressure (Vardanega and Bolton 2013). Zhou and Gong (2001) performed stress controlled cyclic triaxial test to get the degradation response of saturated clay. The clay having a higher overconsolidation ratio results in higher resistance to loading and experiences low degradation. Similar results have been noticed by Vucetic and Dobry (1988) in the case of marine clay. Furthermore, Santos and Correia (2000) discussed about the shear modulus under small (10^{-6} to 10^{-2}) to large strain ($>10^{-2}$) condition. The results indicate that loading frequency and number of cycles are not much significant under small strain condition. Mojezi et al. (2016) studied the dynamic behavior of the unsaturated kaolin soil through suction controlled cyclic triaxial device, and observed increasing trend of shear modulus with the increase in loading frequency that is in the reverse trend as observed by the past researchers. Since, the determination of dynamic soil parameters involves complex equipments and time taking process, L'Heureux and Long (2017) established correlations between shear wave velocity and geotechnical parameters estimated from the various sites of Norwegian clay. Similarly, some of the researchers have attempted to determine the dynamic response of sand mixed with rubber and sawdust (Anastasiadis et al. 2011 and Pan et al. 2019). The rubber has been added in the range 0 to 35% in the sand and exhibits very high damping behavior. However, the mixture of sand-sawdust shows a hysteresis loop shift from symmetrical (willow leaf) to asymmetrical (sharp leaf). They also observed a decrease in dynamic parameters with the increase in sawdust.

The sandy soil normally contains a wide range of particle size and also has an influence of particle uniformity, percentage of fine content, and classification in the dynamic soil properties which was first studied by Iwasaki and Tatsuoka (1977). From the outcomes, this can be concluded that the uniformity coefficient and fine content has negative impact on the shear modulus and negligible impact on the damping ratio of sand. The resonant column test was popular for the dynamic tests, but it is limited to small strain ranges. The increase in the frequency of occurrence of seismic events results in the increase demand of dynamic study especially in the large strain range. Therefore, Kokusho (1980) focused to eliminate the disadvantage associated with cyclic triaxial test to work in the large strain condition (10^{-6} to 10^{-3}) for Toyoura sand. Similar type of study on Brahmaputra sand has been done by Kumar et al. (2017) which shows a decremental trend of damping ratio after 0.75% shear strain. Dammala et al. (2017) has also investigated the dynamic behaviour of Brahmaputra sand and emphasized the use of dynamic soil properties for the seismic ground response analysis that would be helpful for safe design of geotechnical/other structures. From the experimental study, Stokoe et al. (2004) developed the normalized modulus reduction and damping profile for all types of soil using a modified hyperbolic model which was originally given by Hardin and Drnevich (1972). Sitharam et al. (2004) investigated the cyclic behaviour of Ahmedabad sand and found significant variation in the dynamic properties between strain range of 0.053 to 0.5%. This study has been extended for Ahmedabad, Bhuj, and Assam sand to understand the pore water pressure generation under cyclic loading condition (Sitharam and Govindaraju 2007). They observed that the frequency of loading has no effect on the pore pressure development. Whereas Zhang et al. (2019) observed a higher number of cycles for the failure of saturated sand when subjected to high vibration frequency. Ghayoomi et al. (2017) incorporated the concept of suction pressure in the unsaturated clean sand which experiences the increase in shear modulus than that of the dry and saturated condition due to the suction irrespective of the shear strain level. Chakraborty et al. (2020) accessed the effect of saturation on the dynamic properties of sand, the results depict that because of the presence of higher void in the fine-grained soil it gets more affected upon saturation than that of the coarse-grained soil. Similarly, Das and Chakrabortty (2022) determined the influence of the shape of the hysteresis loop in the damping ratio of sand. They stated that the symmetrical method underestimates the damping ratio of sand as compared to that of the asymmetrical one and also witnessed greater influence of shear strain rather than effective confining pressure and frequency of loading.

