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Research Article

Engineering Behavior of Municipal Solid Waste Incinerated Ash with Compressible Soil: An Approach Towards the Waste Utilization & Stabilization of Compressible Soil

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ABSTRACT

The objective of the current study is to improve the strength and drainage capabilities of compressible clayey soil through the utilization of waste-to-energy plant ash. Numerous experiments, including consistency limits tests, compaction tests, unconfined compressive strength, California bearing ratio tests, and permeability tests, have been carried out in the laboratory on various combinations of highly compressible clayey soil and waste-to-energy plant ash or Municipal solid waste incinerated ash. The trial testing results show that adding waste to energy plant ash mix with the soil sample improves the strength properties of clayey soil, reducing the issue of ash dumping as well as developing a healthy environment. According to the test results, the falling head permeability test shows an improvement of permeability from 6.2×10^{-6} to 5.85×10^{-5} cm/sec for soil and soil with 20% MSWI ash mixed proportion respectively. Moreover, the mix produced by adding incineration plant ash may effectively be used as a sub-grade material, achieving cost-effective benefits. The findings showed that adding an adequate amount of bottom ash (20%) and soil sample (80%) made the soil more effective as a subgrade material by decreasing the value of differential free swell and consistency limitations of the soil and the value of UCS increased by more than 146 % and the soaked CBR values increased by 118% was noticed. The leaching test showed that when up to 20% of the ash is combined with the soil, the concentration of heavy metals lies within acceptable limits.

1. Introduction

Municipal solid waste (MSW) management is a concern for both developed and developing countries in terms of the environment and the economy. Due to human action, substantial amounts of MSW are produced every day; therefore, it is essential to manage this amount of waste without affecting the environment. Waste from local municipal collection units is disposed of in landfills after passing through a number of stages [1]. Instead of landfills, incineration of municipal waste is a great strategy to reduce the amount of waste, and the ashes of that waste can be used for various purposes. The incineration of these high-calorie waste components may possess a major role in resource preservation. As a result, developing countries build waste-to-energy facilities that handle the MSW waste and transform it into electricity to satisfy energy needs. Waste-to-energy plants are being suggested in order to achieve waste management

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targets while maintaining conventional energy generation methods [2, 3]. Electricity is produced during the incineration of MSW at the waste-to-energy plant, and significant by-products like fly ash (FA), bottom ash (BA), and fume gases are carefully collected and handled. There are a variety of methods and technologies used to immobilize these residuals [4]. MSWI ash is the residue left behind after municipal solid waste (household waste) is incinerated at waste-to-energy facilities. The incineration process reduces the volume of waste and generates ash, which typically contains various metals and other chemical compounds that were present in the original waste [5]. The generated fly ash may be utilized in a variety of applications as a main raw material, and the bottom ash from incinerators (IBA) is frequently consumed after hydrometallurgical treatment or utilized in the manufacture of cement. However, a significant proportion of this residue is still transferred to land [6].

Incineration is a waste disposal management method by which renewable energy is obtained, and many beneficial works like power generation can be done with this energy. After the incineration process, the volume of solid waste is reduced by 70 to 90 percent of its original volume [7, 8]. In India, massive amounts of municipal solid waste (MSW) are handled through incineration in major cities like Delhi to reduce the amount of waste that enters sanitary landfills [9]. Bottom ash may be utilized in applications for civil engineering, but fly ash is usually classified as harmful in many nations [10]. However, due to a lack of scientific research and a lack of a national regulatory system managing their reuse in India, these wastes are currently disposed of in open dumps, and mining pits [11]. India has controlled sand and gravel mining because of growing environmental worries [12]. Research on the feasibility of utilizing bottom ash to enhance the engineering properties of dune sands was done in 2012 by Mohamedzein et al. [13]. The country's 2018 Sustainable Development Goals (SDGs) would be strengthened and an alternative to traditional aggregates would be offered by employing incinerator bottom ash (IBA) as a replacement for natural aggregates.

Compressible soils generally have a significant amount of inherent shear strength due to the cohesive forces between particles. The shear strength of compressible soils is influenced by factors such as moisture content, effective stress, and soil structure. The strength properties of compressible soils are commonly determined through laboratory tests, including the direct shear test and triaxial shear test. The low shear strength and high compressibility of soil can reduce their bearing capacity, making them unsuitable for heavy structures without appropriate engineering solutions [14]. Compressible soils have a high plasticity index, which means they have a significant range of moisture content where they exhibit plastic behavior. This plastic behavior is characterized by the soil's ability to undergo deformation and retain its shape when subjected to external forces. Plasticity is typically determined using tests such as the Atterberg limits, which include the liquid limit (LL), plastic limit (PL), and shrinkage limit (SL). Soil compaction is a process of removing the air from the soil mass.

