https://africanjournalofbiomedicalresearch.com/index.php/AJBR
Afr. J. Biomed. Res. Vol. 27(4s) (November 2024); 1082-1090
Research Article

Physico-Chemical Behaviour & Microstructural Analysis of Municipal Solid Waste Incinerated Ash Associated with Compressible Soil

Saurabh Kumar[1], Sneha Gupta[2*]

[1]Research Scholar, Civil Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, India.
Emails : saurabhbit074@gmail.com
[2]Assistant Professor, Civil Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, India

***Corresponding author**: Sneha Gupta
*Email: sgce@mmmut.ac.in; Ph: +91-9235552354

Abstract
All around the world, compressible soils can undergo significant volume changes, settlements, and deformations when loads are applied, which poses challenges for construction projects. Numerous researchers have looked into the stabilization of compressible soil by various chemicals and waste products. The new waste material that is now emerging is Municipal Solid Waste Incineration (MSWI) ash, which is a waste product generated by the municipal waste incineration plant. In this research, the stabilization of compressible soil samples has been done with varying percentages of MSWI ash to investigate the best suitable combination of MSWI ash and compressible soil for the stabilization purpose. This research underscores the importance of implementing stringent safety and monitoring protocols when using MSWI ash in construction to protect human health as per USEPA guidelines by conducting the leaching test. In this study, physical, index properties, unconfined compressive strength, and leaching behaviour of soil sample with varying percentage of MSWI ash have been investigated. The obtained results shows that the mixing of MSWI ash in compressible soil as a stabilizer enhances the UCS, MDD and other strength properties of soil by decreasing their plasticity. Microstructural and mineralogical behaviour of soil have also been investigated. It is found that 20% of MSWI ash is required to be mixed with the soil for the optimum results. The study recommends implementing stabilization techniques to minimize heavy metal leaching and calls for continuous monitoring to ensure the safe and sustainable use of MSWI ash in construction projects.

Keywords: Municipal solid waste incineration Ash, Sustainable approach, Microstructural analysis, Heavy metals, Strength properties.

***Author for correspondence: Email**: *sgce@mmmut.ac.in*

Received: August, 2024 *Accepted: November, 2024*

DOI: https://doi.org/10.53555/AJBR.v27i4S.3759

1. Introduction

The increasing population has led to a substantial rise in the generation of municipal solid waste (MSW). In India, an estimated total of 1,70,339 tons per day (TPD) of waste is produced, with approximately 1,56,449 TPD being collected Central Pollution Control Board (CPCB) annual report 2021-22. Direct dumping in open spaces is the most popular method for managing this enormous amount of waste.. To handle MSW, a large number of landfills have been constructed. Many landfills, or dumping grounds, have been set up to handle MSW [1]. However, the communities surrounding these waste sites are at serious danger for health problems. Collective municipal Waste releases toxic gasses throughout the decomposition process, which further affects the local population's health and the quality of the air, and harmful materials leach into the ground, contaminating the soil and groundwater. Direct dumping of municipal solid waste (MSW) at disposal sites poses significant risks to human health and the environment. This practice contaminates the air and soil, leading to various adverse effects. Airborne pollutants from waste decomposition, including harmful gases and particulate matter, contribute to respiratory diseases such as asthma and chronic bronchitis [2,3]. Furthermore, cardiovascular problems and other illnesses might be made more likely by exposure to harmful substances in the air and soil. Therefore, uncontrolled waste dumping produces a dangerous environment that affects the health of surrounding communities and calls for better waste management techniques [4]. Incineration involves the combustion of MSW at high temperatures (850℃-1100℃) in specialized facilities known as waste-to-energy (WTE) plants. The heat generated from incineration can be used to generate electricity or steam for heating purposes [5]. Air Pollution Control (APC) devises are attached to control the harmfull gases emmissions to the environment. Incineration reduces the volume of waste and also recover energy from the incineration process, but it also produces air emissions and ash residue [6].