2.8 DYNAMIC CHARACTERIZATION STUDIES OF STRATIFIED SOIL-ASH DEPOSITS

Past studies, mostly examined the liquefaction potential/dynamic properties of reconstituted homogeneous samples and two mixed coal ash materials (Jakka et al. 2010; Liao et al. 2012; Yoshimoto et al. 2014; Mohanty and Patra 2016; Chattaraj and Sengupta 2017; Reddy et al. 2020). Layered/stratified soil structures generally exist in the form of tailings dams, alluvial and hydraulic fill deposits, foundations of buildings, sedimentary strata, lacustrine, marine deposits, and pavement subgrade layers (Amini and Chakravrty 2004; Xiu et al. 2020). The use of dynamic properties/liquefaction potential evaluated from the homogeneous soil for stratified deposits may lead to erroneous results (or may overestimate/underestimate). The liquefaction mechanism of the stratified deposit is significantly different than that of a homogeneous deposit, which has been properly explained by Fiegel and Kutter (1994) by employing the centrifuge model test. It has been observed from the model test that an apparent water gap was generated between two layered soils during liquefaction. Due to the increase in pore pressure, the apparent water at the interface develops the tendency to counterbalance the overburden pressure. This results in zero effective stress condition that ultimately fails the overlying layer and high-velocity flow occurs. Many researchers focused on the liquefaction characteristics of sand-silt-gravel composite, stratified silty sands, Ottawa sand-silica silt, sand-gravel composite, segregated sand particle's stratification, a stratification of coarse and fine sand, etc. (Amini and Sama 1999; Amini and Qi 2000; Konrad and Dubeau 2003; Amini and Chakravrty 2004; Yoshimine and Koike 2005; Xiu et al. 2020). Also, a brief summary of the past literature on the dynamic studies of stratified soil deposits has been listed in Table 2.6. Amini and Sama (1999) and Amini and Qi (2000) investigated the liquefaction behavior of the uniform and layered coarse-grained soil under a stress-controlled cyclic triaxial test. The results demonstrate that the liquefaction resistance of both the arrangements are not substantially different and also observed an increase in liquefaction resistance with the increase in silt content. Evans and Zhou (1995) have also observed the same increment in liquefaction resistance with the increment in gravel content. Amini and Chakravrty (2004) examined the different sample preparation techniques and did not observe a significant difference in cyclic strength. And found some contradictory results of the decrease in the liquefaction resistance with the increment of confining pressure. The stratification of the sand particles due to their segregation has a significant effect on the resistance to liquefaction because of the dilative behavior (Yoshimine and Koike 2005). Xiu et al. (2020) performed strain controlled cyclic triaxial test on the uniform sand and stratified sand under the inclusion of powdery sand. The results show that the powdered interlayer obstructs the pore water pressure transmission and this will accelerate or retard the liquefaction process. The undisturbed specimens usually show better resistance to liquefaction than that of the remolded specimen (Yoshimine and Koike 2005).

From the above-mentioned literature, this can be concluded that most of the research is focused on the liquefaction study of stratified sandy materials and limited research has been carried out considering the stratification of waste materials and their dynamic properties. Furthermore, the specimen preparation techniques used in the past studies were cumbersome and time-consuming, which can be eliminated by employing the simple technique known as moist tamping technique. Apart from that, past studies are associated with a limited number of variables (e.g., single loading frequency) that can be seen in Table 2.6. In addition, these samples were subjected to a very narrow shear strain during cyclic loading. Furthermore, the dynamic characteristics, particularly the shear modulus and damping behavior of the stratified soil deposit is different from that of the homogeneous soil deposit; therefore, it is significant to investigate the dynamic characteristics of the stratified soil-ash deposit for the safe design of geotechnical structures resting on it.

Table 2.6. Summary of the past literature associated with stratified/layered deposit.

Source	Soil type	Preparation method	Parameters		Key findings
			f	σ_c'	
Ishihara et al. 1980	Tailing materials	• Pluvial spreading through air • Pluvial spreading through air with tapping • Pluvial spreading through air with vibratory compaction	1 Hz	50 or 100 kPa	Non-plastic fine tailing shows lower strength than that of the plastic tailing having PI: 15 to 20.
Fiegel and Kutter 1994	Layered Silt and Sand	• Dry pluviation through air (Centrifuge model tests)	1 Hz	-	The development of pore pressure in layered soil deposits differs from the generation of pore pressure in the uniform soil deposits.
Amini and Sama 1999	Stratified sand-silt-gravel	• Moist tamping (Homogeneous) • Sedimentation (Stratified)	-	100 kPa	For both uniform and stratified soil conditions, increasing the silt content increases the liquefaction resistance of the sand-silt-gravel combinations.
Amini and Qi 2000	Stratified silty sands	• Moist tamping • Wet pluviation	-	50 to 250 kPa	The sample prepared for the uniform and stratified soil shows dissimilar soil fabric but that results in insignificant variation in the liquefaction resistance.
Konrad and Dubeau 2003	Stratified Sand-silt	• Pluviation under water	0.2 Hz	100 kPa	Layering caused a substantially lower cycle resistance than either of the materials in the undrained cyclic triaxial testing on stratified sand-silt samples.
Amini and Chakravrty 2004	Layered Sand-Gravel	• Pluviation through air (Homogeneous) • Wet Pluviation (Layered soil)	-	50 to 250 kPa	For both homogeneous and layered sand-gravel composite, the liquefaction resistance decreases with the increase in confining pressure.