1.1. Geotechnical Behavior

When the amount of water in the compressible clayey soil changes, the volume of the soil starts to change, as a result of which cracks appear on the structures built on this soil. Due to the limited availability of good soil and growth in construction, it is essential to develop certain methods to ensure such soils can be utilized in foundations. The past several decades has seen the development of numerous techniques, such as soil stabilization, driven piles, drilled shafts, or helical piles, Vibro-compaction or dynamic compaction, Geosynthetic Reinforcement, etc. [15]. Soil stabilization is the process of improving the properties of the original soil to enhance its engineering performance and stability by using chemical, mechanical, electro-chemical, and Geosynthetic processes [16]. Several previous studies demonstrated the effectiveness of lime and cement as conventional soil stabilizers. The major drawback of cement and lime is their higher cost, making it unable to use them widely. The accuracy of the sensitivity analyses conducted on various soils using various materials was examined [17]. The swelling and shrinkage behavior of expansive soils may be reduced by MSWI ash [18]. Research has examined the resilience and long-term stability of soil-ash mixes, taking aging, weathering, and degradation into account [19].

The generation of waste from multiple sources has increased extensively as a result of global population growth, and environmentalists around the world are quite concerned about how to properly dispose of this waste. In the last few years, waste materials have been used for soil stabilization. Various waste materials, such as fly ash (FA), granulated blast furnace slag (GGBFS), rice husk ash (RHA), cement kiln dust (CKD), Quarry dust, demolished waste, etc. have been used in numerous research [15], [20-23]. The leaching behavior of contaminants from MSWI ash and their potential impact on groundwater quality has been included [24].

1.2. Environmental Considerations

The utilization of MSWI ash as a soil stabilizer raises environmental considerations related to its potential impact.

According to CPCB Annual Report 2020-21, the total solid waste production in the country of India is 160038.9 tons per day (TPD), out of which 152749.5 tons per day is collected at a collection rate of 95.4% and 50% is treated, 18.4% is dumped, and 31.6% of the total waste is unaccounted for [9]. Landfill MSW contaminates the soil and groundwater. Numerous municipal solid waste (MSW) are produced in metropolitan areas due to the fast expansion of the urban population, which makes it a very difficult task to dispose of waste produced from various sources. It has been demonstrated in the past that using MSWI ash to enhance the geotechnical characteristics of soils is successful [25]. MSWI ash may help to raise shear strength parameters, which will enhance the stability and load-bearing capability of stabilized soils [26]. The consolidation features and settling behavior of cohesive soils may be affected by the addition of MSWI ash. The immobilization of heavy metals in soils can be facilitated by the presence of certain minerals in MSWI ash [27].

It is common practice to use waste material to stabilize soil, and several studies have been conducted to increase the strength and mechanical behavior of compressible clayey soil using fly ash, rice husk ash, cement kiln dust, and other waste material [28].

The main objective of this investigation is to find out the compressible clayey soil's geotechnical characteristics after adding MSWI ash to the soil. Moreover, to identify the best suitable proportion of MSWI ash with soil in the aspect of soil stabilization. Mineralogy studies by X-ray diffraction (XRD) analysis for soil and soil-MSWI ash mix were conducted and analyzed. The leaching behavior of stabilized compressible soil is another focus of this investigation, and the outcomes are compared with acceptable limits.

2. Materials and Methodology

2.1. Soil

Cohesive soils, particularly expansive clays, have the tendency to swell when wet and shrink when dry. This volume change can exert significant pressure on structures and cause damage. The magnitude of swelling and shrinkage depends on the clay mineralogy, moisture content variations, and the presence of chemical compounds that affect the soil's behavior. Soil sample has swelling and shrinkage values in high amounts. Geocell and jute fiber are used to reinforce clayey soil, and the swelling behavior of reinforced soil is investigated. The optimum fiber content is found at 0.80% of the 40-mm length, at which the swelling potential is minimal [29].