Compressible soils may be stabilized and reinforced mainly by utilizing a range of well-studied binder ingredients, including fly ash, cement, lime, etc [7]. However, in order to increase the strength of clay while taking the economics and environment into consideration, current research have focused on solid waste incineration ash as primary and basic additions in addition to activators. Municipal Solid Waste Incinerated (MSWI) ash has been explored as a material for stabilizing the compressible soils in certain geotechnical applications [8]. Stabilization involves improving the engineering properties of the soil to enhance its strength, durability, and workability. When municipal solid waste is burned in an MSWI facility, various materials are combusted, leaving behind residues such as bottom ash and fly ash. Bottom ash (BA) is the heavier ash fraction that settles at the bottom of the incinerator and BA is collected at the bottom of the combustion chamber. Bottom ash typically accounts for the majority of the ash produced in an MSWI facility. Fly ash is the lighter ash fraction that is carried up into the flue gas stream and collected by air pollution control devices, such as electrostatic precipitators or baghouses [9,10].

Waste materials can be beneficially reused as stabilizing agents to improve the engineering properties of compressible soils, such as strength, durability, and workability. There are several waste materials commonly used for soil stabilization such as Granulated Blast Furnace Slag (GBFS), Recycled Concrete Aggregate (RCA), Fly Ash, Cement Kiln Dust (CKD), Waste Plastic, Tire-Derived Aggregate (TDA), Waste Glass etc. [11-14]. But we uses municipal solid waste incineration ash from thermal power plants

The main objective of this research MSWI ash-stabilized compressible soil is to improve the engineering properties of the soil, such as strength, stability, and durability, by incorporating ash materials into the soil matrix. Previous studies have helped to shed information on how MSWI ash affects the engineering properties of soil [15,16]. Although the majority of these research have concentrated on particular areas, like strengthening UCS and CBR values. There's a deficiency in the literature about a thorough analysis of different geotechnical characteristics and micro structural analysis. In order to fill this research gap, the current research will thoroughly investigate the effects of adding different MSWIA contents on the geotechnical characteristics of compressible soil, with incremental rate of 5%. In this study, index properties, Atterberg's limits, particle size distribution, specific gravity, and free swell index of collected compressible soil samples were investigated in the laboratory. The stabilization of collected soil samples has been done with varying percentages (2.5%, 5%, 10%, 15%, 20%, and 25%) of MSWIA to find out the best suitable combination of soil and MSWI ash in the aspects of soil stabilization. Micro structural and mineralogical behavior of soil and MSWI ash combinations have also been investigated on the basis of SEM & XRD analysis. The reuse of ash in construction can thus be a sustainable option, provided that safety measures are rigorously enforced.

2. Material and methods

2.1 Soil

Soil was collected from the Ramgarh Tal, in the south eastern part of the Gorakhpur city (India). The position of the location is 26° 44′ 0″ N, 83° 25′ 0″ E (26.733333, 83.416667) latitude and longitude. The color of the collected soil sample is Yellowish-Brown. The soil is collected in airtight polythene bags and sieved through a 4.75mm sieve, then dried for 24 hours in the oven at 105-110℃. Following this, the soil's engineering parameters were ascertained in a lab and are shown in Table 1. The collected soil samples were found very fine particles and the clay content was found to be high.

The soil sample contained 0% gravel fraction, 41.67% silt fraction, and 58.33% clay fraction. As per ASTM D2487-17 (2017) and ASTM D6913 (2017) , the collected soil sample has been classified into medium compressibility (CI) followed by the particle size and sedimentation analysis.

Table 1. Physical and index properties of collected soil sample

Atterberg Limits	Value (%)
Liquid limit (LL)	49
Plastic limit (PL)	23.16
Shrinkage limit (SL)	6.66
Plasticity index (PI)	25.84

Grain Size Distribution	Value
Silt fraction (%)	41.67
Clay fraction (%)	58.33
Free swell index (%)	65
IS classification	CI
Specific gravity	2.63
OMC (%)	16
MDD (gm/cc)	1.68
UCS (KN/m^2)	245.32
Soaked CBR value (%)	4.24
Unsoaked CBR value (%)	10.66

2.2 MSWI ash

The incinerated ash for this investigation has collected from the MSW incineration plant in New Delhi. The samples were dried in an oven at 105–110 degrees Celsius. A 4.75 mm sieve was used to screen the ash sample [17]. After that, the ash samples were put in an airtight container for later use.. The MSWI ash used for this study has a specific gravity of 2.13, and the physical and index properties as presented in Table 2. The color and shape of MSWI ash utilized in this investigation is Gray and sub-rounded respectively [18]. Particles of medium to fine sand make up the majority of MSWI ash.