Yoshimine and Koike 2005	Stratificaton of clean due to segregation	• Air Pluviation method	0.1 Hz	100 kPa	Under the same modified relative density, the uniformly deposited material express lower resistance to liquefaction than that of the stratified one.
Xiu et al. 2020	Fine and powdery sandy particles	• Soil sedimentation	1 Hz	50 kPa	The thickness of the powdery interlayer has a nonlinear relationship with the cyclic loading necessary for liquefaction.

Note: **f** – Frequency, **σ_c'** **-** Effective confining pressure

2.9 PAVEMENT APPLICATION ASPECT

The application of coal ash in flexible and rigid pavement layers are very popular as stabilizing agent. In past studies, initially the focus was to use coal ash as stabilizing material but gradually the focus has shifted to the implementation of coal ash as replacement of base, subbase or subgrade layer with or without optimum treatment. Some of these studies those are related to pavement applications are listed in the subsequent section.

Osinubi and Edeh (2011) investigated the compaction and California bearing ratio characteristics of reclaimed asphalt pavement stabilized with reconstituted coal ash. From the experimental observations, they have recommended to consider the combination of 40% coal ash (fly ash + bottom ash) + 60% RAP and 10% coal ash + 90% RAP for the use of subbase or subgrade applications. Similarly, Lopes et al. (2012) assessed the applicability of fly ash and bottom ash with lime for the stabilization of sandy silty soil in pavement base application. The results indicate that the stabilized samples show improvement in resilient modulus after curing. Gill et al. (2013) performs the model testing of footing resting on geosynthetic-reinforced coal ash slope. The testing observations reported a significant enhancement of strength and stability when the slope was reinforced with three reinforcing layers. Lee and Fishman (1993) experimentally examined the performance of fine grained soil (aggregate waste) treated with fly ash as highway material in flexible pavement. The load resistance performance confirms its suitability as subgrade material for flexible pavement. Similar type of improvement study has been carried out by Jackson et al. (2007) to stabilize sand using fly ash and bed ash. Along with the experimental study they conducted field performance investigation and concluded that these byproducts are environmentally friendly & technically sound for road construction applications. Zimar et al. (2022) reviewed the application studies of pavement subgrade stabilization of problematic soil (expansive/organic soil) using coal fly ash. After analyzing all these studies this can be suggest that the soil shows improvement in unconfined compressive strength (UCS), California bearing ratio (CBR), and resilient modulus (Mr) with the addition of 15% class C fly ash when kept for 7 days for curing. In the same way, Li et al. (2009) evaluated these parameters (UCS, CBR, Mr) of stabilized soft clay soil using all types of fly ash for base layer application of flexible and rigid pavement. The outcomes show ten times enhancement of CBR and twice enhancement of UCS and Mr compared with strength of soft soil alone. Kumar et al. (2022) also treated the expansive soil with coal ash and found significant improvement in fundamental properties by mixing 10% of coal ash. Alami et al. (2019) considered sand and bottom ash mixture treated with lime and found promising results for 4% replacement of lime as optimum. Tiwari et al. (2021) also observed significant improvement in strength of expansive soil stabilized with bottom ash and coir fibers and recommended for road pavement applications.

Mohammed et al. (2021) analyzed the use of coal bottom ash in construction industry and found to have high potential to offer as alternative of aggregates that will reduces the depletion of natural resources. Nu et al. (2019) explored the sustainable pavement application of coal bottom ash with cement as binding material. The bottom ash performance best suited with 11% cement addition in the application of base and subbase. However, Thi et al. (2021) observed various combinations which is qualified for base course such as bottom ash + 11% Cement, coarse aggregates + 20% fly ash + 3% cement, and local soil + 10% fly ash + 5% cement. Similar type of observations has been witnessed by Wiranata et al. (2022) for coal ash cement stabilized material for base applications. Mogili et al. (2020) investigated the mechanical strength characteristics of pond ash reinforced with randomly distributed polypropylene fibers. The improvement of CBR and Mr values were observed upto 1% fiber content and thereafter it reduces. Sarkar and Dawson (2015) evaluates the economic assessment of pond ash in pavement's subbase applications in comparison with conventional materials. The study finds that stabilizing coal ash with 2% lime might result in an ideal material, and even though a thicker layer might be needed to deliver the same pavement performance, direct cost savings of about 10% may be realized in addition to less easily quantifiable environmental advantages.

The majority of research investigations are oriented towards stabilization of problematic soils using various types of coal ash. There exists very limited study on consideration of coal ash materials as single material for pavement layer replacement with further improvement using geosynthetic materials.

2.10 SUMMARY

The concise summary regarding the aforementioned studies on the homogeneous and stratified soil and soil-ash deposit has been illustrated in this section. The tracking of the generation of coal ash initiated in India since 1990 and also maintained the record of the percentage of coal ash utilization in different areas of Civil engineering.