Soil has been collected from Gorakhpur Ramgarh Tal area for soil sampling and the physical characteristics of the soil were known. The soil sample was subjected to testing for the following parameters: grain size distribution, Atterberg limits (liquid limit, plastic limit), specific gravity, UCS, CBR, etc.

The grain size analysis was conducted using the sieve and sedimentation method in accordance with ASTM D2487-17 standards [30], and it was found from the grain size distribution curve that the soil has intermediate plasticity (CI) and is active since its activity value is 1.23. Several physical characteristics of soil are mentioned in Table 1.

Compressible clayey soils exhibit unique geotechnical properties due to their cohesive nature. Here are some key geotechnical properties associated with soils. The plastic limit of the soil sample taken has been found to be 23.16%, the liquid limit is 49%, and the plasticity index is 25.84%.

Table 1. Physical and index Properties of soil

Engineering properties	Representation	Value
Specific gravity	G	2.63
Water content	w	31.56%
Percentage of soil particles Less than 75-microns	-	58.33%
pH of soil		7.65
Liquid limit (LL)	W_L	49%
Plastic limit (PL)	W_P	23.16%
Plasticity index (PI)	I_P	25.84%
Free swell index	FI	65%
Soil classification	CI	Clay of medium plasticity
UCS value	-	245.32 KPa
Soaked CBR value	-	4.24%
Consistency index	I_C	0.674

2.2. Municipal Solid Waste Incinerated Ash (MSWI Ash)

2.2.1. Physical and Index Properties of MSWI Ash

The sample of MSWI ash was collected from the MSW incineration plant in Okhla, New Delhi. After being oven-dried at 110 ± 5 °C, the collected ash sample is screened through a 4.75-mm IS sieve. Whole ash samples were then placed in an airtight container that will be used thereafter. The physical and index properties of MSWI ash are presented in Table 2. According to fine sieve analysis as per ASTM D6913/D6913M-17 (2017) "Methods of Test for Soils: Grain Size Analysis" [31]. The majority of MSWI ash consists of medium to fine sand particles and the soil used is in the category of intermediate plasticity (CI). The particle size distribution of the soil and MSWI ash is shown in Figure 1.

Table 2. Physical and Index properties of MSWI ash

Sr. No.	MSWI ash Property	Value
1	Color	Grey
2	Shape	Sub-rounded/ Rounded
3	Natural water content	23.98%
4	Specific Gravity	2.13
5	Ash particles greater than 4.75 mm in %	0
6	Ash particles between 4.75 mm to 0.075 mm in %	96.40 %
7	Ash Particles less than 0.075 mm in %	3.6 %
8	Liquid limit (LL)	28.50%
9	Plastic limit (PL)	NA
10	Coefficient of Curvature (Cc)	1.06
11	Coefficient of Uniformity (Cu)	7.36
12	ASTM – Classification	Medium to fine sand
13	Optimum Moisture Content (OMC)	16.00 %
14	Maximum Dry Density (MDD)	14.425 KN/m^3