Table 2. Index and physical properties of MSWI ash

Parameters	MSWI ash
Specific gravity	2.13
Colour	Gray
Natural water content	23.98
Shape	Sub-rounded / Rounded
Liquid limit (LL)	28.50%
Plastic limit (PL)	NA
Coarse grain fraction (%)	96.40
Fine grain Fraction (less than 0.075 mm) (%)	3.6
Coefficient of Curvature (Cc)	1.06
Coefficient of Uniformity (Cu)	7.36
OMC (%)	16
MDD (gm/cc)	1.44

2.3 Methodology

A popular technique for assessing cohesive soil strength is the Unconfined Compressive Strength (UCS) test. The soil sample's compression failure point is determined by measuring the load per unit area in this test. The components of this apparatus include a displacement or strain measurement instrument, a cylindrical mould for the soil sample, and a loading device. A cylindrical shape is prepared by the soil sample for testing, and an axial load is applied gradually or continuously until failure happens. The values of axial strain and stress are recorded during the test. The unconfined compressive strength is the corresponding stress that results from noting the specimen's failure point.

The following formula is used to get the unconfined compressive strength (UCS):

UCS = Maximum Axial Load/Corrected Cross-Sectional Area of the Specimen.

3. Results and Discussion

The engineering properties were determined in the laboratory, and as a result, the soil was compressible in nature. Engineering properties were changed with the varying percentage of MSWI ash, presented in Table 3. With a rise in the proportion of MSWI ash, unconfined compressive strength improved. Hence, it has been investigated that MSWI ash can be used as a cohesive soil stabilizer. The efficiency of MSWI ash in stabilizing very cohesive clayey soils has been explained by Li, L. et al. [19]. The investigation shows that the optimum stabilization has occurred in soil mixed with 20% MSWI ash.

Table 3. Engineering Properties of soil with various percentages of MSWI ash

Engineering Properties	collected soil sample	97.5 S/ 2.5 MSWIA	95 S/ 5 MSWIA	90 S/ 10 MSWIA	85 S/ 15 MSWIA	80 S/ 20 MSWIA	75 S/ 25 MSWIA
Silt (%)	69.13	75.67	80.66	82.47	81.93	89.75	85.83
Clay (%)	30.87	24.32	19.33	17.52	18.06	10.25	14.16
LL	46.5	45.4	43.3	41.4	40	38.5	36.7
PL	24.2	23.9	23.1	21.8	21.1	21.0	20.8
PI	22.3	21.5	20.2	19.6	18.9	17.5	15.9
SL	6.66	9.2	9.56	10.57	10.78	11.88	12.01
Free swell index (%)	46	45	42	38	30	23	20
OMC (%)	16.6	17.4	18.3	18.6	19	20.8	21
MDD(g/cc)	1.68	1.65	1.60	1.58	1.54	1.52	1.50
UCS (KN/m^2)	245.3	270	340	424	510	585	604.5
Unsoaked CBR value (%)	10.66	12.0	13.84	15.20	16.90	19.72	20.64
Soaked CBR value (%)	4.24	4.6	5.5	7.0	8.5	9.1	9.26

3.1 Impact on Moisture-Density Correlation

Table 3 shows how the optimum moisture content (OMC) of collected soil samples changes as the MSWI ash percentage increases. When mixed with MSWI ash, clayey soils often show an increase in OMC. This is because the coarse particles in the ash raise the void ratio, which means that more water is needed for the best possible compaction. when the percentage of MSWI ash is increased in the soil, more water is required to complete the hydration process. Soil particles due to moisture in the compressible soil dispersion process take place.

The changes in maximum dry density (MDD) with MSWI ash percentage. When MSWI ash mixed with soil than combination of soil-ash composite has a lower MDD than the normal clayey soil. MSWI ash generally has a lower specific gravity compared to Collected soil sample. When MSWI ash mixed with soil, this reduces the overall specific gravity of the mixture, resulting in a lower MDD.

3.2 Impact on Consistency Characteristics

Figure 1 display the impact of MSWI ash on consistency limits. Research has found that when the percentage of MSWI ash in a compressible soil sample is increased, there is a decrease in the LL, PL, PI but increases the shrinkage limit. Pozzolanic materials, like MSWI ash, have a significant impact on soil index features because they minimize the flocculation thickness and form a double layer with soil particles [20]. When a pozzolanic material is added to the soil to improve its plasticity, cation exchange occurs initially until the process of flocculation is completed, as stabilizer was added to clayey soils, a cation interchange reaction happened, which caused the thickness of the double layer to decreases.