According to the central electricity authority record, in India the amount of fly ash produced over a period of 25-year is approximately 3335.9 MT, of which only 55% (1834.83 MT) have been used and the remaining 45% (1501 MT) is still in their unutilized form. These coal ashes generally possess a hazardous compound that has higher possibility to contaminate the surface or sub-surface water bodies. In addition, there are several problems associated with the coal ash are respiratory issues, harmful to human health, it requires huge amount of land for its disposal for further use, affect the biodiversity near to disposal, contaminates the soil. Considering all the above challenges it is significantly important to focus on the solution, this will only possible when its physical and chemical characteristics is known along with its static and dynamic load transfer behaviour. Therefore, in order to contribute towards the solution, previous researchers have done extensive study on the coal ash and soil that has been briefly discussed in this chapter and summarized as follows:

- The researchers started with the fundamental characterization of coal ash, so that its type or classification, its pozzolanic properties, shape of the particles, chemical constituents can be determined. These fundamental characterizations help in the selection of coal ash in its applications. For example, high pozzolanic fly ash would be prefer for the application in cement or for the production of concrete.
- After that, researchers focused on the geotechnical properties of the coal ash for successful application in the field. From this characterization, the composition of various particle sizes (sand, silt, clay), the degree of compaction (MDD and OMC), its permeability behaviour, non-plastic nature can be predicted. Also, the important parameter like cohesion and angle of internal friction has been determined for bearing capacity and slope stability analysis. From consolidation analysis, the primary consolidation/settlement behaviour can be predicted prior to construction.

The researchers extensively explored the geotechnical investigation of different coal ash so that it will be easy to achieve the desired properties at the desired point of time.

- Similarly, most of the researchers also attempted to stabilize the problematic soil such as expansive soil, high clay content soil, collapsible soil, black cotton soil, loess, lateritic soil, marine clay, and soft soil utilizing coal ash especially fly ash and bottom ash. Coal ash being the non-plastic nature reduces the swelling and shrinkage potential of the problematic soil and also helps in the improvement of its maximum dry density, CBR value, shear strength parameters. These studies have widened the application scope of coal ash that ultimately reduces the existing dumped ashes.
- In the geotechnical exploration of stratified soil, the researchers were mostly targeted to evaluate its stratified properties, e.g., equivalent Young's modulus, equivalent coefficient of permeability, equivalent shear strength parameters etc. Since, the stratified soil has different load transfer behaviour as compared to that of the homogeneous soil, therefore it is essential to investigate the equivalent property of the layered deposit. Also, it was observed considerable difference between the equivalent property determined in the laboratory and theoretically estimated. The application of waste materials usually accomplished in layered form of particular thickness.
- Sufficient experimental dynamic investigation has been done by previous researchers on coal ash, clayey soil, and sandy soil. Maximum independent variables (relative density, shear strain, loading frequency, effective confining pressure) have been incorporated in the wide shear strain range conditions by researchers. The influence of these variables was used to determine the dynamic

shear modulus and damping ratio of soil. The researchers also developed multiple models from the experimental data that can be used to predict the dynamic behaviour in the absence of experimental data. In addition, many researchers have performed ground response analysis of the coal ash and soil using the dynamic properties obtained from the laboratory.

- From the dynamic experimental studies of the stratified soil deposit, this can be deduced that the researchers precisely focused on the liquefaction study of the sand or silty soil deposit. And also considered water pluviation technique or sedimentation followed by consolidation technique for the laboratory sample preparations which takes much time to prepare. Every dynamic past study on the stratified soil considered limited independent variables that too only frequency and effective confining pressure. Furthermore, very limited research is available considering stratified soil deposit that has been tested under narrow shearing strain range.

From the above discussion, this can be concluded that a very large number of studies are available corresponding to the fundamental and geotechnical characterization of homogeneous and stratified soil deposit. Similarly, sufficient investigation on the determination of dynamic soil parameter has been done considering the small strain (Bender element or Resonant column) and large strain (Cyclic triaxial) experimental setup. But very limited dynamic studies are available on the stratified soil-ash deposit. All dynamic studies focused on the liquefaction susceptibility of the stratified sandy and silty soil deposit with a limited number of independent variables. Since, the implementation of waste material is usually done in multiple layers and for safe/sustainable application of these materials need prior examination in all aspect.

Whereas none of the researchers have attempted to explore the dynamic behaviour and liquefaction susceptibility of the stratified soil-ash deposits. This research gap motivates for the present study in which a homogeneous and stratified soil-ash arrangement has been considered under the influence of all the independent variables for wide shear strain condition.