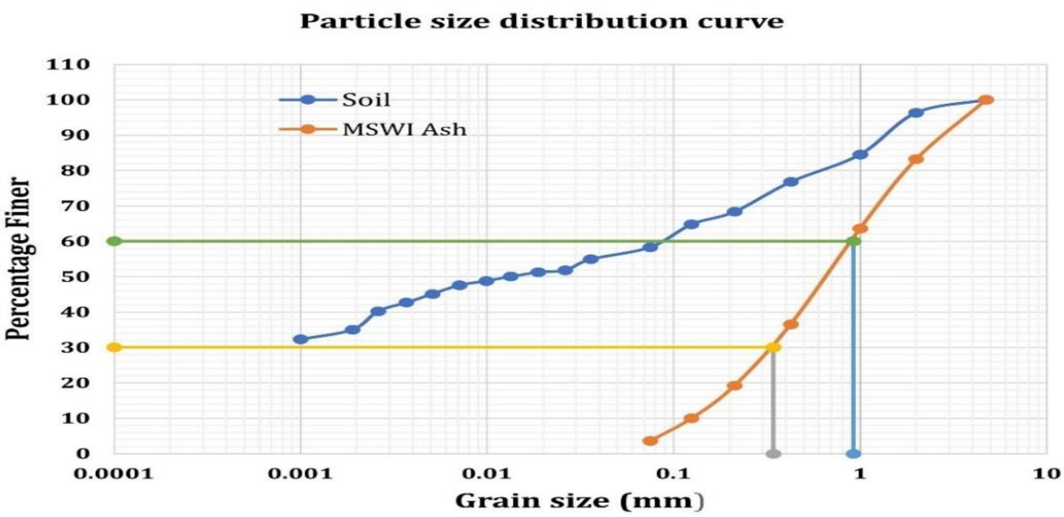

Fig. 1. Particle size distribution curve of Soil and MSWI Ash

2.2.2 Physicochemical Characteristics

MSWI ash exhibits distinct chemical and physical properties that can influence the performance of soil as a soil stabilizer. The chemical composition of MSWI ash typically contains oxides of silica, alumina, calcium, iron, and other elements [32]. The physical properties of MSWI ash like particle size, shape, porosity, and specific gravity affect the engineering behavior of soil. The geotechnical properties of MSWI ash are OMC, MDD, bulk density, shear strength, unconfined compressive strength, compressibility, and permeability have been investigated. MSWI ash is typically composed of fine particles, with particle sizes ranging from 0.1 to 5 mm. MSWI ash has a bulk density of 5 to 1.5 KN/m^3 and has a low shear strength, typically ranging from 0.1 to 0.5 kPa. MSWI ash is highly compressible, with a coefficient of compressibility ranging from 0.1 to 0.5. MSWI ash has a low permeability, typically ranging from 10^{-7} to 10^{-9} cm/sec [33].

2.3. Combination of Soil and MSWI Ash Admixture

Table 3 shows the different combinations of soil and soil-ash mixture.

Table 3. Combination of soil & MSWI ash mixes with identification

Combinations	Identification
100% soil	100 S/ 0 MSWIA
97.5% soil + 2.5% MSWI ash	97.5 S/ 2.5MSWIA
95% soil + 5% MSWI ash	95 S/ 5 MSWIA
90% soil + 10% MSWI ash	90 S/ 10 MSWIA
85% soil + 15% MSWI ash	85 S/ 15 MSWIA
80% soil + 20% MSWI ash	80 S/ 20 MSWIA
75% soil + 25% MSWI ash	75 S/ 25 MSWIA

3. Results and Discussion

3.1. Consistency Limits for Soil-Ash Mixture

Figure 2 shows the consistency limits of soil and MSWI ash mixes. It was found that the plasticity index was decreased with the increase of MSWI ash in the soil. The plasticity index of stabilized soil decreased to 7.25% up to 25% replacement of soil particles by MSWI ash. The rapid decrement in plasticity index up to 80 S/ 20 MSWIA combination and beyond this further addition of MSWI ash results in the marginal decrement in plasticity index. Pozzolanic materials, such as MSWI ash, have a significant impact on soil index characteristics because soil particles form a double layer with ash and reduce the flocculation thickness. The non-plastic behavior of MSWIA is the main cause of the reduction in the plasticity index. The soil particles may experience a strong binding impact with up to an 80 S/20 MSWIA combination, which would reduce their ability to hold water. After the soil reaches its saturation level, further addition of MSWI ash might not significantly reduce the plasticity index. The addition of MSWI ash to the soil led to an increase in the UCS, a decrease in the liquid limit, and a reduction in differential free swell. Previous research also documented the effects of adding MSWI ash and lime to black cotton soil [34].

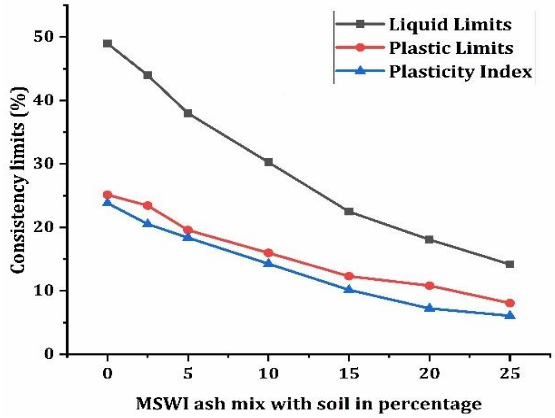

Fig. 2. Consistency limits of soil and MSWI ash mixes

3.2. Compaction Characteristics

Figure 3 shows the change in maximum dry density (MDD) with MSWI ash percentage. OMC and MDD decreased when MSWIA was added to clay in increasing amounts (2.5–25%). The compaction qualities of cohesionless soils can be improved by MSWI ash, leading to a decrease in maximum dry density and an increase in OMC [13]. While adding MSWI ash to the cohesive soil, both dry density and OMC were found to decrease.