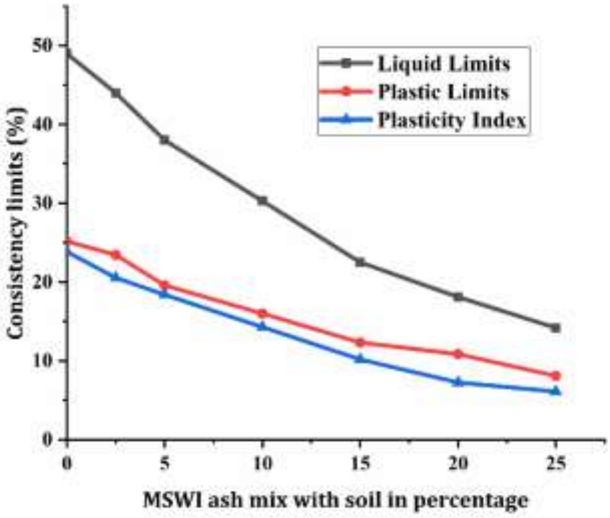

Figure 1. Consistency limits of soil and MSWI ash mixes

3.3 Impact on Strength Characteristics (Unconfined Compressive Strength)

Soil has been tested for Unconfined Compressive Strength (UCS) in compliance with ASTM D2166/D2166M-16 (2016). The UCS results for the various percentages of MSWI ash and variations in the UCS value of the specimen failure pattern with MSWI ash content are shown in Figure 2. The UCS of the mixture continued to rise until the MSWI ash percentage in the soil reached 20%, but the further increase in strength was quite limited. For 20% of the MSWI ash additive, an increase in soil strength of around 146% of the initial strength was seen.

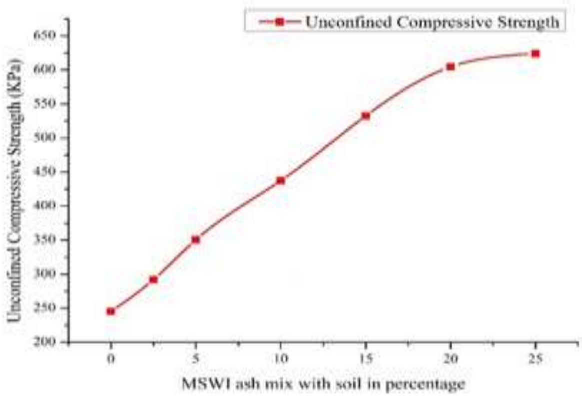

Figure 2. UCS values with varying MSWIA on soil

3.4 Impact on CBR value

The CBR test has been done according to ASTM D1883–21 (21AD) . The CBR values in soaked and unsoaked conditions with the different percentages of MSWI ash mixed with the soil. The soaked CBR value (soaking period 96 hours) of compressible soil was 4.24%, which increased to 9.26% on adding 20% MSWI ash, representing a rise of 118%. Typically, when MSWI ash content increases, the CBR values measured increase as well. This increase may be due to the presence of adequate calcium, which is required for the synthesis of the primary chemicals (CSH and CAH) that contribute to strength gain.

3.5 Physico-Chemical Properties of MSWI Ash and Compressible Soil Mixture

The analysis of physico-chemical properties revealed significant changes in the behavior of compressible soil when mixed with municipal solid waste incineration (MSWI) ash. The alkaline characteristics of the MSWI ash was reflected in the soil-ash mixture's much higher pH as compared to the native soil. Because it can affect heavy metal mobility and the overall integrity of the soil-ash matrix, this rise in alkalinity is critical.

With an increase in ash concentration, a small drop in the soil-ash mixture's specific gravity was noted. This decrease is explained by the fact that the ash particles in natural soil have a lower density than the mineral particles. Furthermore, the Atterberg limits of the soil changed as a result of the presence of MSWI ash, and the plasticity index generally decreased, suggesting a decrease in the soil's plasticity. This alteration in plastic behavior implies that the soil becomes more workable and less compressible for use in building applications.

3.6 Environmental Considerations and Leaching Behavior

Leaching tests revealed that certain heavy metals, such as lead, cadmium, and chromium, were present in leachates from the soil-ash mixture. The concentration of these metals was found to increase with higher ash content, particularly under acidic conditions. The pH-dependent leaching behavior indicates that the environmental stability of the soil-ash mixture could be compromised in acidic environments, posing a risk of groundwater contamination [21,22].