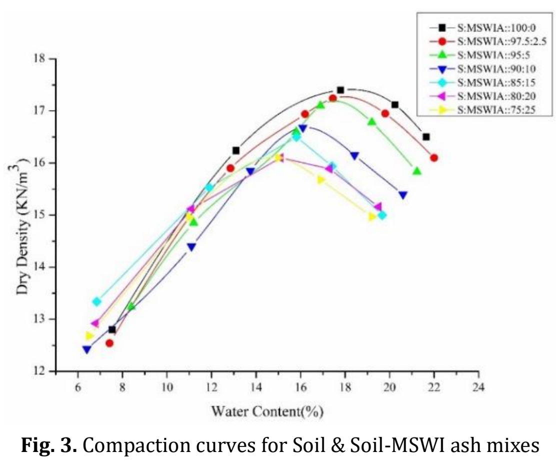

Fig. 3. Compaction curves for Soil & Soil-MSWI ash mixes

Figure 4 demonstrates the changes observed in optimum moisture content (OMC) and maximum dry density (MDD) when soil interacts with various percentages of MSWI ash. It was investigated that the values of optimum moisture content and maximum dry density decreased with an increase in MSWI ash percentages. This pattern was also included in some research. The above activity may happen due to the less specific gravity of MSWI ash as compared to the clay particles and the clustering of clay components during the cation exchange process.

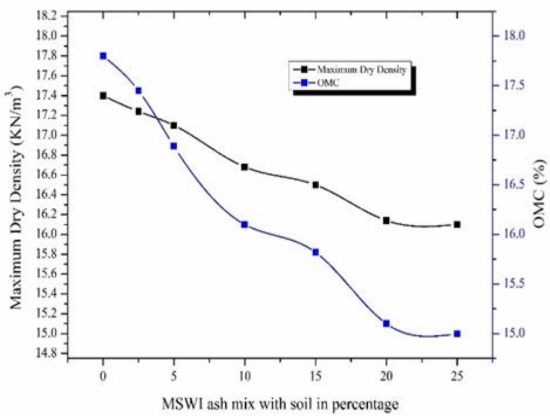

Fig. 4. MDD & OMC values with different combinations of Soil and MSWI ash

3.3. Unconfined Compressive Strength (UCS)

Soil's unconfined compressive strength (UCS) is a measurement of its capacity to bear axial compression without requiring lateral support. A compression testing device is used to perform the unconfined compression test. Figure 5 displays the UCS results with respect to the different percentages of MSWI ash. The UCS value of the Compressible clay soil sample is 245.32 KPa which rises to 292, 350.6, 437.4, 532.6, 604.5, and 624 KPa on adding 2.5, 5.0, 10, 15, 20, and 25 % MSWIA. Clay particles have a net electrical charge, which is typically positive on the ends and negative on the faces [35,36]. Pozzolanic components, including alumina and amorphous silica, are commonly found in MSWIA. When these materials are combined with water and calcium hydroxide, pozzolanic reactions occur. Calcium aluminate hydrate (C-A-H) gel and calcium silicate hydrate (C-S-H) gel are produced during pozzolanic processes [37,38]. The incorporation of MSWI ash into cohesive soils can increase their strength parameters, such as cohesion and angle of internal friction. The treated soil's failure pattern shows brittleness brought on by the development of gel compounds. The amount of void ratio in the compressible soil was lowered by such CSH and CAH compounds. For the analysis of the UCS test, we have to use ASTM D2166/D2166M-16 (2016) [39]. The pozzolanic interaction between compressible soil and MSWIA may be the cause of this behavior.

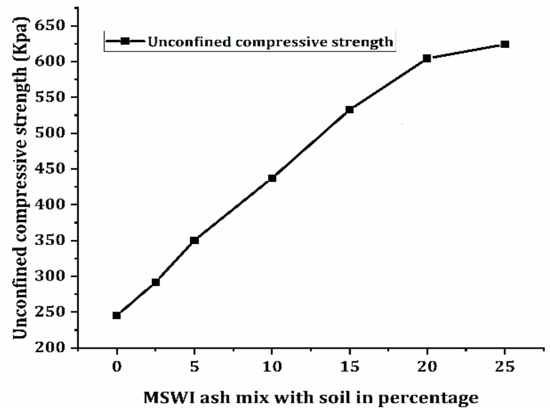

Fig. 5. Graph of the UCS with varying MSWI ash in soil

3.4. California Bearing Ratio (CBR) Test

Figure 6 shows the CBR values in soaked conditions with the different percentages of MSWI ash mixed with the soil. The existence of sufficient calcium, which is necessary for the formation of the main compounds (CSH and CAH) that contribute to strength gain, and these compounds may be the cause of this rise. The CBR results of the soaked sample were found to be the specified results as compared to the CBR value of the unsoaked soil sample. A soil sample was taken for the soaked CBR evaluation, and the soil sample's CBR value was 4.24% after 96 hours of soaking. After adding 20% MSWI ash to the soil sample, the value of soaked CBR becomes 9.26%, which is 118% more than the value of normal soil. The main reason for this increase is due to the addition of the coarse elements of MSWI ash to the elements of the normal soil sample. According to the ASTM D1883–21 (21AD) [40], the obtained CBR value is suitable for use as a sub-grade pavement material.

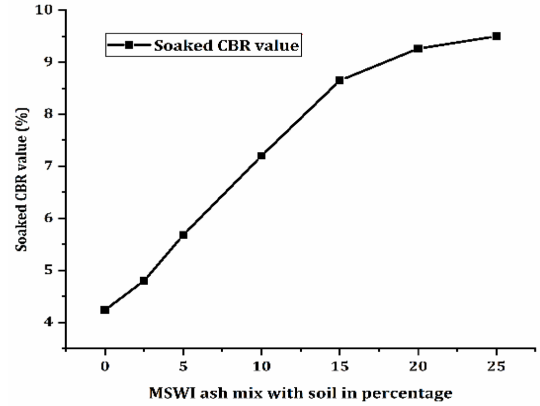

Fig. 6. CBR values for varying MSWI ash in soil

3.5. Permeability and Drainage

Highly compressible soils generally have low permeability due to their fine particle size and compact structure. Due to the low hydraulic conductivity in such soils, the flow of water in the soil is interrupted, but the permeability of the soil is based on many other factors such as soil structure, compaction, and the presence of fissures or cracks [23].

Given soils have low permeability, compressible soil does not allow water to pass through easily. This can result in poor drainage conditions, leading to water accumulation and potential problems such as erosion, stability issues, and the weakening of foundation soils. MSWI ash can modify the hydraulic conductivity and drainage characteristics of cohesive soils. To determine the two separate drainage qualities of clayey soil alone and when combined with MSWI Ash, an ASTM D2434–19-compliant falling head permeability test was conducted (Table 4).

Table 4. Coefficient of permeability with different combinations of Soil and MSWI ash

Combination of materials	Coefficient of permeability (cm/sec)
Soil: 100	$6.2*10^{-6}$
Soil: MSWIA: 97.5: 2.5	$1.12*10^{-5}$
Soil: MSWIA: 95: 5	$3.6*10^{-5}$
Soil: MSWIA: 90:10	$4.5 * 10^{-5}$
Soil: MSWIA: 85:15	$5.08*10^{-5}$
Soil: MSWIA: 80:20	$5.85 * 10^{-5}$

3.6. Leaching Test

Leaching tests are usually conducted to assess the release of certain metals and other substances from the ash under specific conditions, such as acidic or alkaline environments, to simulate potential scenarios in the environment or during waste management practices. There are various leaching test methods used to determine the leaching behavior of MSWI ash and common regulatory standards such as the Toxicity Characteristic Leaching Procedure (TCLP) and the European standard EN 12457 are often employed [42]. These tests measure the concentration of specific elements and substances leaching from the ash over a specific period.

The leaching test value of MSWI ash refers to the number of certain contaminants that can potentially leach out of the ash when it comes into contact with water or other liquid substances. According to EPA SW-846 test method 1311 [43], the leaching of heavy metals from MSWI ash and various soil-ash proportion specimens was evaluated. The study compares the results to the allowable limits as per the USEPA 2016 guidelines and focuses on the leaching behavior of stabilized soil.

Major pollutants found in MSWI ash by leaching tests typically include various metals and metalloids. These pollutants are present in the ash due to their presence in the original waste materials that were incinerated. Major pollutants found in MSWI ash and various soil-ash proportions are presented in Table 5.