The results underscore the importance of implementing stabilization measures, such as the addition of binders or encapsulation techniques, to minimize leaching risks. The use of alkaline additives, for example, could help maintain a stable pH and reduce metal solubility. Additionally, long-term monitoring of the soil-ash mixture is recommended to assess the potential for leaching under varying environmental conditions. some commonly monitored heavy metals and their typical leaching concentrations are given in table 4. Heavy metal concentrations drop to 20% below permissible limits when MSWI ash content is introduced to the soil. It has been observed that the concentration of heavy metals in the soil does not fall under acceptable levels if more than 20% of the ash is mixed with the soil.

Table 4. Concentrations of heavy metals for different ratios of soil- MSWI ash

Heavy Metals	MSWI Ash (mg/l)	80% Soil + 25% MSWI Ash (mg/l)	80% Soil + 20% MSWI Ash (mg/l)	85% Soil + 15% MSWI Ash (mg/l)	Acceptable limits as per USEP 2016
Lead (Pb)	125.40	1.21	1.15	0.9	1.2
Cadmium (Cd)	24.32	0.5	0.42	0.045	0.6
Chromium (Cr)	22.25	13	11.5	10.8	15
Nickel (Ni)	8.6	1.2	0.9	0.90	2.0
Arsenic (As)	0.12	0.07	0.02	0.02	0.05
Mercury	0.02	0.001	0	0	0
Barium	400	120	80	75	140
Chlorides	3.8	2.7	2	1.8	2.5
Sulphates	1	0.65	0.6	0.5	0.6

3.7 Morphological studies of soil and soil-MSWI ash composite material

3.7.1. SEM study of compressible soil and Soil-MSWI ash composite

Soil structure has been analysed by SEM analysis. SEM images are used to examine how the geo-morphology of soil particles has changed. Figure 4 (a). represent the SEM pictures of collected soil sample and it show the Interweaving bunches assemblage of clay particles and figure 4 (b). shows the SEM image of the soil mixed with 20% of MSWI ash. SEM analysis shows that MSWI ash reduced the voids which explains the increase in the strength and increase in the UCS and reduced plasticity indices.

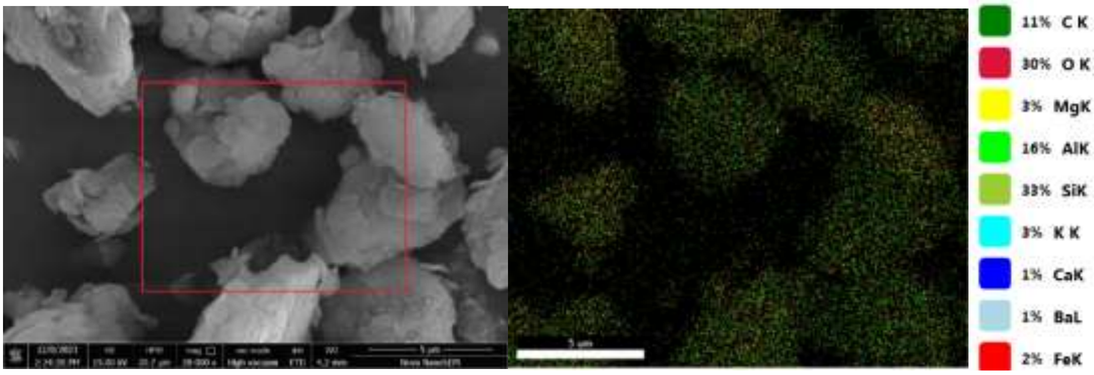

Figure 3 (a) SEM images of Soil Sample

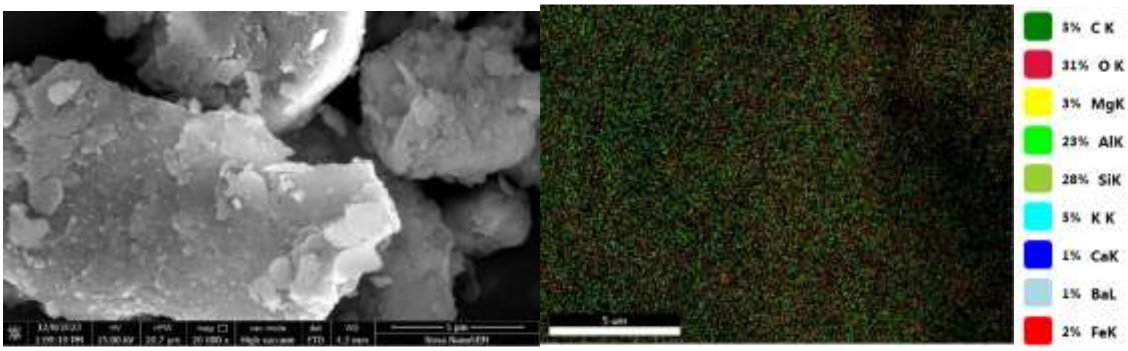

Figure 3 (b). SEM image of combination of soil and MSWI (80 S / 20 MSWIA)

A study of the microstructure of stabilized composite soil revealed that the presence of large amounts of C-S-H and C-A-H gels in stabilized composites soil makes them stronger strength and better at encasing heavy metals. The SEM investigation showed that the matrix had improved, confirming the stronger pozzolanic reaction of MSWI ash and the therefore higher strength due to the increased surface area.

3.7.2. XRD study of compressible soil and Soil-MSWI ash composite

The XRD test results are displayed in Figure 4(a) for untreated compressible clay soil and in Figure 4(b) for stabilized compressible clay soil. The three most common minerals found in the soil samples are quartz, kaolinite, and illite [23]. The XRD profile peaks of the stabilized soil sample and the ordinary soil sample are different. Fig. 4(c) compares the XRD test results for stabilized and untreated compressible clay soil. The treated soil's decreased mineral content has caused modifications to the XRD profile's peaks. At two theta-degree angles—25.36, 29.29, and 45.65—stabilized soils contain the minerals C-A-S-H, quartz (SiO3), calcite (CaCO3). The fact that calcite is present in the stabilized soil range indicates that the carbonation of calcium is what causes the calcite to be present in the soil.

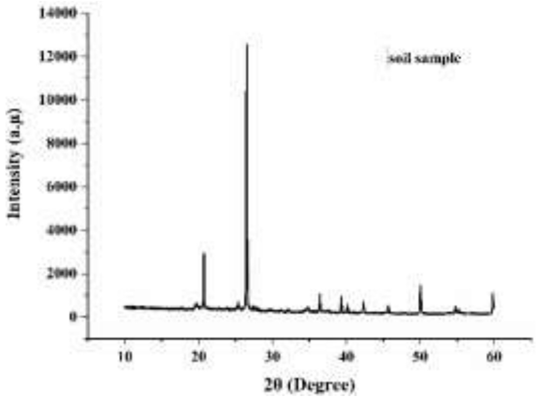

Figure 4 (a). XRD curve of natural soil sample

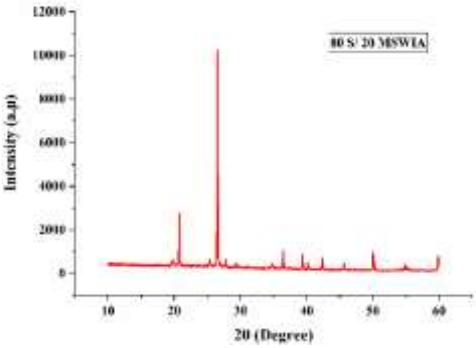

Figure 4 (b). XRD curve of 80 S/ 20 MSWIA

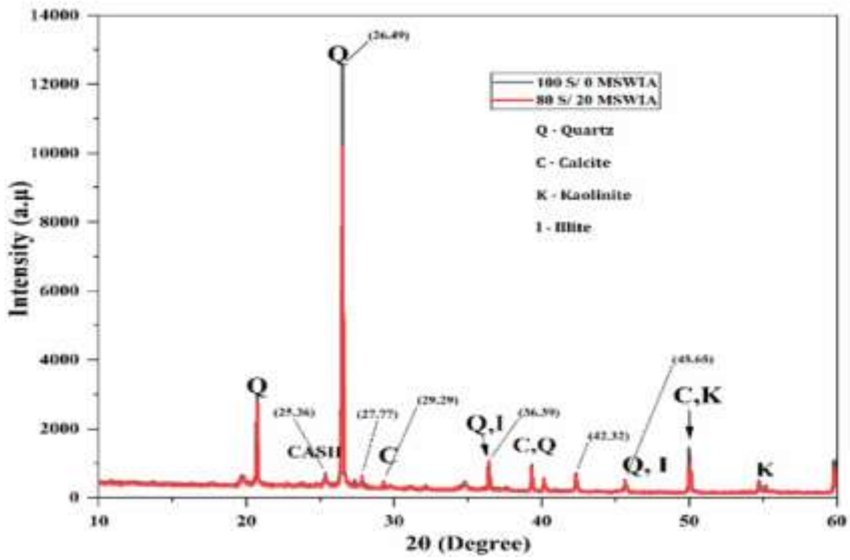

Figure 4 (c). XRD curves for stabilized soil (80 S/ 20 MSWIA) and natural soil sample