When MSWI ash content is added to the soil, heavy metal concentration falls under acceptable limits, up to 20%. If more than 20% of the ash is mixed with the soil, we have found that the concentration of heavy metals in the soil does not fall within acceptable limits.

Table 5. Heavy metals concentration for various soil-ash proportion

Heavy Metals	MSWI Ash (mg/kg)	80% Soil + 20% MSWI Ash (mg/kg)	85% Soil + 15% MSWI Ash (mg/kg)	90% Soil + 10% MSWI Ash (mg/kg)	95% Soil + 5% MSWI Ash (mg/kg)	97.5% Soil + 2.5% MSWI Ash (mg/kg)	Acceptable limits as per USEPA 2016 (mg/kg)
Lead	125.40	1.15	0.9	0.75	0.5	0.28	1.2
Cadmium	24.32	0.42	0.045	0.038	0.02	0.015	0.6
Chromium	22.25	11.5	10.8	9.8	8.2	5.8	15
Nickel	8.6	0.9	0.90	0.75	0.4	0.25	2.0
Arsenic	0.12	0.02	0.02	0.01	0	0	0.05
Mercury	0.02	0	0	0	0	0	0
Barium	400	80	75	68	50	42	140
Chlorides	3.8	2	1.8	1.4	1.2	1.0	2.5
Sulphates	1	0.6	0.5	0.45	0.25	0.20	0.6

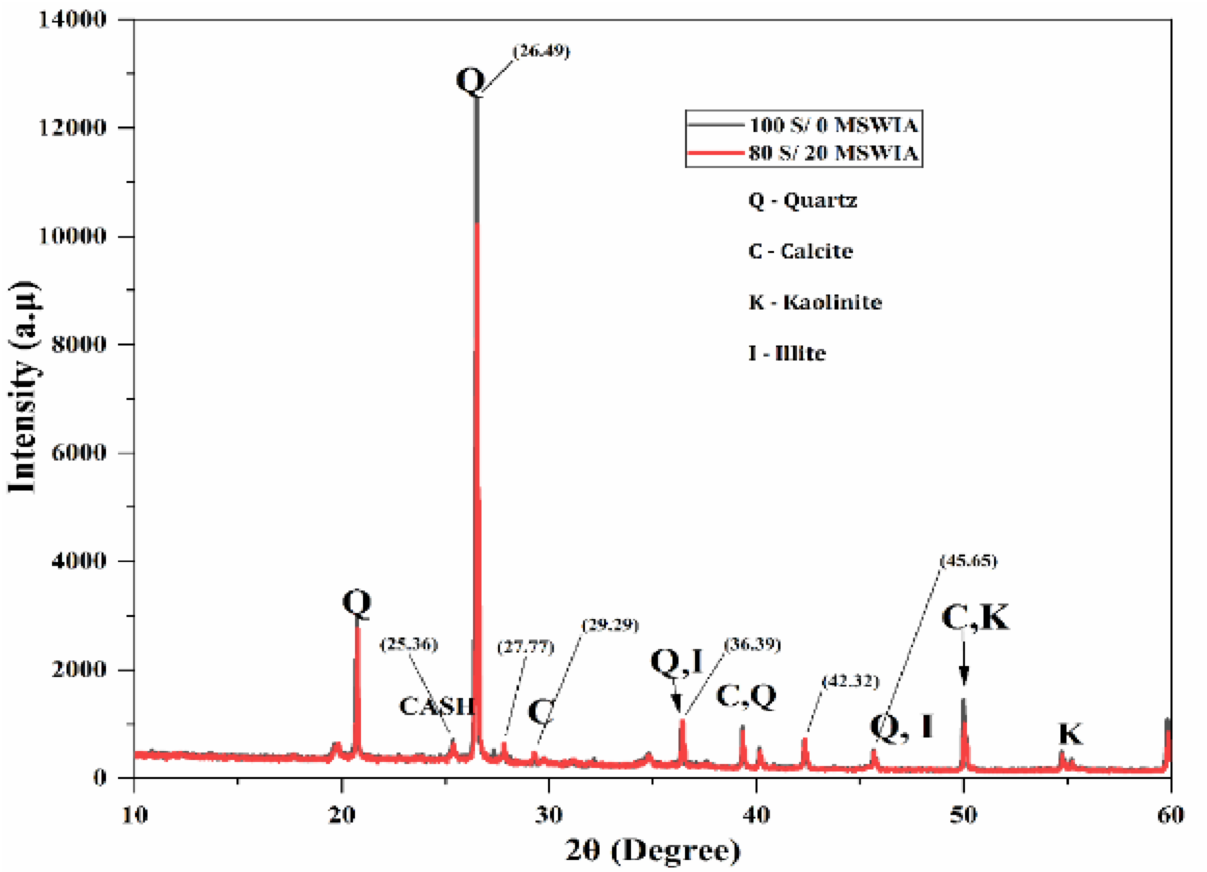

Fig. 7. XRD curves for stabilized soil and natural soil sample

3.7. Effect of MSWI Ash on XRD Study of Compressible Soil

Figure 7 shows the XRD test results for untreated and stabilized compressible clay soil. The predominant minerals found in the soil samples are illite, kaolinite, and quartz. The normal soil sample and the stabilized soil sample both have distinct XRD profile peaks. The decrease in mineral components in the treated soil has led to changes in the peaks of the XRD profile. Two theta-degree angles of stabilized soils indicate the occurrence of C-A-S-H, calcite (CaCO3), and quartz (SiO2) minerals at angles 25.36, 29.29, and 45.65. The presence of calcite in the spectrum of stabilized soil indicates that calcite is present in the soil due to the carbonation process of calcium. Previous studies [44] have reported a similar outcome. This CaCO3 formation reduces the voids and makes them dense in the compressible clay soil sample. The peak intensity has increased at angles 27.77, 42.32, and 36.39 in comparison to the untreated soil sample because larger crystals tend to produce sharper and more intense diffraction peaks.

4. Conclusions

The following findings can be made based on laboratory research done on compressible clayey soil & soil-MSWIA ash mixes.

1. When MSWIA was added to compressible clayey soil, the soil liquid limit and plastic limit were reduced by 60% and 49%, respectively, at a 20% MSWIA concentration. Research indicates that MSWIA is beneficial in enhancing clayey soils' plasticity properties. Adding MSWIA content to clayey soil showed a reduction in the MDD and OMC values. The MDD was found to decrease from 17.4 KN/m^3 to 16 KN/m^3 and the OMC decreased from 17.8% to 15% with the addition of 0 to 20% (by weight).
2. The addition of MSWIA enhanced the compressible clayey soil's unconfined compressive strength value. A stabilized soil sample achieved the highest UCS value at 20% MSWI ash. It was observed that the soil tends to improve the UCS with the addition of MSWI Ash. The UCS value of untreated soil is 245.32KPa and when 20% MSWI is added, the UCS value increases to 604.5 KPa.

3. Through the CBR test, it was found that the CBR value increases when MSWI ash is added to the untreated soil. With the addition of MSWI ash to the untreated soil, the soaked CBR value increased from 4.24% to 9.26%, which is 118% higher than the initial value.
4. When 20% MSWIA was added to compressible clayey soil, the permeability increased from $6.2 * 10^{-6}$ cm/sec to $5.85 * 10^{-5}$ cm/sec. The MSWIA particles have higher permeability of MSWIA in comparison to clayey soil may be the cause of the increase in permeability after adding MSWIA.
5. In the mineralogical study by XRD test, it was found that some peak height of stabilized soil at an angle between 25º and 40º increases, which ensures the formation of C-A-S-H in the treated soil, and also decreases the height of quartz ($CaCO_3$) due to the contribution of MSWI ash and soil.
6. The result of the Toxicity Characteristic Leaching Procedure (TCLP) marks the presence of heavy metals like lead, Chromium, Cadmium, Nickel, Magnesium, Arsenic & Barium and other elements like chlorides and sulphate; in MSWI ash and various soil- MSWI ash mixes. The concentration of the above-mentioned heavy elements and metals increases with the increase of MSWI ash percentage in soil. The concentration of heavy metals and elements in MSWI ash as well as in the combinations of soil and MSWI ash mixes were investigated within the permissible limits as per the USEPA 2016 guidelines.

This research paper provides a comprehensive analysis of the stabilization of compressible clayey soil using MSWI ash. The study's outcomes can guide engineers, researchers, and practitioners in selecting appropriate mix designs and optimizing the use of MSWI ash for highly compressible soil stabilization projects, considering factors such as strength enhancement, durability, and cost-effectiveness. The stabilized soil can be used as a subgrade material in road construction.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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