4. Conclusions

This study indicates that MSWI ash is beneficial for stabilization of compressible soil, even though the stabilization is dependent on chemical composition, fineness and percentage of MSWI ash added to the soil as well as the type of parent soil. According to the results, the soil became more effective as a subgrade material by reducing the value of differential free swell and consistency limitations. The value of UCS increased by more than 146%, and the soaked CBR values increased by 118%, when a sufficient amount of MSWI ash (20%) and soil sample (80%) was added. The obtained results revealed that the UCS and CBR values of the compressible soil are improved by using MSWI ash as a soil stabilizer. SEM examination of stabilized compressible soil also supports the observed results..The mineralogical investigation using the XRD test revealed that the addition of MSWI ash and soil results in a drop in the height of quartz ($CaCO3$) and an increase in certain peak height of stabilized soil at an angle between 10º and 60º, which ensures the development of C-A-S-H in the treated soil. The incorporation of MSWI ash into compressible soil has the potential to significantly improve shear and compressive strength properties, thereby enhancing the engineering performance of the soil.

In conclusion, while soil-MSWI ash mixtures can be used in road construction, the potential human health risks necessitate careful assessment, risk management, and regulatory oversight. Without appropriate mitigation measures, the use of such materials could lead to significant health hazards, particularly in areas of prolonged exposure. Therefore, a balanced approach involving risk minimization, ongoing monitoring, and the adoption of safer alternatives is crucial to safeguard human health in road construction projects using soil-MSWI ash mixtures.

5. References:

1. Bansal D, Gupta G, Ramana GV. Environmentally responsible disposal and reuse of MSW incineration bottom ash: assessment from two Indian plants. Clean Technologies and Environmental Policy. 2023;26:1439–1454. https://doi.org/10.1007/s10098-023-02550-y.
2. Intelligent technologies powering clean incineration of municipal solid waste: A system review
3. Zhao XY, Yang JY, Ning N, Yang Z. Chemical stabilization of heavy metals in municipal solid waste incineration fly ash: a review. Environmental Science and Pollution Research. 2022;29:40384–40402 https://doi.org/10.1007/s11356-022-19649-2.
4. Kumar S, Singh D. Municipal solid waste incineration bottom ash: a competent raw material with new possibilities. Innovative Infrastructure Solution. 2021;6: 201. doi.org/10.1007/s41062-021-00567-0.
5. Singh Randhawa K, Chauhan R. Stabilizing black cotton soil in subgrade with municipal solid waste incineration ash for lowering greenhouse gas emission: A review. Materials Today: Proceedings. 2021. doi: 10.1016/j.matpr.2021.08.037.
6. Junyu Tao, Zaixin Li, Chao Chen, Rui Liang, Shuang Wu, Fawei Lin, Zhanjun Cheng, Beibei Yan, Guanyi Chen. Intelligent technologies powering clean incineration of municipal solid waste: A system review. Science of The Total Environment. 2024;935. https://doi.org/10.1016/j.scitotenv.2024.173082.
7. Sakr M, El-Sawwaf M, Azzam W. Improvement of shear strength and compressibility of soft clay stabilized with lime columns. Innovative Infrastructure Solution. 2021;6:133. https://doi.org/10.1007/s41062-021-00509-w.
8. Chand Malav, Lal Yadav, Krishna Kumar, Gupta N, Kumar S. A review on municipal solid waste as a renewable source for waste-to-energy project in India: current practices, challenges, and future opportunities. Journal of Cleaner Production. 2020;277:123227. Doi: 10.1016/j.jclepro.2020.123227.
9. Datta M, Gupta G. Somani M. Geo environmental Considerations for Bulk Reuse of MSW Residues from Old Dumps and WTE Plants in Geotechnical Applications. Indian Geotechnical Journal. 2021;51:63–83. https://doi.org/10.1007/s40098-020-00491-7.
10. Kumar S, Gupta S, Singh N. Characterization and Sustainable Utilization of Municipal Solid Waste Incineration Ash: A Review. In: Al Khaddar, R., Singh, S.K., Kaushika, N.D., Tomar, R.K., Jain, S.K. (eds) Recent Developments in Energy and Environmental Engineering. TRACE 2022. Lecture Notes in Civil Engineering, vol 333. Springer, Singapore 2023. https://doi.org/10.1007/978-981-99-1388-6_30.
11. Vydehi KV. Baig Moghal AA. Effect of Biopolymeric Stabilization on the Strength and Compressibility Characteristics of Cohesive Soil. Journal of Materials in Civil Engineering. 2022;34(2):1-12. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004068.
12. Jun Liu, Zhengdong Wang, Guangming Xie, Zhenlin Li, Xu Fan, Weizhuo Zhang, Feng Xing, Luping Tang, Jun Ren. Resource utilization of municipal solid waste incineration fly ash - cement and alkali-activated cementitious materials: A review. Science of The Total Environment. 2022;852. https://doi.org/10.1016/j.scitotenv.2022.158254.
13. Barman D, Dash SK. Stabilization of expansive soils using chemical additives: A review. Journal of Rock Mechanics and Geotechnical Engineering. 2022;14:1319-1342. https://doi.org/10.1016/j.jrmge.2022.02.011.
14. Li Z, Fan TW, Lun MS. Optimization of municipal solid waste incineration for low-NOx emissions through numerical simulation. Scientific reports. 2024;14:19309. https://doi.org/10.1038/s41598-024-69019-w
15. Sikder, S., Toha, M., Rahman, M.M. (2024). Municipal Solid Waste Incineration: An Incredible Method for Reducing Pressures on Landfills. In: Souabi, S., Anouzla, A. (eds) Technical Landfills and Waste Management. Springer Water. Springer, Cham. https://doi.org/10.1007/978-3-031-55665-4_7
16. Assi A, Bilo F, Zanoletti A, Valsesia A, Zacco A. Zero-waste approach in municipal solid waste incineration: Reuse of bottom ash to stabilize fly ash.

Journal of Cleaner Production. 2019;245: 118779. https://doi.org/10.1016/j.jclepro.2019.118779.

17. Singh, D., Kumar, A. Geo-environmental application of municipal solid waste incineration ash stabilized with cement. Journal of Rock Mechanics and Geotechnical Engineering. 2017;9(2):370–375. https://doi.org/10.1016/j.jrmge.2016.11.008.
18. Singh, D., Kumar, A. Mechanical characteristics of municipal solid waste incineration bottom ash treated with cement and Fiber. Innovative Infrastructure Solution. 2019;4(61). https://doi.org/10.1007/s41062-019-0247-7.
19. Li L, Zang T, Xiao H, Feng W, Liu Y. Experimental study of polypropylene fibre-reinforced clay soil mixed with municipal solid waste incineration bottom ash. European Journal of Environmental and Civil Engineering. 2020; 1–17. doi:10.1080/19648189.2020.1795726.
20. Varaprasad BJS, Joga JR, Joga SR. Reuse of Municipal Solid Waste from Incinerated Ash in the Stabilization of Clayey Soils. Slovak Journal of Civil Engineering. 2020;28(4). Doi:10.2478/sjce-2020-0024.
21. Kumar S, Gupta S. Engineering Behaviour of Municipal Solid Waste Incinerated Ash with Compressible Soil: An Approach Towards the Waste Utilization & Stabilization of Compressible Soil. Mechanics of Advanced Composite Structures. 2024; 24:85-96. https://doi.org/10.22075/macs.2024.32197.1575.
22. Singh, N., & Kumar, V. (2024). A Study on Geotechnical Behaviour of Municipal Solid Waste Ash Treated with Fiber and Cement. Civil Engineering Infrastructures Journal. https://doi.org/10.22059/ceij.2024.375087.2049.
23. Sendilvadivelu, A., Dhandapani, B., & Vijayasimhan, S. Strength, mineralogical and microstructural studies on clayey soil stabilized by bio-stabilized waste ash with lime. Journal of Material Cycles and Waste Management.2023;25(6):3625-363. https://doi.org/10.1007/s10163-023-01782-w.